Cooperative Uplink Inter-Cell Interference (ICI) Mitigation in 5G Networks

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A thesis submitted to the University of Hertfordshire in partial fulfilment of the requirements for the degree of Doctor of philosophy

The programme of research was carried out in the Science and Technology Research Institute (STRI), School of Engineering and Technology,

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United Kingdom.

July 2016

ABSTRACT

In order to support the new paradigm shift in fifth generation (5G) mobile communication, radically different network architectures, associated technologies and network operation algorithms, need to be developed compared to existing fourth generation (4G) cellular solutions. The evolution toward 5G mobile networks will be characterized by an increasing number of wireless devices, increasing device and service complexity, and the requirement to access mobile services ubiquitously.

To realise the dramatic increase in data rates in particular, research is focused on improving the capacity of current, Long Term Evolution (LTE)-based, 4G network standards, before radical changes are exploited which could include acquiring additional spectrum. The LTE network has a reuse factor of one; hence neighbouring cells/sectors use the same spectrum, therefore making the cell-edge users vulnerable to heavy inter cell interference in addition to the other factors such as fading and path-loss. In this direction, this thesis focuses on improving the performance of cell-edge users in LTE and LTE-Advanced networks by initially implementing a new Coordinated Multi-Point (CoMP) technique to support future 5G networks using smart antennas to mitigate cell-edge user interference in uplink. Successively a novel cooperative uplink inter-cell interference mitigation algorithm based on joint reception at the base station using receiver adaptive beamforming is investigated. Subsequently interference mitigation in a heterogeneous environment for inter Device-to-Device (D2D) communication underlaying cellular network is investigated as the enabling technology for maximising resource block (RB) utilisation in emerging 5G networks. The proximity of users in a network, achieving higher data rates with maximum RB utilisation (as the technology reuses the cellular RB simultaneously), while taking some load off the evolved Node B (eNodeB) i.e. by direct communication between User Equipment (UE), has

been explored. Simulation results show that the proximity and transmission power of D2D transmission yields high performance gains for D2D receivers, which was demonstrated to be better than that of cellular UEs with better channel conditions or in close proximity to the eNodeB in the network. It is finally demonstrated that the application, as an extension to the above, of a novel receiver beamforming technique to reduce interference from D2D users, can further enhance network performance.

To be able to develop the aforementioned technologies and evaluate the performance of new algorithms in emerging network scenarios, a beyond the-state-of-the-art LTE system-level-simulator (SLS) was implemented. The new simulator includes Multiple-Input Multiple-Output (MIMO) antenna functionalities, comprehensive channel models (such as Wireless World initiative New Radio II i.e. WINNER II) and adaptive modulation and coding schemes to accurately emulate the LTE and LTE-A network standards.

ACKNOWLEDGEMENTS

I owe my deepest gratitude to my supervisor Dr. Pandelis Kourtessis for giving me this opportunity and believing in me all the way through providing guidance and support. Any attempt at any level cannot be satisfactorily completed without the support and guidance of him. I would also like to thank my supervisor Prof. John M. Senior for his constant support and motivation that has encouraged me.

Secondly I would like to express my immense gratitude to Dr. Milos Milosavljevic who is not only a supervisor but an excellent mentor and a friend who was there for me even in busy times providing help and support to achieve my goals during my research.

This is also a great opportunity to thank my friends Dr. Ahmed Amate, Dr Xiaojun Zhai, Dr. Wansu Lim, Dr. Efstratios Sofianos and all my colleagues in D437 for establishing a friendly working environment and also for giving me valuable advice.

At last but not least, I would like to thank my parents, my sister, Sachi, my housemates and all my friends and family who were there for me, supporting me in easy and hard times during the time of my academic life.

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GLOSSARY

1G	First generation
2G	Second generation
3G	Third generation
3GPP	3rd Generation Partnership Project
4G	Fourth generation
5G	Fifth generation
ADC	Analogue to Digital Conversion
AWGN	Additive white Gaussian noise
BBU	Baseband unit
BS	Base station
CAPEX	Capital expenditure
CDF	Cumulative distribution function
CoBF	Coordinated beamforming
CoMP	Coordinated multipoint
CoSH	Coordinated scheduling
CR	Cognitive Radio
CRAN	Centralised Radio Access Network

D2D	Device-to-Device
DL	Downlink
DSP	Digital Signal Processing
EPC	Evolved packet core
HDTV	High-definition television
HetNet	Heterogeneous network
IMT-A	International mobile telecommunications Advance
IP	Internet protocol
IoT	Internet of Things
ITU	International telecommunication union
ISD	Inter-site distance
JP	Joint processing
LTE	Long term evolution
LPM	Link performance model
LQM	Link quality model
LTE-A	Long-term evolution Advanced
M2M	Machine to Machine
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access

OPEX	Operational expenditure
QoE	Quality of Experience
QoS	Quality of service
RAN	Radio access network
RAT	Radio access technology
RRH	Remote Radio Head
ROI	Region of interest
SE	Spectral efficiency
SLS	System-level simulator
SIC	Self-interference cancellation
SC-FDMA	Single carrier frequency-division multiple access
UL	Uplink
WiFi	Wireless fidelity
WiMAX	Worldwide interoperability for microwave access
WINNER	Wireless world initiative new radio
WLAN	Wireless local area network
WMAN	Wireless metropolitan area network
WPAN	Wireless personal area network
WA	Wrap around

DECLARATION

The following papers are either under review or already published, and parts of the materials are included in this thesis:

- (Invited) T. Pitakandage, M. Milosavljevic, P. Kourtessis, and J. M. Senior, "**Cooperative 5G switched and adaptive receiver beamforming for fibre wireless networks**," in 2014 16th International Conference on Transparent Optical Networks (ICTON) 2014, pp. 1-4.
- (Invited) T. Pitakandage, M. Milosavljevic, P. Kourtessis, and J. M. Senior, "**Cooperative uplink inter-Cell interference (ICI) mitigation in 5G Fibre Wireless (FiWi) networks**," in 2015 17th International Conference on Transparent Optical Networks (ICTON) 2015, pp. 1-4.

Chapter 1

1. Introduction

1.1 Mobile Communication

In recent years, wireless communication networks have developed rapidly and the explosion of mobile services such as Internet of Things (IoT) with numerous low-cost Machine Type Communications (MTC) devices, intelligent wearable devices, vehicular sensors and environmental sensors etc has greatly increased the demand for higher wireless data rates to be delivered over cellular networks [1, 2]. It has been reported that in the near future, i.e. year 2020, some of the prime objectives or demands that need to be addressed are increased capacity, improved data rates, decreased latency, and better Quality of Service (QoS) [3].

Fifth Generation (5G) mobile is expected to be in operation around 2020, aiming to change the world by providing solutions to increasing internet data traffic which has driven the capacity demands for currently deployed Third Generation (3G) and Fourth Generation (4G) wireless technologies [4]. Societal development will lead to changes in the way mobile and wireless communication systems are used. Essential services such as e-banking, e-learning, and e-health will continue to proliferate and become more mobile [5]. On-demand information and entertainment (e.g., in the form of augmented reality) will progressively be delivered over mobile and wireless communication systems. These developments will lead to an avalanche of mobile and wireless traffic volume, predicted to increase a thousand-fold over the next decade [6, 7].

In a recent International Telecommunication Union (ITU) survey, it is highlighted that third generation (3G) mobile-broadband coverage is extending rapidly by covering 7.40 billion users in 2015 compared to 7 billion users in 2011 as illustrated in Figure 1-1 [2].

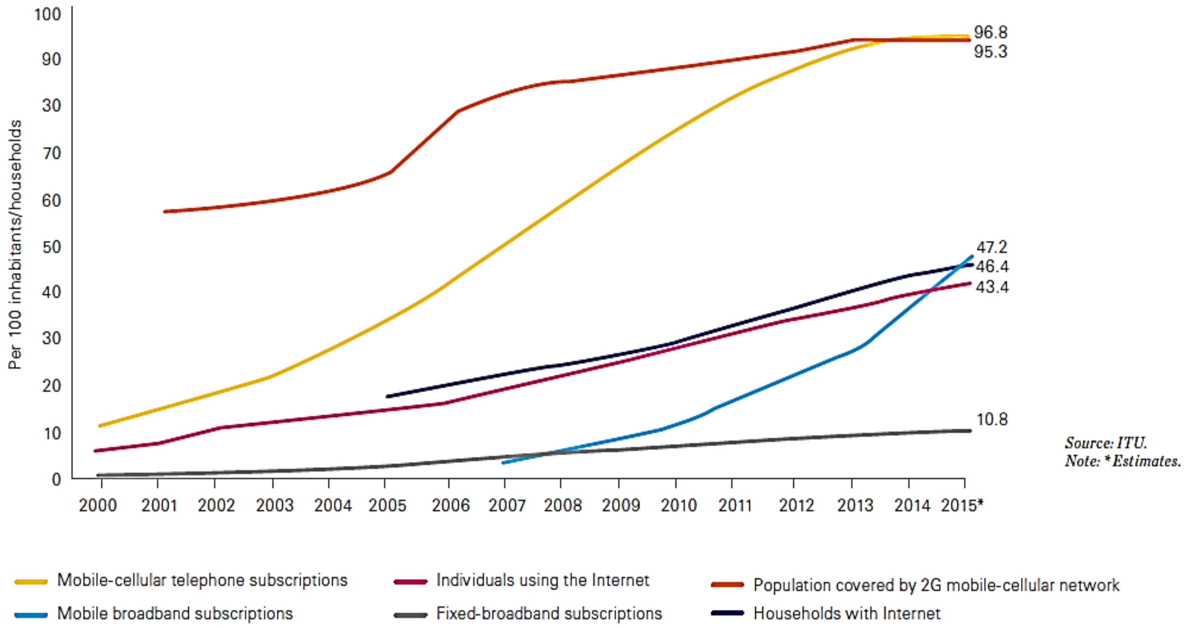

Figure 1-1: 15 Years of Information and communications Technology (ICT) growth (2000 to 2015) [2]

According to ERICSSON [1], advanced mobile technology will be globally ubiquitous by 2020 with 70 percent of people using smartphones and 90 percent covered by mobile broadband networks. Smartphones make up the majority of mobile broadband devices today and subscriptions are expected to have more than doubled by 2020, reaching 6.10 billion [1, 8].

The number of mobile broadband subscriptions is growing globally by around 30 percent year-on-year, increasing by approximately 150 million in the first quarter (Q1) of 2015 alone [1]. Long Term Evolution (LTE) continues to grow strongly and has reached around 600 million subscriptions, with approximately 105 million additions in Q1 of 2015 as shown in Figure 1-2 [1, 2]. Wideband Code Division Multiple Access/ Global System for Mobile (WCDMA/GSM) added around 60 million during Q1. The majority of 3G/4G subscriptions have access to Enhanced Data rates for GSM (GSM/EDGE) as a fall-back, although GSM/EDGE-only subscriptions declined by 30 million [8].

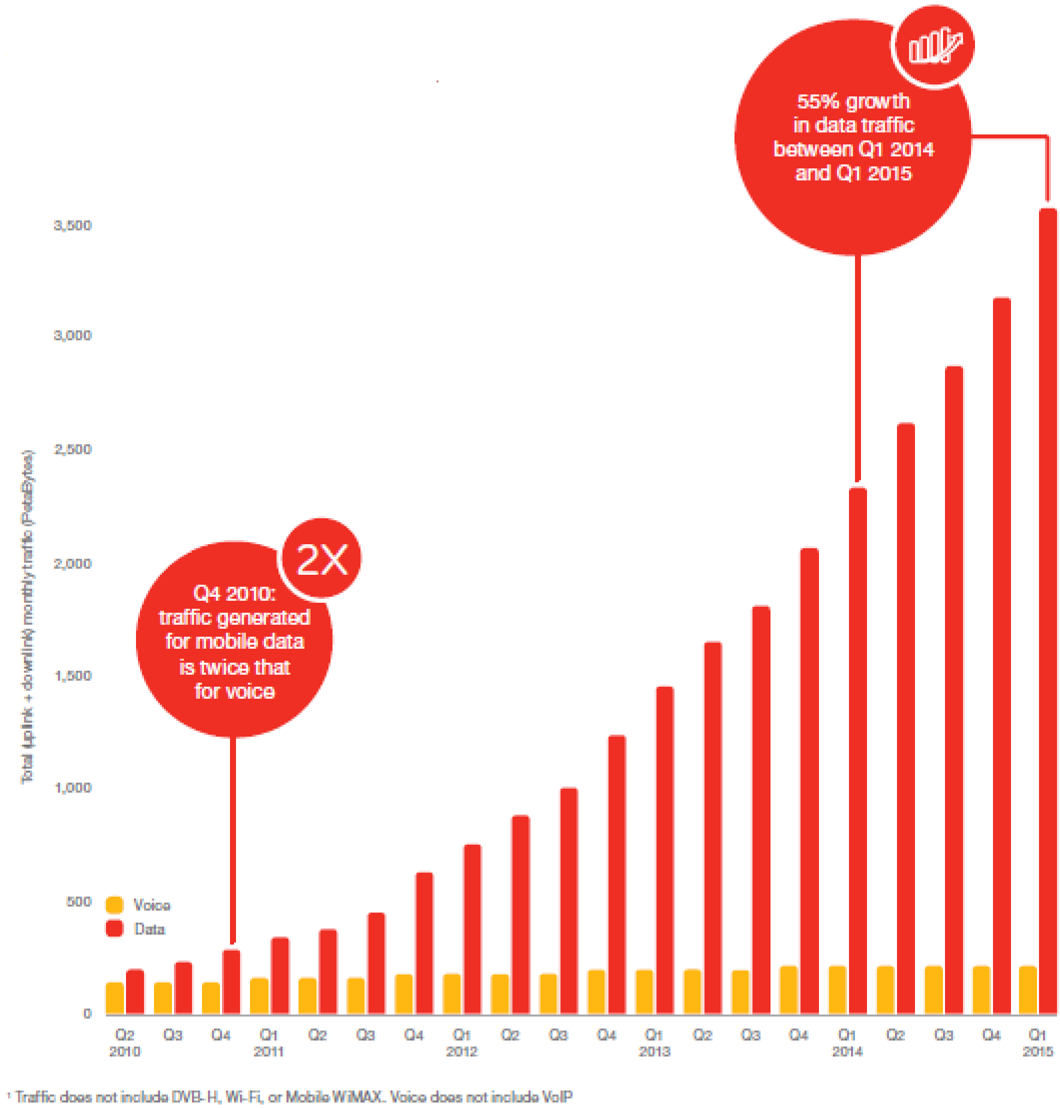

Figure 1-2: Uplink + Downlink monthly traffic growth compared to voice services [1]

New network functionalities and service capabilities are being implemented for both data and voice. These include improvements to both downlink and uplink speeds and new ways to efficiently deliver content at a certain quality level, e.g. LTE Broadcast. Improved voice quality and new, richer communications services like mobile HD voice (HD voice services using Adaptive Multi Rate Wideband technology (W-AMR)), Voice over LTE (VoLTE), video calling and enriched messaging are enabled by IP-based networks. Furthermore, with native Wireless-Fidelity (Wi-Fi) calling functionality now available on smartphones, users can be offered operator voice and communication services (SIM-based) over Wi-Fi.

1.1.1 4G Deployment

The following Figure 1-3 depicts the global coverage of 4G-LTE deployment in recent years as published in [9].

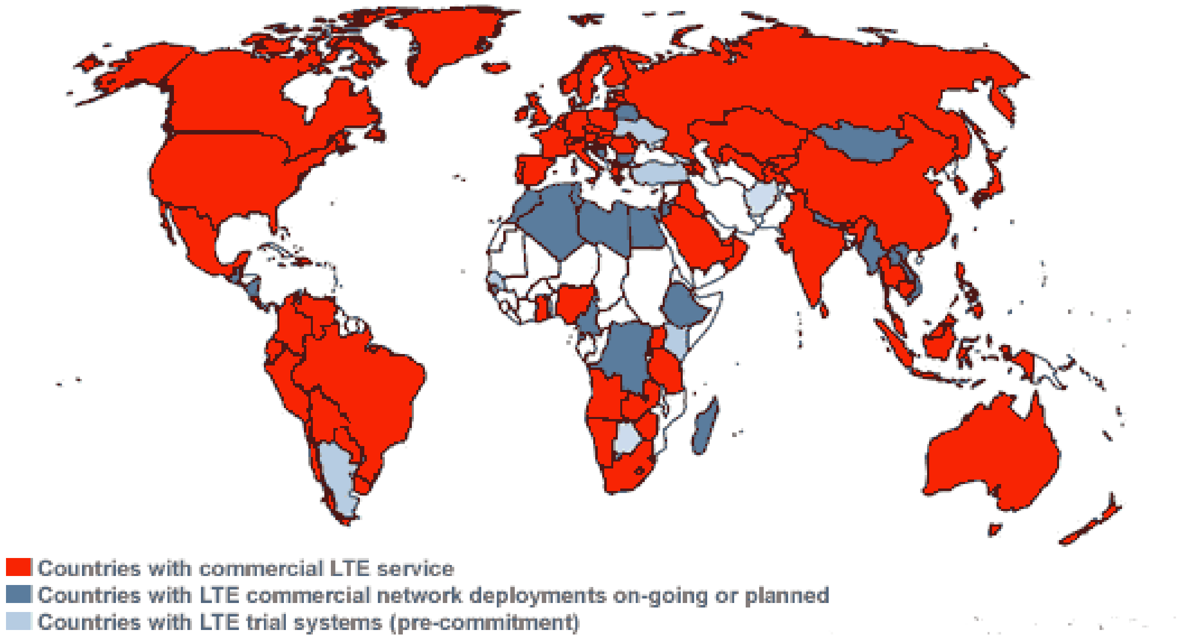

Figure 1-3: Map of 4G-LTE deployment [9]

According to a survey by Global mobile Suppliers Association (GSA) (an association with members such as Qualcomm, Ericson, Huawei, etc.) and the GSMA intelligence data, there were 352 operators with live commercial 4G-LTE networks globally as of the end of January 2015, with more than half of the world's mobile markets covered by at least one LTE operator [9, 10]. Most of the LTE operators with more than 30% of the total (108) are in Europe, followed by Asia Pacific (66), Latin America (55) and North America (47). Even though Asia Pacific region accounts for only one in six of the world's LTE operators, it provides almost half (47%) of LTE connections, largely due to substantial LTE bases in South Korea, Japan and China. Compared to the 14% of Europe connections, North America accounted for around a third (32%) of all LTE connections. It is also predicted that by the end of 2015 more than 10% of connections globally will be on LTE, with this share rising to more than three in every ten connections by 2020 [9-11].

1.1.2 Network Performance and Limitations of Current 4G Networks

Following the successful standardisation of High Speed Packet Access (HSPA), the 3rd Generation Partnership Project (3GPP) has specified the Universal Mobile Telecommunications System (UMTS) Terrestrial Radio-Access Network or UTRAN — LTE to meet the above mentioned increasing performance requirements of mobile broadband [12]. The peak throughput is 300Mbps in Downlink (DL) and 75Mbps in Uplink (UL), 2-3 time higher spectrum efficiency than Rel. 6 HSPA, very low latency around 5ms in Radio Access Network (RAN) and 100ms for connection setup time [13-15].

LTE offers extensive support for spectrum flexibility, supports both Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) and targets a smooth evolution from earlier 3GPP systems such as Wideband Code Division Multiple Access /High Speed Packet Access as well as 3rd Generation Partnership Project 2 systems such as CDMA2000 [3, 16, 17].

LTE downlink is implemented based on Orthogonal Frequency-Division Multiple Access (OFDMA) [18] and the uplink is based on the Single-Carrier Frequency Division Multiplexing Access (SC-FDMA) scheme where it has a low peak to average power ratio compared to OFDMA [19, 20]. Hence SC-FDMA transmission scheme was selected since it provides more energy efficiency from the User Equipment (UE) processing power requirement perspective [21].

Long Term Evolution Advanced (LTE-Advanced) known as Rel. 10 is an evolution of Rel. 8, therefore distinctive performance gains up to 1Gbps in downlink and 500Mbps in uplink peak data rates were achieved by using the new techniques such as carrier aggregation and

Multiple-Input-Multiple-Output (MIMO). LTE-Advanced should satisfy all the relevant requirements for LTE Rel. 8 [22, 23]. Secondly it should be fully backward compatible with Rel. 8. Therefore, a set of UEs for LTE-Advanced must be able to access Rel. 8 networks, and LTE-Advanced networks must be able to support Rel. 8 UEs. LTE-Advanced also shall meet or exceed the International Mobile Telecommunications Advanced (IMT-Advanced) requirements within the ITU-R time plan [24, 25]. The target peak data rate for the downlink was set to 1Gbps and the target peak data rate for the uplink was set to 500 Mbps [25]. Furthermore, new techniques like MIMO [26], carrier aggregation, coordinated multipoint (CoMP) and relaying were introduced in order to achieve the required capacity gain, along with more reliable communication [25].

LTE and LTE-Advanced are an Orthogonal Frequency Division Multiplexing (OFDM) based network utilize a frequency re-use of one (denoted by N = 1) [27]. A frequency re-use of N = 1 implies that the base stations in cells transmit on all available time-frequency resource blocks (RBs) simultaneously. However the resulting interference limited system for N = 1 deployment will not achieve the full potential capacity particularly for users at the cell edge. This is due to the high inter-cell interference, since all the cells use the same spectrum [28]. Therefore it becomes one of the main performance limitations of the 4G LTE network as the cell edge performance is compromised. Over the years the importance of inter-cell interference, has been recognised, and various techniques used from the days of GSM to mitigate its effects. Lot of research has been done in this area especially in downlink with the introduction of techniques like CoMP.

Multi-path fading is another limitation where obstacles in the surrounding environment attenuate the propagated signal, leading to flawed detection of the received signal [29]. Due to transmission power limitations in mobile terminals, the constraint on the (uplink) link budget will impose the need for smaller cell sizes or better interference mitigation techniques [30, 31].

In this direction scarcity of radio spectrum (which is finite and expensive) is also a major issue with wireless communication in general since it leads to inefficient spectrum usage. This requirement is driven by the need to meet targeted higher data throughputs for users not only near the base stations, but also at cell edge. This limits the LTE from providing the increasing high data rate requirements and quality of service (QoS). The trend of increasing demand for high QoS at the user terminal (UEs), coupled with the shortage of wireless spectrum, requires more advanced wireless communication techniques such as CoMP, joint reception, smart antennas to provide solutions, specially to mitigate inter cell interference to increase the cell edge throughput [32].

1.2 The use of Cooperative Inter-cell Interference Mitigation in 4G Networks and Beyond

Since the standardization and deployment process for the 4G technologies (LTE, LTE-Advanced) are mostly established, it is time for the research community to explore and research on what is likely to come next [33, 34]. It is anticipated that trillions of wireless nodes in IoT with diversified applications and services will be available in 5G wireless communication systems. These devices, however, may not be handled efficiently by the current wireless communication networks, which were not designed for frequent small data packets and simultaneous massive access [35, 36]. In this direction 5G studies are gaining more momentum worldwide, in an attempt to provide solutions for the exponential increase of mobile data traffic by 2020 [37, 38]. There are several projects and research initiatives working on 5G as mentioned in 3GPP RAN 5G workshops [39] which includes METIS and

METIS II [40, 41], 5GNOW [42], Combo [43], MOTO [44], MCN and iJOIN [45], etc. The following diagram (Figure 1-4) illustrates the 5G networks and services vison.

Figure 1-4: 5G Networks and services vision [46]

As illustrated in Figure 1-4 in order to meet the expected high throughput targets, small cells will be pushed further leading to Ultra Dense Networks (UDN). 5G will also introduce new radio area network paradigms such as Device to Device (D2D), Moving Networks (MN) and many more novel technologies as described in the next section.

1.2.1 Work towards the Development of Future Generation Networks

3GPP has been working on various aspects in the framework of 4G LTE-Advanced to enhance the spectrum utilisation and to provide the required bandwidth requirements. Mainly it introduced features including carrier aggregation; enhanced Inter-Cell Interference Coordination (eICIC), Co-ordinated MultiPoint (CoMP), advanced Heterogeneous Network (HetNet) capabilities, Massive MIMO and Device to Device communication as key enablers for future 5G networks. LTE-Advanced can aggregate up to five carriers (up to 100 MHz) to increase user data rates for all users. A HetNet is an attractive means of expanding mobile network capacity which is composed of multiple radio access technologies, architectures, transmission solutions, and base stations of varying transmission power. By enabling the hyper-dense HetNets (small-cells) and by integrating macro-cells with Pico and Femto-cells the anticipated 1000x capacity increase could be achieved. But this is only possible with advanced interference management techniques such as CoMP and Further-enhanced Inter-Cell Interference Coordination (FeICIC/IC) [47, 48]. These interference mitigation techniques are important for interference coordination between small cells, on the network side and also to cancel interference on common channels, on the device side.

Enhanced receivers play a crucial role in further improving LTE-Advanced. Devices that cancel inter-cell interference on both control and data channels provide more capacity and better data rates, particularly at cell-edges which will increase the user experience. Managing and cancelling interference in dense small cell deployments is even more beneficial to increase the overall performance [49, 50].

Extending LTE-Advanced to the unlicensed spectrum will benefit both 3G/4G operators and users where the operators can leverage on both licensed and unlicensed spectrum using a unified network to expand data capacity. Nevertheless users get seamless broadband experience and robust connectivity because of the fixed connection to the licensed spectrum. Cognitive Radio (CR) enables secondary users (unlicensed users of a spectrum) to sense/find and utilise the spectrum when it is not in use by the primary users (licensed users) with interference control for transmission between the respective users [51]. D2D communications is a peer to peer link which does not use the cellular network infrastructure, but enables LTE based devices to communicate directly with one another when they are in close proximity. This could allow large volumes of data to be transferred from one device to another over short distances/ close proximity by using a direct connection without the need of going via the cellular network itself, thereby avoiding problems with overloading the network. When the devices are in close proximity, by enabling D2D several benefits such as higher data rates to remote users from the cellular infrastructure, reliable communication to communicate locally if a network failure occurred, and power savings to users in various applications can be achieved [52]. These technologies introduced for 4G is envisioned for implementation in the LTE-Advanced network even though they are strong candidate technologies for the 5G networks. However some of the technologies mentioned come with some technical challenges that require solutions before their full implementation in future networks.

1.3 Research Motivation

To explore the full 4G potentials the aforementioned limitations should be resolved by appropriate research. As mentioned in the earlier section one of the critical challenges that the mobile industry will face is the inter-cell interference due to the expected significant cell densification. Research in this direction can be used to implement and amend new techniques or as a reference point for vendors and service providers to improve and develop their individual services.

Cell-edge interference in addition to fading and path-loss which is commonly experienced in wireless communications is a major factor limiting 4G networks to achieve its full potential. Therefore major research has been produced in recent five to six years on developing inter-cell interference coordination using CoMP algorithms primarily in downlink to improve the cell-edge performance of UEs in order to be able to support the required 10-fold increase in spectral efficiency on the roadmap from 4G to 5G. In 2010, EASY-C [53] a major project, provided the principal proof-of-concept which gained significant experience in the implementation and application of the CoMP concepts to improve cell-edge user data rate and spectral efficiency. CoMP transmission and reception actually refers to a wide range of techniques that enable dynamic coordination or transmission and reception with multiple geographically separated eNodeBs. Its aim is to enhance the overall system performance by utilising the resources more effectively and improve the end user service quality. Yet there are limited references on similar work taking place in uplink cell-edge interference mitigation. However in the present day, the demand for uplink communication has become a critical factor, across networks and technologies [50, 54]. It can be seen that the user behaviour in uplink is equally important as the downlink. Even in the optical domain, research is carried out to achieve higher symmetric data rates, compared to the asymmetric data rates which was well-known few years back. A higher transmission rate for uplink has attracted the attention of main research communities and telecoms providers' worldwide [36, 39, 42, 55]. In order to support this paradigm shift in mobile communication, radically new solutions for the air interface need to be developed. Uplink Inter-cell interference could be reduced using CoMP techniques, similar to those in downlink, and advanced receivers with smart antennas since it is one of the most critical factors which reduce the spectral efficiency of the system.

In view of the aforementioned analysis, this thesis proposes a novel uplink CoMP interface mitigation technique for future mobile networks. The novel technique using smart antennas can also be used to enhance the joint reception in a heterogeneous environment. Later part of the thesis will investigate its performance in a D2D environment. This technology enables the performance of the antenna to be altered to provide the performance that may be required to undertake performance under specific or changing conditions. The smart antennas include signal processing capability that can perform tasks such as analysis of the direction of arrival (DoA) or angle of arrival (AoA). There are two types of smart antennas which is switched beam and adaptive arrays. The switched beam smart antennas are designed to have several fixed beam patterns where adaptive antenna arrays allow the beam to be continually steered to any direction to allow for the maximum signal to be received and to nullify or mitigate the interference from interfering UEs. These techniques can be also used with conjunction to joint reception to increase the spectrum utilisation improvement for users' further away (cell-edge) from the eNodeB, or with relatively poor channel condition.

Moving towards the 5G networks, Device-to-Device (D2D) communications underlying cellular networks have been recently proposed as a promising technology to satisfy the increasing demand for local data traffic, and also to provide better user experience in the next generation 5G cellular networks. Another main enhancement for future 5G wireless systems is integrating the standard coverage of traditional macro-cells with small cells of reduced dimensions. By using the D2D technology significant gains can be achieved with close distance transmission between user equipment without traditionally going through a base station. Most existing literature is limited to studying D2D communication for UEs in the same cell (inside the Macro-cell). Therefore the later parts of this research study investigates on inter-site D2D communication. To that extent, this work is tackling the interference issues in uplink direction, and focused on investigating on technologies to improve the recent 4G networks and endorse their suitability as candidate technologies for the future 5G network implementations.

1.4 Research Contributions

The major contributions of this thesis are highlighted as follows:

- ✓ A comprehensive state-of-the-art uplink system-level model was developed using MATLAB programming to evaluate the performance of proposed algorithms for the next-generation 4G/ 5G networks. The detail of the simulation environments (rural, urban, etc) and channel models were presented. The network architecture, transmission modes and scheduling algorithms of the LTE network were evaluated to identify the most efficient parameters for the research to follow.

- ✓ To provide direct coverage to areas where capacity is needed, an inter-cell interference mitigation method based on adaptive smart-antenna was proposed. Adaptive antenna in the proposed technique is complemented by the presence of switched antenna beamforming, applicable to selective cluster UEs saving on processing power at the evolved Node B (eNodeB). The performance of the cell-edge users was then illustrated, and a novel CoMP algorithm was proposed, which was shown to improve the performance of users in the network by reducing the effect of interference on the cell-edge users.

- ✓ Multi-site connectivity using joint reception with receiver beamforming was then implemented. The model was used to illustrate the spectrum utilisation improvement with joint reception for users' further away (cell-edge) from the eNodeB, or with relatively poor channel condition. Joint reception in heterogeneous networks was then taken into consideration which entails the low power RRUs to provide better uplink reception with reduced interference adjustment of UE transmitter power depending on the SINR feedback of the UEs in its existing cell. This was implemented to maintain a good performance between the eNodeBs and cell-edge users in the network even with the simultaneous sharing of resources between the network entities.

- ✓ D2D communication in a heterogeneous environment (small-cell) was then investigated. This differed from the current use of the scheme which is limited to UEs in the same cell to increase cell capacity and improve cellular user experience in a macro-cell environment. In this case, D2D communication was implemented in a small-cell environment to perform inter-cell communication between the D2D users.

This has shown further improvement in the cell throughput compared to standard and joint reception techniques either presented as a result of the research conducted in this thesis or elsewhere in literature.

1.5 Thesis Outline

Chapter 2 of the thesis provides a thorough literature review of 4^{th} and 5^{th} generation cellular networks including technologies such as smart adaptive antenna systems, CoMP techniques, small cells and D2D communication. Chapter 3 starts with a detailed description of the developed system level simulator which will give an introduction to the MATLAB based state-of-the-art uplink system level simulator model implemented for this research study. Chapter 4 will illustrate the inter-cell interference mitigation method based on adaptive smart-antennas. It is concluded by presenting the cell-edge performance enhancements by implementing the proposed novel CoMP receiver beamforming technique. This is followed by Chapter 5 which investigates on the joint reception/processing using the proposed receiver beamforming technique. It provides detail in how multi-site connectivity enhances the cell-edge throughput and spectral efficiency. Chapter 6 discuses and evaluates the D2D communication in a HetNet environment. The designed architecture is progressively enhanced to evaluate the performance of D2D users in an inter-cell/site environment. Finally, Chapter 7 summarises the work conducted throughout this research programme and subsequently discusses the potential evolution and technical difficulties this would involve.

Chapter 2

2. Cooperative Uplink Inter-cell Interference Mitigation towards Realisation of Future Generation 5G Network

2.1 Introduction

This chapter highlights the most up to date literature review on the topologies, technological advances and application scenarios of 4G and emerging 5G cellular networks with an emphasis on the solutions for interference mitigation. The explored topologies focus mainly on LTE and LTE-Advanced as the predominant 4G network, discussing their envisaged limitations towards the implementation of future 5G networks, with respect to primarily cell edge interference cancellation performance but also heterogeneous environment (small-cell), where this research focuses on providing solutions. Technologies such as smart adaptive antenna systems, Co-ordinated Multi Point (CoMP) techniques, small-cells and Device-to-Device (D2D) communication are discussed as projected techniques/technologies and developments towards efficient radio resource utilisation to achieve the future 5G capacity demand and quality of service.

2.2 Developments of Legacy Cellular Networks and Advances towards 5G

The first generation (1G) of cellular networks fulfilled basic mobile voice services (analogue phone calls). The second generation (2G) networks introduced capacity, security and coverage. The most adopted 2G wireless standard is known as Global Systems for Mobile Communications (GSM). GSM introduced data services for mobile with a better coverage and enabled the various mobile phone networks to provide the services such as text messages, picture messages and multi-media messages (MMS). All text messages sent over 2G are digitally encrypted, allowing for the transfer of data in such a way that only the intended receiver can receive and read it.

This was followed by the third generation (3G), where the specifications called for 144Kbps while the user is on the move in an automobile or train, 384Kbps for pedestrians, and up to 2Mbps for stationary users. This was a big step up from 2G bandwidths which uses 8 to 13Kbps per channel to transport voice signals for the GSM standard [56]. The ITU prescribed performance targets for fourth generation (4G) networks such as better data rates (300Mbps using LTE and up to 1Gbps using LTE-A), lower latency (5ms), accessibility, availability and mobility. These targets were matched with the emergence of LTE under the auspices of 3GPP. 4G networks provides access to a wide range of telecommunication services, including advanced mobile services, supported by mobile and fixed networks, which are increasingly packet based, along with a support for low to high mobility applications and higher data rates, in accordance with service demands in multiuser environment.

The fifth generation (5G) should be a more intelligent and robust technology that has flexible infrastructure capable of handling the ever-increasing demand for data and providing connectivity for future technologies like the Internet of Things (IoT). Examples of these capabilities include very high achievable data rates over 1Gbps (10Gbps in specific scenarios such as indoor and dense outdoor environments), very low latency of less than or equal to 1ms (end-to-end round trip delay), ultra-high reliability, and the possibility to handle extreme device densities [57, 58]. Some of the key technology components include extension to higher frequency bands, advanced multi-antenna transmission, data/control separation, flexible spectrum usage, complementary device-to-device communication and backhaul/access integration (smart backhaul and front-haul e.g.: CRAN, Xhaul) [58-60]. An overview of the cellular network standards evolution and their data rate capabilities are summarised in Figure 2-1 [61].

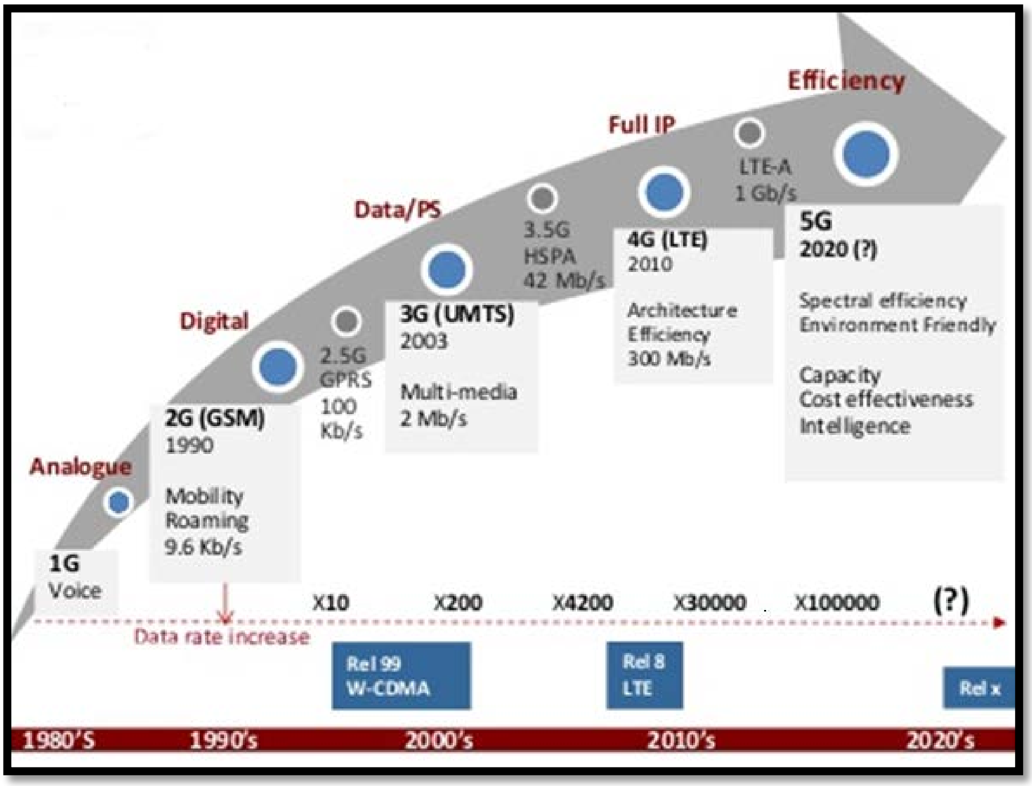

Figure 2-1: Technology and standards evolution towards 5G [61]

As represented in the timeline of Figure 2-1, data traffic in mobile communication systems has been increasing at an enormous rate with the spread of smartphones and tablets [62]. In the decade beyond 2020, it will be necessary to support 1000 times higher mobile data volume per area [6], 1ms end-to-end round trip delay (latency), 90% reduction in network energy usage together with new wireless broadband communication services [40].

The following subsections provide a general overview of the LTE and LTE-Advanced (4G) network architectures. Furthermore it concentrates on highlighting theory and technologies that are relevant to algorithms and performance evaluations carried out in this research. These include the physical layer design, architectural design and technologies such as CoMP, smart antennas, joint reception and D2D underlaying cellular networks.

2.3 Requirements and System Architecture of 4G Networks

Over the last few years the demand for accessing the internet using mobile devices has increased rapidly. To provide the solution for this growing demand the candidate solution should be able to provide a framework for high mobility broadband services and cell-edge performance. Following the successful standardization of High Speed Packet Access (HSPA), the 3GPP specified the Universal Mobile Telecommunications System (UMTS) terrestrial radio-access network or UTRAN LTE to meet the increasing performance requirements of mobile broadband mentioned above [12].

At the time of its development and in preparation for its deployment, when compared to WiMAX (IEEE 802.16 standard) which comes from Institute of Electrical and Electronics Engineers (IEEE family), LTE has gained more popularity since it provided higher bandwidth with increased overall system capacity, higher mobility, reduced latency, improved spectral efficiency and cell-edge performance [63] which is of significance to the work in this thesis. LTE is an all-IP network that provides seamless mobility and required QoS for triple-play services and has an added advantage over mobile WiMAX since it uses the evolution of existing UMTS infrastructure, currently being used by mobile service providers worldwide [64].

2.3.1 Long Term Evolution (LTE Rel. 8 and 9)

The peak throughput of LTE Rel.8 is 100Mbps (300Mbps for 4x4 MIMO configuration) in downlink and 50Mbps in uplink, 2-3 time higher spectrum efficiency than Rel. 6 HSPA, very low latency around 5ms in RAN and 100ms for connection setup time. With Rel.8, the first version for LTE specification, which was completed in March 2009, the LTE standard is now being developed towards commercialization in various countries [65]. Table 2-1 below summarizes the major system specifications of LTE Rel.8 provided by ITU [65, 66].

Table 2-1: Major system requirements for LTE Rel.8 [14]

Bandwidth	Support of scalable bandwidth (1.4, 3, 5, 10, 20MHz)
Peak data rate	DL: 100Mbps UL: 50Mbps
Latency	
Transfer delay in RAN	5ms (one-way)
Connection setup delay	100ms
Antenna configuration	**Spectrum efficiency [bps/Hz]**
UL: 1 x 2	0.8
UL: 2 x 4	N/A
DL: 2 x 2	1.6
DL: 4 x 2	1.7
DL: 4 x 4	2.7

LTE offers extensive support for spectrum flexibility, both frequency-division duplex (FDD) and time-division duplex (TDD) and targets a smooth evolution from earlier 3GPP system such as Wideband Code Division Multiple Access (WCDMA)/ HSPA as well as 3rd Generation Partnership Project 2 systems such as cdma2000 [67].

The radio access network of LTE consists of only evolved NodeBs (eNodeBs), which are basically 'intelligent' radio base stations. These eNodeBs are capable of allocating radio resources among its connected user equipment in a distributed manner without the involvement of any core network elements compared to base transceiver station (BTS) of previous networks. A typical LTE network architecture is shown in Figure 2-2 [68].

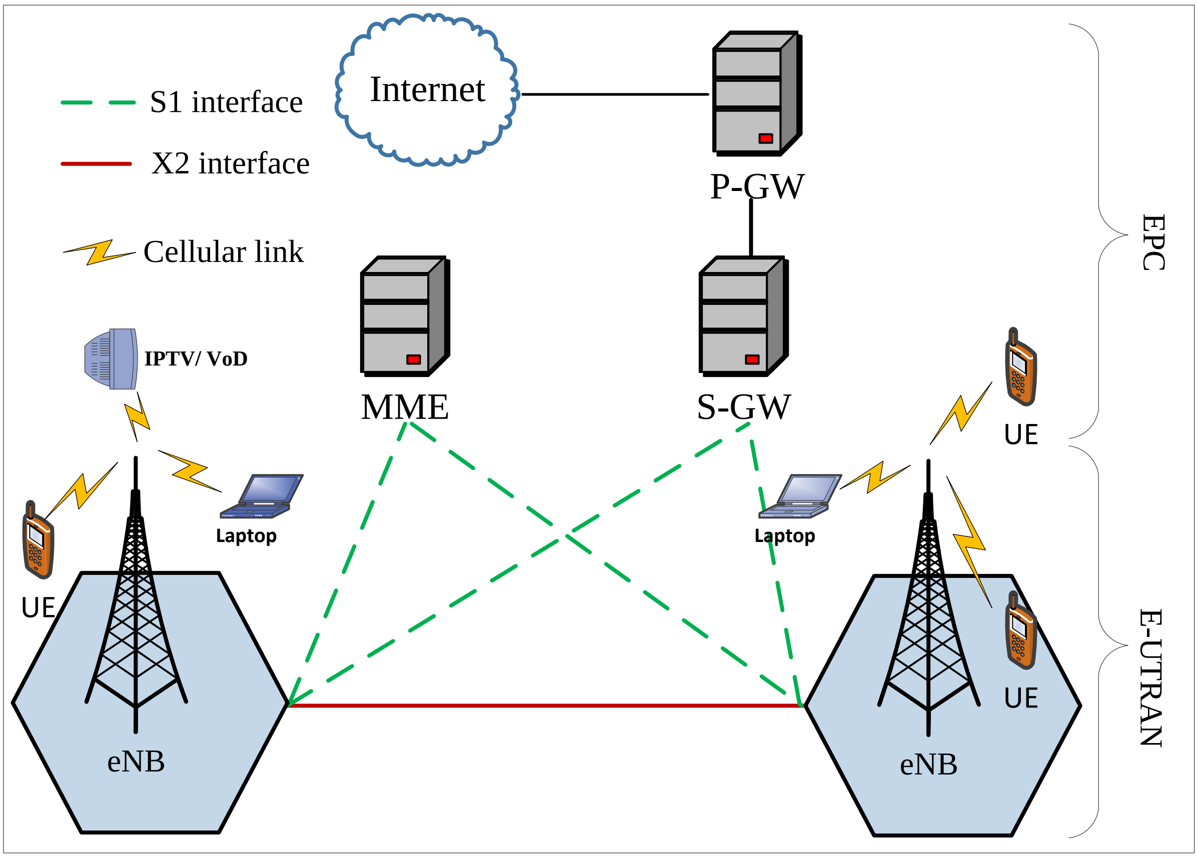

Figure 2-2: LTE network architecture [62]

The eNodeBs are connected to each other through the X2 logical interface which facilitates direct communication between neighbouring cells and to the LTE core network (also referred to as Evolved Packet Core (EPC) through the S1 interface, which is dedicated to data and control plane signalling transport. The EPC can be also connected to other 3GPP and non-3GPP radio-access networks. The EPC consists of a Mobility Management Entity (MME), a Serving GateWay (S-GW), and a Packet Data Network GateWay (PDN-GW). These core network elements facilitate proper management of LTE network elements and provide links to other networks. The mobile terminal is denoted as user equipment (UE). When compared to UTRAN Rel. 6 some functionalities performed by the Radio Network Controller (RNC) in UTRAN, such as ciphering and header compression, is performed by the eNodeBs in LTE. Further, handovers between eNodeBs are handled through packet forwarding over the X2 interface rather than by means of a central Automatic Repeat reQuest (ARQ) entity in the RNC as in UTRAN [12, 65, 68, 69].

Orthogonal Frequency-Division Multiplexing (OFDM), with data transmitted on a large number of parallel, narrow-band subcarriers in combination with a cyclic prefix , is the core of the LTE downlink radio transmission [3]. And the transmission is robust to time dispersion on the radio channel without a requirement to resort to advanced and complex receiver-side channel equalization [3, 21]. In addition to its advantages for a low-complexity receiver design, the multicarrier concept enables the operation of LTE in many system bandwidths up to 20MHz by adapting the number of subcarriers used to the allocated system bandwidth [21].

In the downlink, above mentioned properties simplifies the receiver baseband processing with reduced terminal cost and power consumption as a consequence. This is significantly important considering the wide transmission bandwidths of LTE [3]. The transmitted signal is organized into sub frames of 1ms duration, each consisting of 14 or 12 OFDM symbols, depending on whether normal or extended cyclic prefix (CP) is used. Ten sub frames form a radio frame [3]. The subcarrier spacing of the LTE is 15 kHz with two CP lengths, in both the up and downlink. One of the most important characteristics of the LTE is its ability to utilize both the TDD & FDD frame structures which is shown in Figure 2-3 [3].

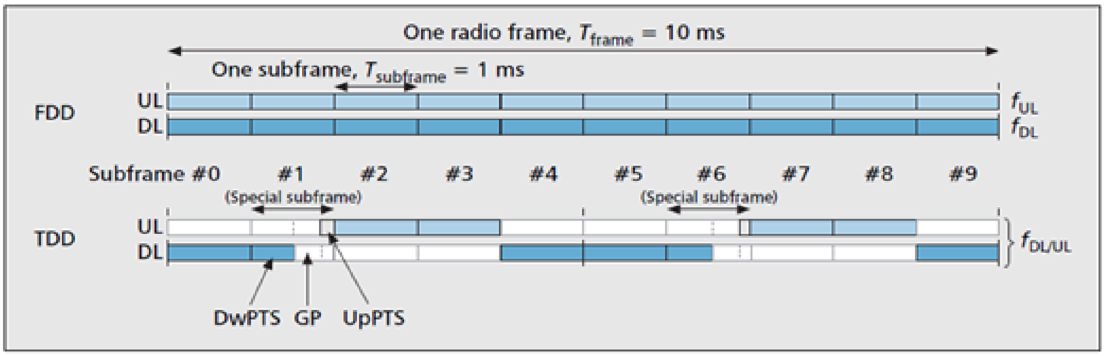

Figure 2-3: LTE frame structure [4]

As illustrated, out of the two frame structure types of the LTE (TDD and FDD), the FDD is optimised to coexist with the 3.84Mb/s UMTS system. Therefore it is commonly considered in most literature. It contains 10 sub-frames with a total of 10ms (each sub-frame having two slots of 0.5ms), and has similar frame structure for DL and UL with different channels and signal positions in each case [3].

OFDM supports multi-user access because within a transmission interval, subcarriers can be allocated to different users [12]. In the downlink it uses OFDM but in uplink, single-carrier frequency-division multiplexing (SC-FDM) is implemented via Discrete Fourier Transform spread OFDM (DFT-SOFDM) [21]. This is because higher priority is given to achieving wider area coverage than achieving higher performance by utilizing the robustness against multipath interference in a multicarrier approach [17], since SC-FDMA signals have better peak-to-average power ratio (PAPR) properties compared to an OFDMA signal.

Figure 2-4 illustrates the resource grid structure for LTE uplink. The transmitted signal in each slot is described by a resource grid where the bandwidth allocated to a UE is in the form of a resource block (RB). The resource grid comprises of 12 subcarriers and a number of SC-FDMA symbols which differs for different CP length and system bandwidth.

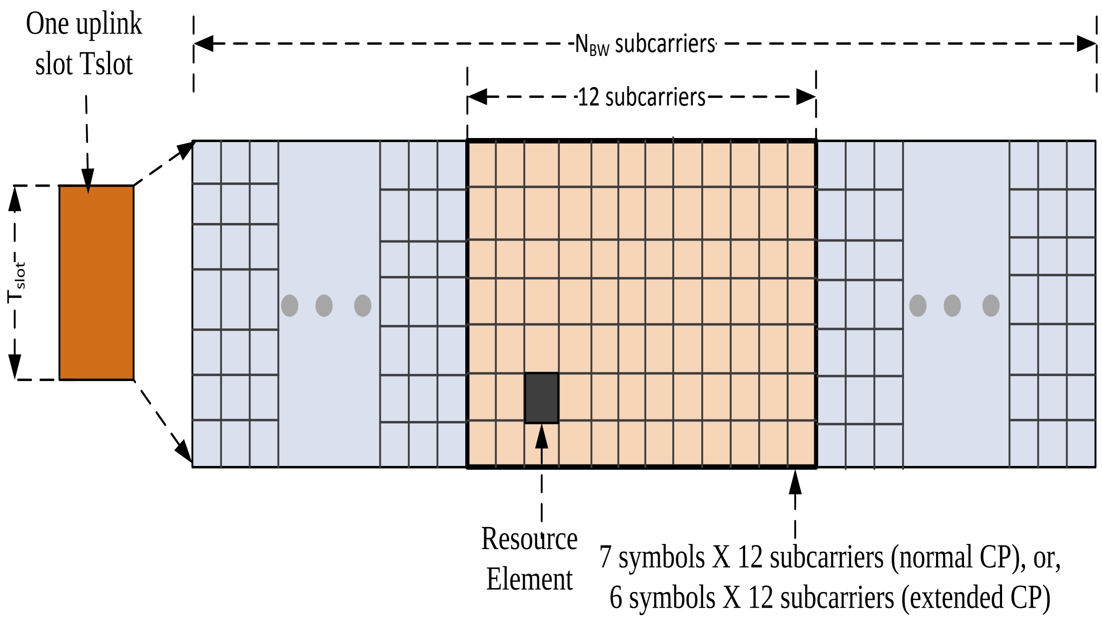

Figure 2-4: Resource grid structure for LTE [64]

The number of SC-FDMA symbols in a slot depends on the cyclic prefix length (Normal or extended cyclic prefix) configured by higher layers. Therefore when using normal cyclic prefix RB consists of 84 resource elements (RE) and when cyclic prefix extended is used it consist of 72 REs. A single RE can carry a single modulation symbol hence 2 bits when using QPSK, 4 bits when using 16QAM and 6 bits when using 64QAM [3, 70].

Although the LTE system is far superior to the existing systems in many aspects including throughput, delay, and spectrum efficiency, the 3GPP worked on further enhancements of LTE towards Rel. 9 completed in June of 2010 [17]. The main target of LTE Rel. 9 is to enhance some of the features introduced in Rel.8. Some of these features are Closed Subscriber Group (CSG) control which is a mechanism to limit cell access rights to only users belonging to the CSG [71]. Self-Organizing Networks (SON) is another enhancement which automatically organize or optimize the system parameters [72].

Multimedia Broadcast/Multicast Services (MBMS) which is a bearer service for broadcast/multicast transmission of data, to transmit the same information to all interested terminals in an area over a common bearer [73] and LoCation Services (LCS) which supports the following three positioning methods; Assisted-Global Navigation Satellite System, Observed Time Difference of Arrival (OTDOA) and Enhanced-Cell ID (E-CID) [17, 74, 75].

2.3.2 LTE-Advanced (Rel. 10) Requirements

Long Term Evolution Advanced (also known as LTE-Advanced/ LTE Rel.10) significantly enhances the existing LTE Rel.8 and supports much higher peak rates, higher throughput and coverage resulting in a better user experience [21]. When compared to LTE Rel.8, LTE-Advanced provides lower latency and round-trip delays (5ms), better peak spectrum efficiency (downlink: 30bps/Hz; uplink: 15bps/Hz), reduce inter cell interference, and support coexistence between the various flavours of cells macro-cells, micro-cells, femto-cells, and so on [76]. It also introduces carrier aggregation, advanced uplink (UL) and downlink (DL) spatial multiplexing, coordinated multipoint transmission, and heterogeneous networks with special emphasis on Type 1 and Type 2 relays. Relays are being designed to provide greater coverage, while using in-band backhaul via the existing radio interface [21, 76].

LTE-Advanced will be an evolution of Rel.8, therefore distinctive performance gains from LTE Rel.8 are requested. LTE-Advanced should satisfy all the relevant requirements for LTE Rel.8 [77]. Secondly it should be fully backward compatibility with Rel.8. Therefore, a set of user equipment for LTE-Advanced must be able to access Rel.8 networks, and LTE-Advanced networks must be able to support Rel.8 UEs.

LTE-Advanced should also meet or exceed the IMT-Advanced requirements within the ITU-R time plan. The target peak data rate for the downlink was set to 1Gbps and the target peak data rate for the uplink was set to 500 Mbps. It is noted, however, that this requirement is not mandatory and is to be achieved by a combination of base stations and high-class UEs with a larger number of antennas. The table below illustrates the requirements and target values for LTE-Advanced with those achieved in the LTE Rel. 8 [78-80].

Table 2-2: System performance requirements for LTE-Advanced [80]

	DL/UL	**Antenna configuration**	**LTE Rel. 8**	**LTE-Advanced**
Peak data rate	DL	300Mbps (4 x 4 MIMO)		1Gbps
	UL	75Mbps (64QAM)		500Mbps
Peak spectrum efficiency [bps/Hz]	DL	15 (4 x 4 MIMO)		30 (up to 8 x 8 MIMO)
	UL	3.75 (64 QAM SISO)		15 (up to 4 x 4 MIMO)
Capacity Cell spectral efficiency [bps/Hz/cell]	DL	2 x 2	1.69	2.4
		4 x 2	1.87	2.6
		4 x 4	2.67	3.7
	UL	1 x 2	0.74	1.2
		2 x 4	-	2.0
Cell-edge user spectral efficiency [bps/Hz/cell/user]	DL	2 x 2	0.05	0.07
		4 x 2	0.06	0.09
		4 x 4	0.08	0.12
	UL	1 x 2	0.024	0.04
		2 x 4	-	0.07

2.4 Interference Avoidance and Cancellation

In LTE-Advanced interference mitigation is included in the specifications, even though implementations of these techniques are left open for the vast research community vendors. Interference mitigation has therefore been in the mainstream of the research agenda of standardization bodies and forums and of the wider research community. To begin with CoMP transmission and reception techniques have been in the forefront of development, exploiting the cooperation between base stations, using a fast backhaul network, in order to significantly reduce the interference among UEs and in overall network performance. In particular scenarios where neighbouring eNodeBs transmit at the same time, and naturally on the same frequency resources to UEs who are relatively close together would experience relatively high interference from adjacent cell. Inter-cell interference is categorized into two groups which are intra cell and inter cell interference as shown in Figure 2-5 [81].

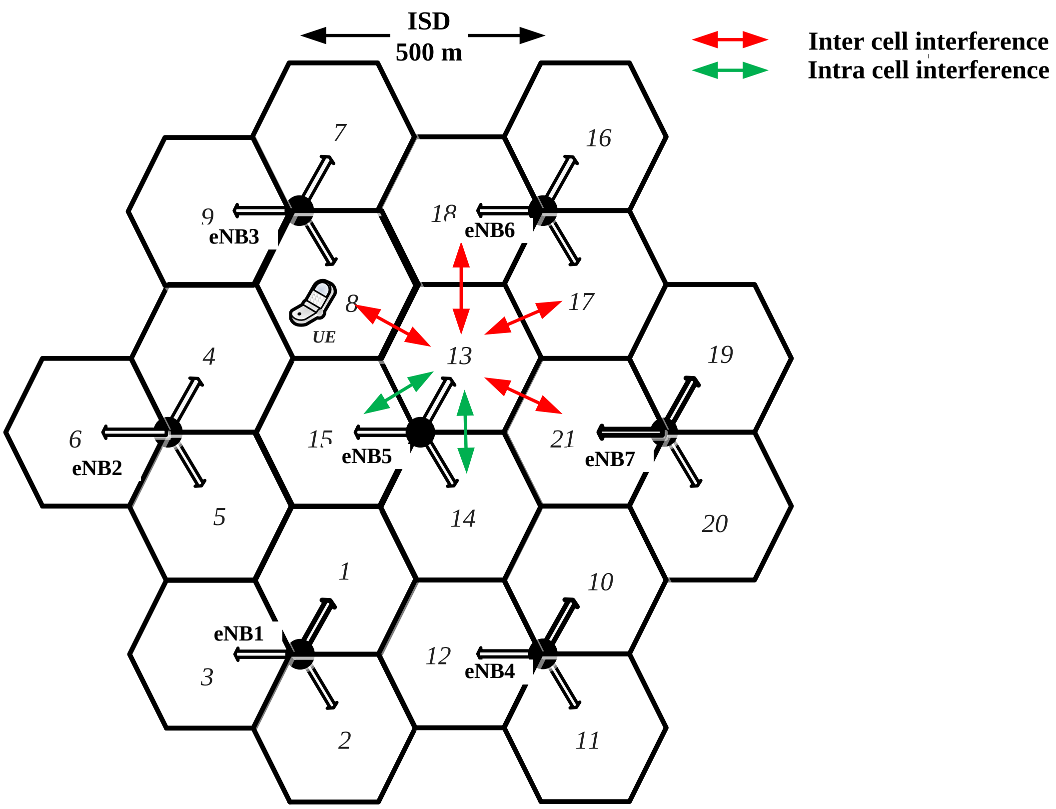

Figure 2-5: Intra and inter-eNodeB inter-cell interference [75]

UEs receive dominant interference from the first tier of interferers, intra cell interference from own eNodeB between sector 13 and 15 and between 13 and 14, and inter cell interference from the cells of other neighbouring eNodeBs (e.g.: sector 13 and18, 13 and 21) are illustrated in Figure 2-5. Interference originated from cells of own eNodeB (intra cell) should be handled separately as eNodeBs can take appropriate measures themselves without the need for inter eNodeB communication through the X2 interface [81, 82]. Based on the approaches used, mitigation techniques are generally categorized into three major classes, i) interference cancellation, ii) interference averaging, and iii) interference avoidance techniques [81].

With respect to the former, there are several ways to perform interference cancellation. As explained in [81, 83] receivers can generally estimate and subtract interference from conflicting sections of a received signal. As proposed in [81], another method of interference mitigation is by using interference averaging techniques such as frequency hopping, which guides UE's access a certain range of channels instead of being constrained to a certain pattern [81]. Frequency hopping will then average out the interference effect from the given UEs. [83-85] investigated and suggested the successive interference cancellation method added to the physical layer of a wireless network. Interference avoidance, being the latter of the three classes mainly focuses on optimizing effective reuse factors that are achieved through the restrictions on frequency and power allocations to achieve the goals such as higher throughput and spectral efficiency in the general network performance as presented in [81]. When using this technique the scheduler will allocate resources to the UE at the cell edge with minimal interference, by the use of the X2 interface for the eNodeBs to communicate and exchange certain information with other eNodeBs. Therefore it will improve the throughput of the LTE network, and equally take full advantage of the dense reuse pattern of LTE to achieve as close as possible to its specified data rates mentioned in the standards.

By using CoMP techniques to achieve interference avoidance/cancellation, will increase the overall system throughput and significant improvements at the cell-edge and this will provide enhanced fairness to the overall system. The next section will give an overview to the CoMP transmission and reception technique.

2.4.1 Coordinated Multi-Point (CoMP) for Interference Mitigation

LTE-Advanced is based on OFDM which splits a high rate data stream into a number of lower rate streams and transmits them by a set of orthogonal subcarriers. Therefore, it has immunity to intra cell interference due to the orthogonality between subcarriers [27]. However by using CoMP techniques inter cell interference can be exploited or mitigated by cooperation between sectors or different sites [86].

Coordinated multi-point transmission and reception is a network multiple-input multiple-output transmission technology being considered for the 3GPP LTE-Advanced standard [40], and a promising candidate for future 5G cellular standard being developed by 3GPP standardization group [32, 39]. Cell-edge users mostly suffer from throughput reduction due to bad coverage and consequently unexpected transmission delays. Hence, in order to increase the reliability and capacity of the services for the UEs at the cell-edges, CoMP utilizes cooperation among neighbouring eNodeBs [32, 87]. Antennas of multiple cell sites are used in such a way that they can contribute to increase the quality of the received signal at the UE/ eNodeB and drastically reduce the inter cell interference. To achieve this, very fast inter-eNodeB connections are needed. There are mainly two types of CoMP that differ in the degree of coordination. They exhibit and are known as co-ordinated scheduling/beamforming (CS/CB) and joint processing/ reception (JP/JR). They are shown in Figure 2-6 [32].

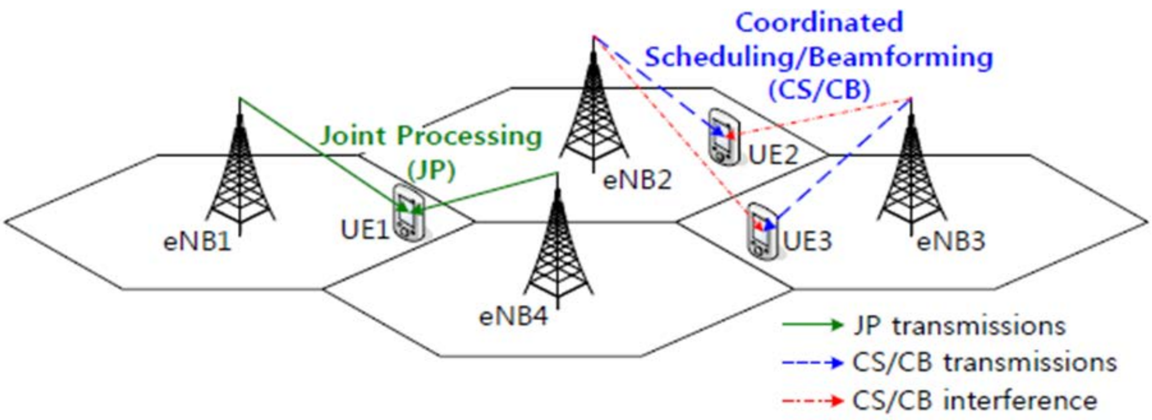

Figure 2-6: CoMP architecture for JP and CS/CB transmission [31]

With JP, signals designated for single user equipment are simultaneously transmitted from multiple neighbouring eNodeBs. These eNodeBs cooperate in order to work as a single transmitter with geographically separated transmit antennas [32].

Since data is transmitted from different base stations at the same time, tight synchronization and a very high speed link between base stations are required. Two modes of operation are possible to demonstrate joint processing, shown in Figure 2-7: fast cell selection, where only one base station is transmitting at a time and joint transmission where data is transmitted from different eNodeBs at a time and they are coherently combined at the terminal [88].

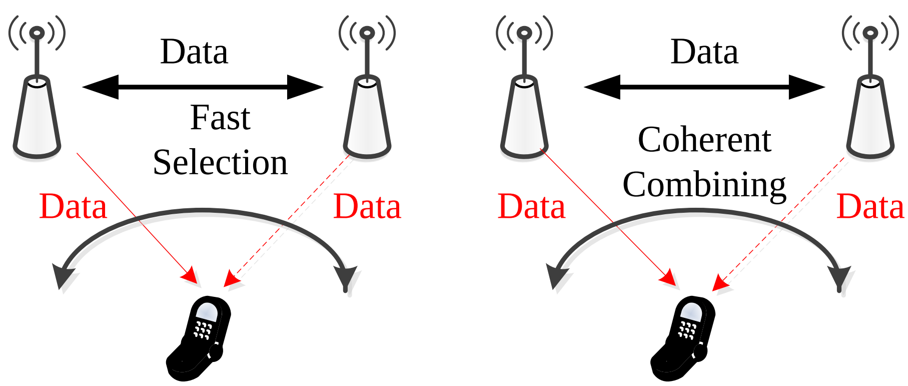

Figure 2-7: Joint processing techniques [82]

In co-ordinated scheduling/ beamforming, UE scheduling and beamforming are dynamically coordinated among neighbouring eNodeBs in order to control and/or reduce the interference among different transmissions as shown in Figure 2-8 [32].

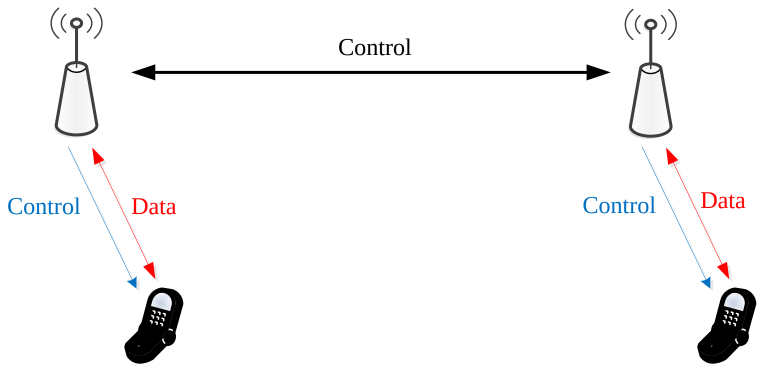

Figure 2-8: Co-ordinated beamforming/ scheduling [31]

Beamforming is more efficient due to its narrow beam spatial characteristic. However inter cell coordination is a natural way to improve the interference performance in the cell-edge. In addition the requirements for synchronization among base stations and backhaul capacity are lower to joint processing if a centralized radio access network approach is used [88].

CoMP is a main element on the LTE roadmap beyond Release 9. In LTE Release 11, some simpler CoMP concepts appeared, but it is generally expected that advanced CoMP concepts will take longer to be mature enough for commercial use [53]. In [89] an intelligent algorithm is designed and implemented to dynamically adjust CoMP configuration to optimize system performance. In this algorithm, base stations cooperatively divide CoMP and non-CoMP users according to user traffic scenarios and cooperatively adjust configuration of CoMP users. To enable all cell-edge UEs enjoy the merit of CoMP joint processing, CoMP joint transmission based on a distributed cooperation approach using inter eNodeB interface such as X2 interface has been proposed in [90]. In the distributed cooperation, CoMP joint transmission can be realized in a distributed manner, so that CoMP this can be used at any cell border. [91] propose a distributed CoMP set selection scheme for cellular heterogeneous networks (HetNets), where each access point can exchange information only with their neighbours. Any CoMP decision at an access point is based on the feedback information from the neighbour stations, increasing both coverage and throughput gains. In [92] a novel and low-complexity CoMP joint reception scheme for uplink which combines effective antenna selection is proposed. Compared with original CoMP joint reception, the proposed CoMP with antenna selection can significantly reduce the computational complexity with acceptable performance loss. By witnessing the literature, using CoMP techniques to achieve interference cancellation in both uplink and downlink, the achievable throughput will increase significantly at the cell-edge.

Beamforming and joint reception are CoMP technique which can be achieved by the use of antenna arrays. The next section will concentrate on the use of smart antennas which have been gaining popularity in recent times, as a means to enhance data rates and reduce interference.

2.4.2 Smart Antennas and Beamforming

Beamforming is a widely used technique for interference reduction and directed transmission of energy in the presence of noise and interference [93]. Beamforming can be used in the uplink or downlink of multiuser systems to maximize the signal to interference plus noise ratio (SINR) of particular user/receiving equipment. Smart antennas have been gaining popularity in literature recently, as a means of enhancing data rates. The reason behind this development is the availability of high-end processors to handle the complex computations involved.

In beamforming, as mentioned in the previous section, both the amplitude and phase of each antenna element are controlled. Combined amplitude and phase control can be used to adjust side lobe levels and steer nulls. And the major advantage of a digital beam-former (smart antennas) is that phase shifting and array weighing can be performed on digital data rather than in hardware [94]. Techniques like adaptive beamforming can be used to achieve higher SNR thereby enhancing data rates. Smart antenna systems generally consist of an array of multiple closely packed antennas which are terminated in a sophisticated signal processor, which can adjust or adapt its own beam pattern in order to emphasize on signals of interest while minimizing interfering signals [94]. It can form a single beam or multiple beams directed towards a particular user or users.

By concentrating transmit power towards the device or the active subscriber it can increase the overall and cell-edge link budget by reducing the interference which results in an increase of overall network capacity as shown in Figure 2-9.

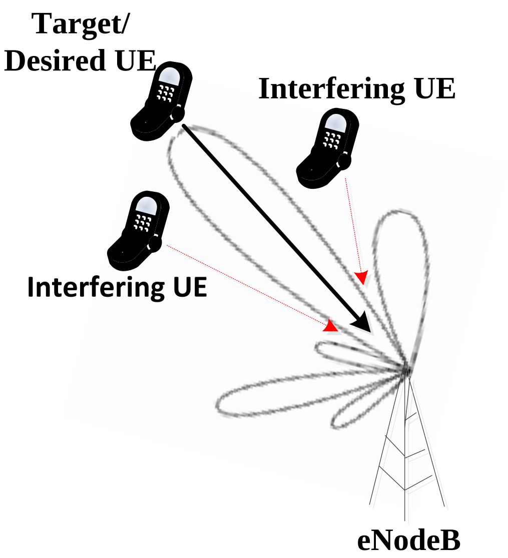

Figure 2-9: Beamforming smart antenna system

There are two types of smart antenna implementations; the switched beam and adaptive array. The switched beam systems have several fixed beam patterns. The most appropriate pattern, depending on the conditions of the detected signal at any particular instance will be selected by the control elements within the antenna. When an incoming signal is detected, the base station determines the beam that is best aligned in the signal of interest's direction and then switches to that beam to communicate with the user, shown in Figure 2-10 [71].

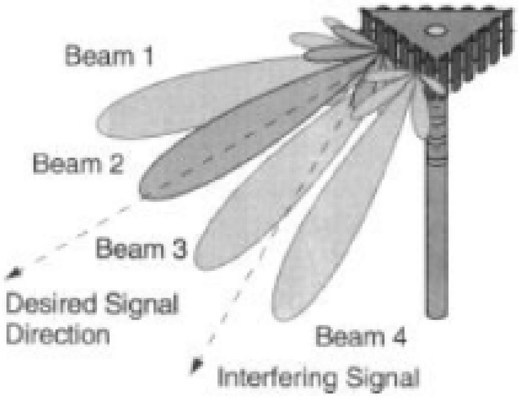

Figure 2-10: Switched beam smart antenna system [67]

The Switched beam approach is simpler and not as expensive compared to the fully adaptive approach. It provides a considerable increase in network capacity when compared to the traditional omnidirectional antenna systems or sector based systems. The disadvantage of this method is that it cannot distinguish between direct signal and interfering and/or multipath signals as shown in Figure 2-11.

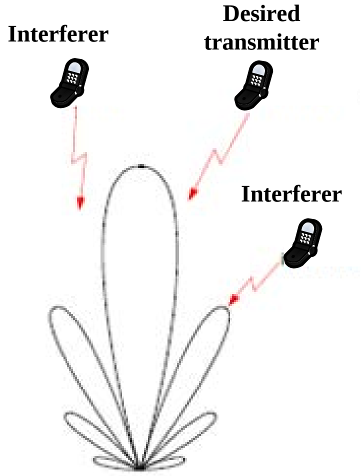

Figure 2-11: Direct signal and interfering and/or multipath signals from interferers

What becomes apparent is that the limitation of the switched beam pattern is that it is restricted to the available predetermined set of beams. And as can be seen in Figure 2-11, the user of interest does not lie directly in the middle of the main beam. At the same time, interferers are not located in a radiation null.

This problem leads to undesired enhancement of the interfering signal, in cases more than the desired one. Therefore compared to the adaptive arrays it offers limited co-channel interference suppression since it has no null steering.

Adaptive smart antenna arrays allow the beam to be continually steered to any direction in order to be able to detect the maximum good signal power and/or interference null, increasing capacity and signal to noise ratio while, reducing multipath and co-channel interference.

This technique is commonly employed in which the system is able to operate in an interference environment by adaptively modifying the antenna array pattern so that the nulls are formed in the angular locations of the interference sources as shown in Figure 2-12 [95].

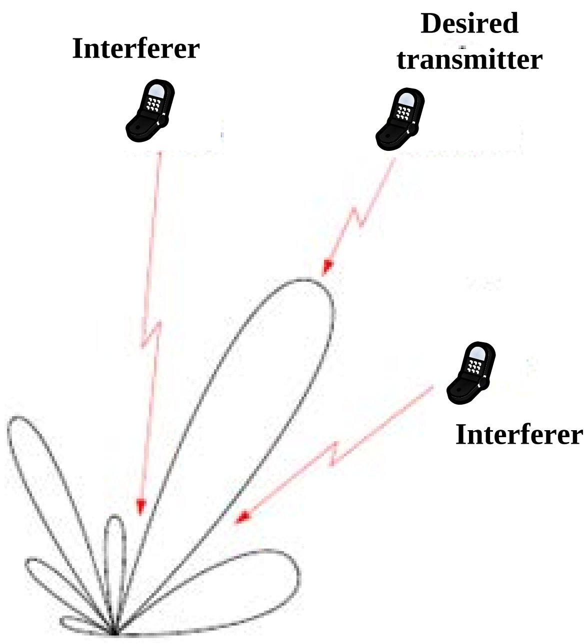

Figure 2-12: Adaptive smart antenna array

In this approach multiple antenna elements are used which are individually weighted using Digital Signal Processing (DSP) to produce a desired directivity pattern. Compared to the switched beam approach this method has better interference rejection capability, even though it needs complicated adaptive algorithms to steer the beam and the nulls. Adaptive antennas provide increased capacity and coverage compared to the switched beam method. The disadvantages of adaptive antennas are that it is not easy to implement in existing systems and it is expensive compared to switched beam techniques. Although both systems seek to increase gain with respect to the location of the users, there are several constraints for achieving this due to interference, noise, multipath and poor channel conditions. To overcome such constraints a highly advanced technology is required. This is where the need for an intelligent receiver (receiver beamformer) comes into the foreground in order to emphasize signals of interest and to minimize the interfering signals, which will be discussed in chapter 4.

2.4.3 Device to Device (D2D) Communication

Cognitive radio [96] has equally gained much attention in recent years primarily due to the offered potential to reusing the assigned spectrum. Cognitive radio networks have therefore been developed in order to enhance throughput and coverage. In this direction D2D communication utilises the cellular spectrum: with potential of better QoS as it occurs in the controlled cellular spectrum.

As a successor and inspired by cognitive radio and relay networks, D2D have recently been investigated as a potential way to improve secondary user throughput [40, 88, 97]. As a type of cognitive technology, D2D communication could optimize the system capacity over the shared uplink (UL) or downlink (DL) resources while fulfilling prioritized cellular service constrains [96, 98]. D2D communications underlaying a cellular infrastructure has been proposed as a means of taking advantage of the physical proximity of communicating devices, increasing resource utilization, and improving cellular coverage [99].

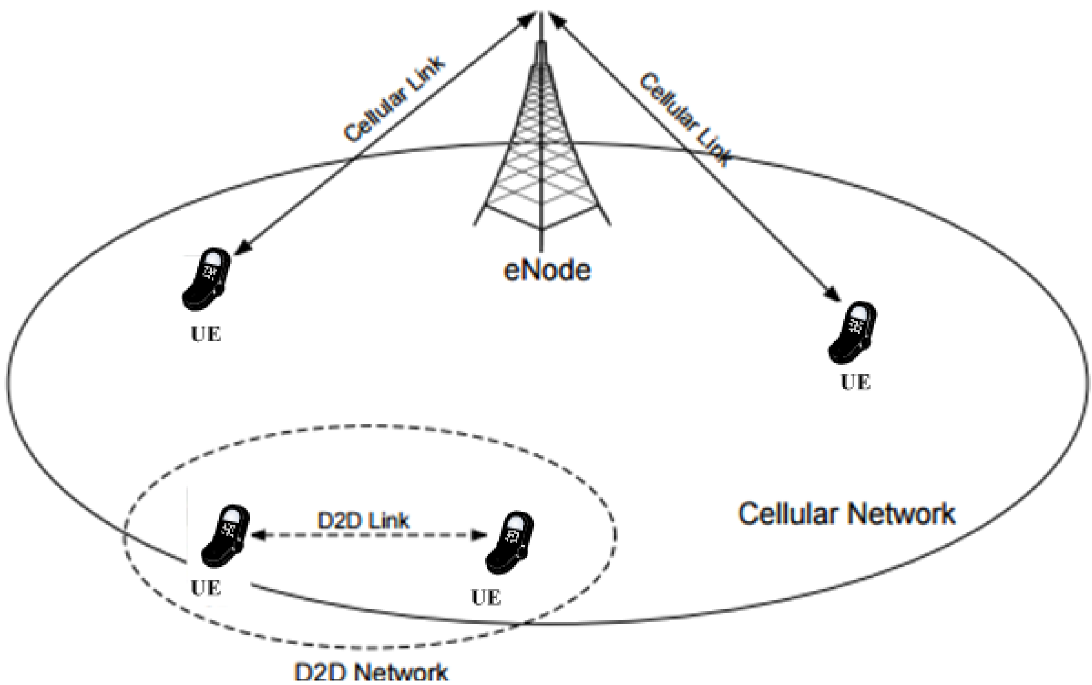

Figure 2-13: D2D Communication: Technology and Prospect [92]

In D2D-enabled cellular networks, data communications between user equipment can be completed by two modes: the cellular mode and the D2D mode where UEs bypass the base station and directly communicate with each other. Usually the transmission mode is selected based on the distance between UEs [100]. Figure 2-13 [101] represents a simple D2D communication scenario. The eNodeB transports the cellular traffic, while the D2D transmission is carried out using the D2D link with partial involvement of the eNodeB (network assisted) for handling control information and session setup.

There are two different types of D2D, with network assist and without network assist as shown in Figure 2-14 [101]. A major difference between D2D communications over a cellular network (network assisted) and a traditional D2D system is that D2D communications in a cellular network assume the underlay of a cellular network. This provides significant potential advantages to device discovery such that resource allocation, interference coordination, and collision avoidance can be carried out more efficiently.

However, it must also support the cases where the network coverage is not available. As an example, coverage holes due to imperfect cell coverage or temporary failure of network access points, implying that D2D communications must be sustained when devices are partially or completely lost or outside the network coverage [102].

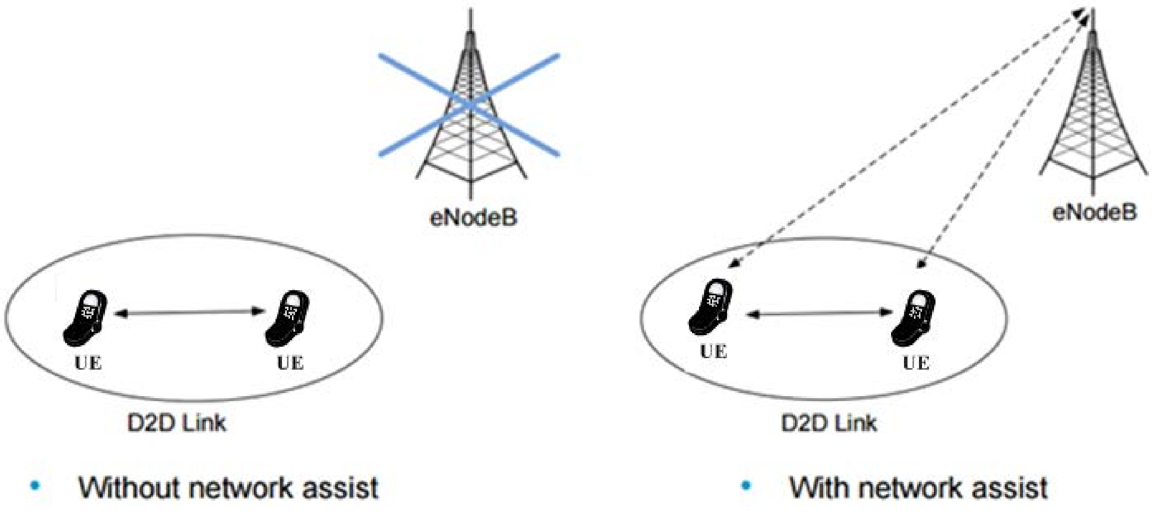

Figure 2-14: D2D communication with and without network assist [100]

D2D pairs should keep a certain distance away from base stations and primary cellular UEs to avoid generating or receiving heavy interference. As D2D communications underlaying a cellular infrastructure introduce many new interference scenarios such as resources sharing between D2D communications and cellular networks, also additional interference introduced by new D2D transmissions, interference management becomes more critical. Some of the key design questions raised in the implementation of the D2D technology include interference mitigation and resource allocation in the integrated networks (network with cellular and D2D UEs) amongst others. Current research topics of interference management include mode selection, resource allocation and power control. Power control is a common method studied for performance improvement of networks with different entities (both D2D and cellular) [103]. It involves the adjustment of the D2D transmitter power and/or the eNodeB transmitter power, or adopting some CoMP functionalities such as beamforming using smart antennas to achieve it. Several contributions have been provided in literature to identify efficient techniques to achieve the above in an integrated environment.

In [104], a novel scenario which is based on the coexistence of coordinated system (CoMP) and D2D for Interference management is presented, enhancing system throughput and energy efficiency. It uses coordination and zero forcing algorithm to mitigate inter and intra cell interference. In [105], an antenna based solution where transmit and receive beams are formed based on the channel state information (CSI) through traditional D2D links was presented.

5G is expected to also support heterogeneous networks, with macro-cells, micro-cells, small-cells, and relays [106]. One way to expand an existing macro-network, while maintaining it as a homogeneous network, is to “densify” it by adding more sectors per eNodeB or deploying more macro-eNodeBs. However, reducing the site-to-site distance in the macro-network can only be pursued to a certain extent because finding new macro-sites becomes increasingly difficult and can be expensive, especially in city centres. An alternative is to introduce small cells through the addition of low-power base stations Home eNodeBs (HeNodeBs) or Relay Nodes (RNs) or Remote Radio Heads (RRH) to existing macro-eNodeBs. Site acquisition is easier and cheaper with this equipment which is also correspondingly smaller [107, 108]. Nokia Siemens Networks [24, 55] has shown that a thousand fold increase in network capacity with a 10 Mbit/s minimum downlink user data rate can be achieved by a HetNet configuration that reuses all the existing macro sites and deploys ten times as many outdoor micro sites [55]. Femto-cell networks are currently seen as a new communication paradigm for the ever increasing ubiquitous wireless traffic demands. Being pervasive by nature, its proximity to the subscriber opens a new world of possibilities for the development of applications.

Small cells are primarily added to increase capacity in hot spots with high user demand and to fill in areas not covered by the macro network both outdoors and indoors. They also improve network performance and service quality by offloading from the large macro-cells. The result is a heterogeneous network with large macro-cells in combination with small-cells providing increased bitrates per unit area [107]. Among them, D2D communication and cloud computing services demanded by smartphones could be moved from large server farms to Home eNodeBs, provided that these are equipped with computational and storage resources, thus improving user experience on latency and download/upload speed.

In view of the general overview of heterogeneous networks and D2D technology in the above subsection, the issue of interference between the simultaneous transmission of cellular and D2D traffic in a small-cell environment has been identified as a key issue in realising the hybrid network. Thus, specific algorithms proposed for interference mitigation in the network will be further presented in Chapter 6 to compare and contrast implementation methods and performance results with the algorithm proposed in this research work.

2.5 Architectural Developments and Research Initiatives in 5G

While the deployment of 4G mobile services increasing gradually worldwide, offering unpresented services and data rates, research in 5G is progressing at an equal pace if not faster looking at closing even more the gap between new user requirements and what can be practically offered by 4G [109]. Unlike in the past, 5G will also focus on new air interfaces and spectrum together with LTE and WiFi to provide universal high-rate coverage and a seamless user experience. In order to support this, the core network will also have to reach unprecedented levels of flexibility and intelligent [54].

Industry will play the major role in the 5G Infrastructure Public Private Partnership (5GPPP) with respect to the necessary long-term investment in global standardization and the integration of technological contributions into complex interoperable systems. A high-level overview of the 5G roadmap, as seen from 5G Infrastructure PPP, is depicted in Figure 2-15 [46].

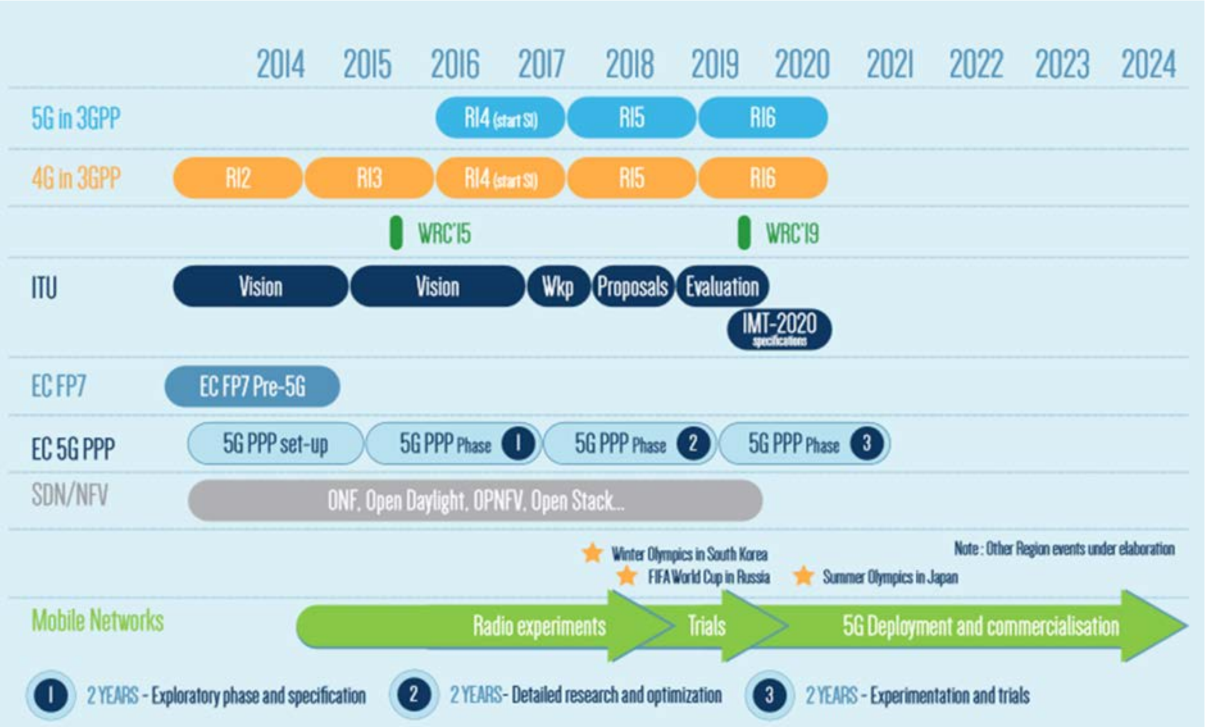

Figure 2-15: 5G Roadmap [46]

The 5GPPP association in the EU Horizon 2020, the EU Framework Programme for Research and Innovation has already committed 700M€ of Public funds over 6 years (2015-2021). The start of commercial deployment of 5G systems is expected in years 2020+, following the research phase and the standardization and regulatory phases. As it can be seen the exploratory phase to understand detailed requirements on 5G future systems and identify most promising technical and technological options started back in 2014, subsequently kicking off the research and development phase.

Figure 2-16 [110] presents a high-level view of potential 5G network topologies and associated technologies. Architectures and network designs are being proposed to efficiently use the current spectrum and future spectrum to achieve the required high data rates. As it can be seen from the figure the major candidates supporting the implementation of 5G includes CoMP, D2D communication and heterogeneous (ultra dense networks) networks. There are some major projects with the aim of achieving these goals.

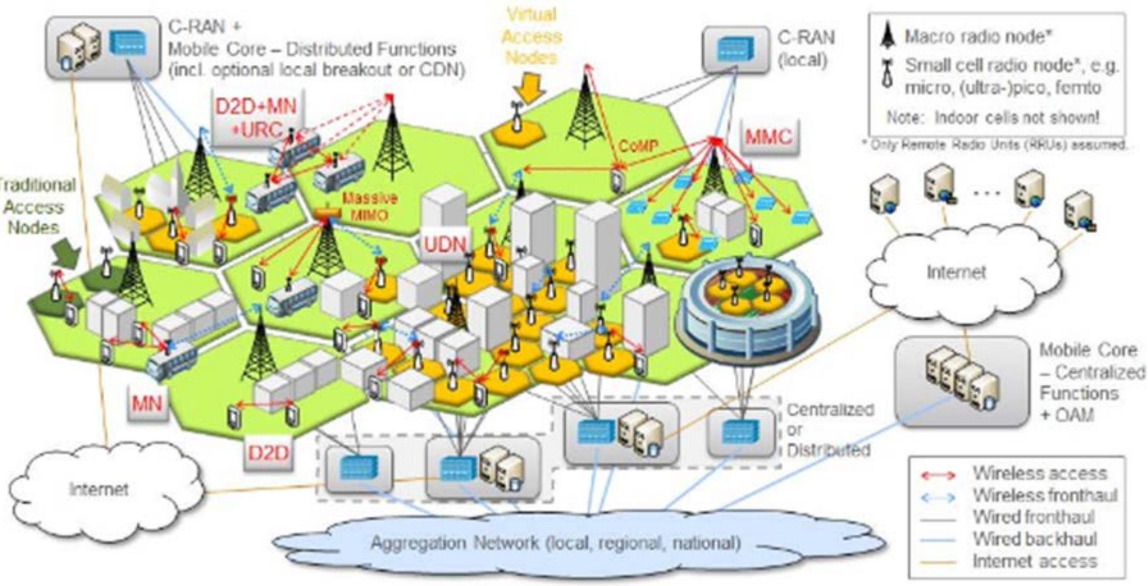

Figure 2-16: High-level topological view of 5G network architecture [110]

Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) and METIS II [40] are an integrated research project partly funded by the European Commission under the Framework Programme7 (FP7) research framework [41, 111]. It aims at laying the foundation for the beyond 2020 wireless communication systems by providing the technical enablers needed to address the predicted very challenging requirements. Some of the technical goals derived from the main objectives of METIS and METIS II [110] are as follows;

- 1000 times higher mobile data volume per area,
- 10 to 100 times higher typical user data rate,
- 10 to 100 times higher number of connected devices,
- 10 times longer battery life for low-power devices,
- 5 times reduced end-to-end (E2E) latency, reaching a target of 5ms for road safety applications

Figure 2-17 illustrates the METIS 5G scenarios [40].

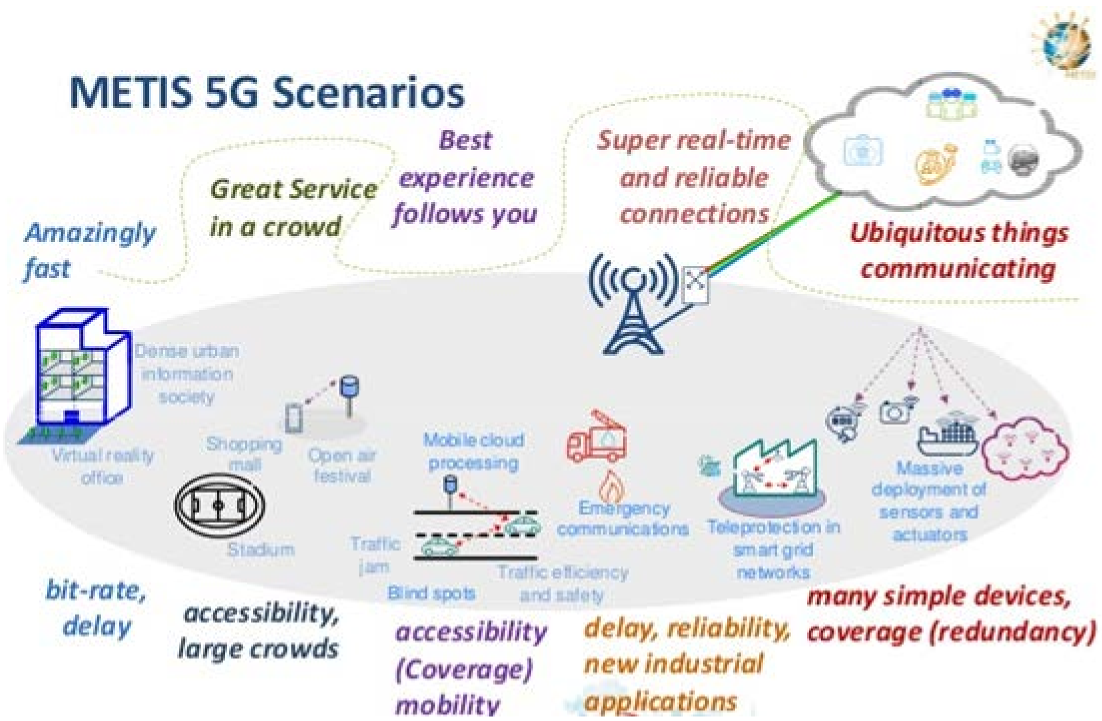

Figure 2-17: METIS 5G scenarios [40]

In addition to the cost to build, upgrading and expanding the mobile broadband network infrastructure is becoming greater. However these challenges towards mobile network can be overcome with new approaches to RAN architectures. There are RAN architectures ranging from centralized RAN to fully distributed RAN. The Centralized, Co-operative, Clean and Cloud RAN (CRAN) concept has been promoted by China Mobile Research Institute (CMRI) [112]. The CRAN architectures with ideal backhaul are 3GPP standard complied and enjoys significant benefits. Energy efficiency can be achieved due to less power consumption of air conditioning and other site support equipment due to the consolidation of Base-Band Unit (BBU) processing. Less Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) due to the combined BBUs which allows centralized management and operation. This leads to significant cost savings on site rentals and maintenance. Advanced transmit and receive techniques such as CoMP can be implemented using the CRAN infrastructure, due to very low latency in the core, leading to remarkable network capacity improvements. BBU pooling can serve as a local breakout point to offload core network traffic to different network nodes as well as different radio access technologies if available [113, 114].

Figure 2-18 illustrates a typical CRAN network architecture [115].

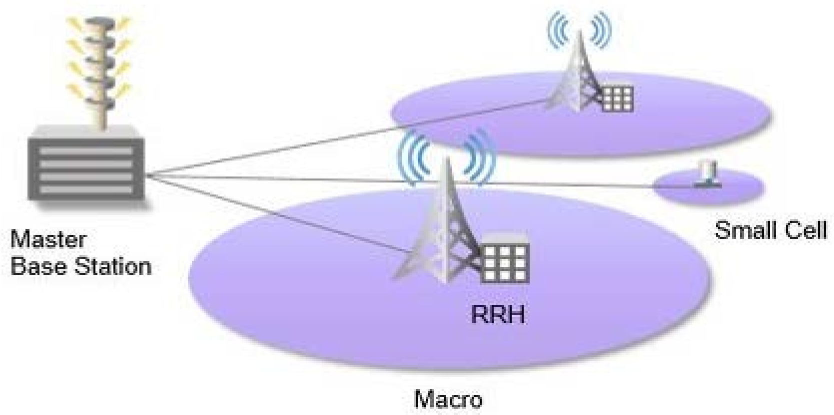

Figure 2-18: CRAN network architecture [115]

CRAN decouples the master base station/ BBU from the Remote Radio Head (RRH), allowing centralized operation and management of BBU and scalable deployment of RRH distributed to locations where coverage or capacity is required, while BBU processing is centralized in one location [116, 117], which can greatly improve the utilization of processing resources.

Networks will continue to become increasingly heterogeneous as we move toward 5G. A key feature therein will be increased integration between different Radio Access Technologies (RATs), with a typical 5G enabled device having radios capable of supporting not only a potentially new 5G techniques (e.g., at mmWave frequencies), but also 3G, several releases of 4G LTE including possibly LTE-Unlicensed [118], several types of WiFi, and perhaps direct D2D communication, all across numerous spectral bands. Hence, determining which standard(s) and spectrum to utilize and which BS(s) or users to associate with will be a truly complex task for the network [54, 119].

Ultra-dense networks with small-cell deployments require a high degree of coordination as offered by centralised processing due to strong inter-cell interference. Furthermore, heterogeneous backhaul solutions should be used to connect small-cells and core network. In order to support centralised processing and a heterogeneous backhaul, challenges on access and backhaul must be simultaneously tackled. Interworking and JOINt Design of an Open Access and Backhaul Network Architecture for Small Cells based on Cloud Networks (iJOIN) [45] project introduced the novel concept RAN-as-a-Service (RANaaS), where RAN functionality is flexibly centralised through an open IT platform based on a cloud infrastructure. iJOIN delivered a joint design and optimisation of access and backhaul, operation and management algorithms, and architectural elements, integrating small-cells, heterogeneous backhaul, and centralised processing [45].

5th Generation Non-Orthogonal Waveforms (5GNOW) [42], is a major research initiative which questioned the design targets of LTE and LTE-Advanced. 5GNOW have developed new PHY and MAC layer concepts and ideas being better suited to meet the upcoming needs with respect to service variety and heterogeneous transmission setups in future generation 5G networks. 5GNOW mainly build upon continuously growing capabilities of silicon based processing [42].

The key objective of 5G NOvel Radio Multiservice adaptive network Architecture (5GNORMA) is to develop a conceptually novel, adaptive and future-proof 5G mobile network architecture. The architecture is enabling unprecedented levels of network customisability, ensuring stringent performance, security, cost and energy requirements to be met [120].

Self-Management for Unified Heterogeneous Radio Access Networks (SEMAFOUR) [121] project designs and develops a unified self-management system. This enables the network operators to holistically manage and operate their complex heterogeneous mobile networks. Its aim is to take the operation and management of mobile wireless networks to the next level by creating a management system that enables an enhanced quality of user experience, improved network performance, improved manageability and reduced operational costs. The SEMAFOUR projects' two key objectives are; development of multi-RAT / multi-layer Self-Organising Network (SON) functions that provide a closed control loop for the configuration, optimisation and failure recovery of the network across different RATs (UMTS, LTE, WLAN) and cell layers (macro, micro, pico, femto) and design and development of an integrated SON management system, which interfaces between operator-defined performance objectives and the set of multi-RAT / multi-layer SON functions [121].

Flexible and efficient hardware/ software platform for 5G network elements and devices (Flex5Gware) [122] is a project where the objective is to deliver highly reconfigurable hardware (HW) platforms together with HW-agnostic software (SW) platforms targeting both network elements and devices and taking into account increased capacity, reduced energy footprint, as well as scalability and modularity, to enable a smooth transition from 4G mobile wireless systems to 5G. This approach will be necessary so that 5G HW/SW platforms can meet the requirements imposed by the anticipated exponential growth in mobile data traffic (1000 fold increase) together with the large diversity of applications (from low bit-rate/power for Machine-to-Machine (M2M) to interactive and high resolution applications) [122].

2.6 Summary

This chapter has provided an overview and a thorough discussion of the evolution of wireless networks to and from the 4th generation. Limitations of the current networks when providing the higher data rates and spectral efficiency as expected with the future generation 5G networks was discussed. Furthermore, technology enhancements and solutions towards achieving the required higher data rates for the current 4G and future generation networks (i.e. 5G) were discussed.

The increasing demand for high speed broadband access supporting higher data rate delivering capabilities for internet services with mobility has gained a huge attention in telecom industry. New technologies and architectures providing such services at low cost and high efficiency to the operators and end users are taken in to consideration. When considering about the wireless technologies, preliminary 4G standards such as LTE Rel.8 & 9 and mobile WiMAX are the major candidates for 4G which provided better system performance compared to the preceding generations. As a successor of LTE, LTE-Advanced provides peak throughput of 1Gbps in downlink and 500Mbps in uplink and very low latency of 5ms in Radio Access Network (RAN) and 100ms connection setup time. LTE-Advanced fulfils and even suppresses some of the IMT-Advanced requirements.

However one of the key limiting factors for LTE-Advanced is inter-cell interference which will significantly lower the spectral efficiency of the cell-edge users because of the universal reuse factor (reuse factor of 1). To fulfil the demands of the future generation 5G networks and to achieve the full capabilities of 4G, this interference issue should be overcome. By using smart antennas and CoMP techniques to achieve interference avoidance/cancellation, the system throughput can achieve significant improvements at the cell-edge. By coordinating and combining signals from multiple antennas, CoMP helps deliver a more consistent user experience for users on the cell-edge or moving into new cells and instigating a handover. By using adaptive antenna technology, can essentially turn the signal interference at the cell-edge into a useful signal and help operators optimise the network. There are some major research initiatives such as METIS-II funded by Horizon 2020 supporting research towards achieving this.

Heterogeneous networks and Device-to-Device (D2D) communication are currently seen as a new communication paradigm for the ever increasing ubiquitous wireless traffic demands. The main reason for focusing on smart antennas and CoMP is to overcome the massive effect of the cell-edge UE performance degradation due to the reuse factor 1. This has a significant impact on D2D communication in a heterogeneous network environment due to its ability to utilise the spectrum simultaneously with the cellular entities with minimum interference.

The next chapter of the thesis presents a comprehensive system-level design of a state-of-the-art 4G LTE simulator developed using MATLAB programming to perform new research addressing cell-edge interference leading the way towards 5G networks. These include appropriate channel modelling and enhancements using smart antennas to perform CoMP, which will further incorporate the technologies implemented such as D2D to carry out further research investigations.

Chapter 3

3. State-of-the-art System Level Simulator for Cellular Networks

3.1 Introduction

This chapter presents a complete system-level design and implementation of a state-of-the-art uplink MATLAB based System Level Simulator (SLS) for Long Term Evolution Advanced (LTE-Advanced). The simulator also depicts new functions that allow the development of novel techniques and algorithms to investigate, in the uplink of cellular networks, Co-ordinated MultiPoint (CoMP), the performance of small-cells (heterogeneous networks) scenarios and Device-to-Device (D2D) underlaying cellular communication, providing critical technological achievements towards next generation networks. The simulator supports new transmission links between multiple eNodeBs and UEs allowing the demonstration of (multi-cell multi-user) enabling interference management and network planning optimization for both rural and urban environments. It follows the 3GPP specifications for the propagation of LTE-Advanced including 4G compatible path-loss models, eNodeB/UE specifications, smart-antennas amongst other features.

The performance evaluation of the new system level simulator is drawn in consideration of a dense network scenario with a large number of eNodeBs providing coverage to a high population of mobile users. The basic cell layout setup consists of 7 eNodeBs. Each eNodeB consists of 3 hexagonal cell sectors forming a site. To provide more practical simulation scenario, UE generation is done randomly and are allowed to move freely. The performance is measured by cumulative distributions from multiple iterations and averaged.

Other than presenting a 4G compatible system level simulator, further work took place to incorporate CoMP functionalities for investigation interference cancellation in uplink. In particular the new system simulator is able to perform investigations in beamforming, including receiver beamforming and joint reception using smart adaptive antennas. Performance evaluation figures such as statistical analysis for coverage, interference, throughput and spectral efficiency can be collected and further analysed.

Further programming to extent the simulator functionalities beyond standard network topologies and into small cells have also carried out in this research project and will be presented together with the achieved performance in subsequent chapters.

3.2 Link to System Level Modelling

The main tools applied for radio access networks evaluation are Link Level Simulators (LLS) and System Level Simulators (SLS) [123]. In realistic deployment scenarios both simulators would be required for network benchmarking. Link level simulators evaluate the physical layer properties [124] of a network including data transmission and the channel and propagation models relevant to the Media Access Control (MAC) layer, where the network configuration comprise a single base station and a single user.

In link-level simulations the drawn performance metrics are usually limited to bit error rate (BER) and signal to noise ratio (SNR). On the other hand SLS is used for simulating multiple eNodeBs and multiple UEs [125, 126], taking into account the scheduling, radio resource allocation and management algorithms, network protocol operation etc [123, 127].

Figure 3-1 shows the OSI layer stack and the layers modelled by each simulator. System level simulators draw on performance metrics expressing the system throughput, user fairness, user-perceived quality of service (QoS), queue status, service level agreement, network load, etc.

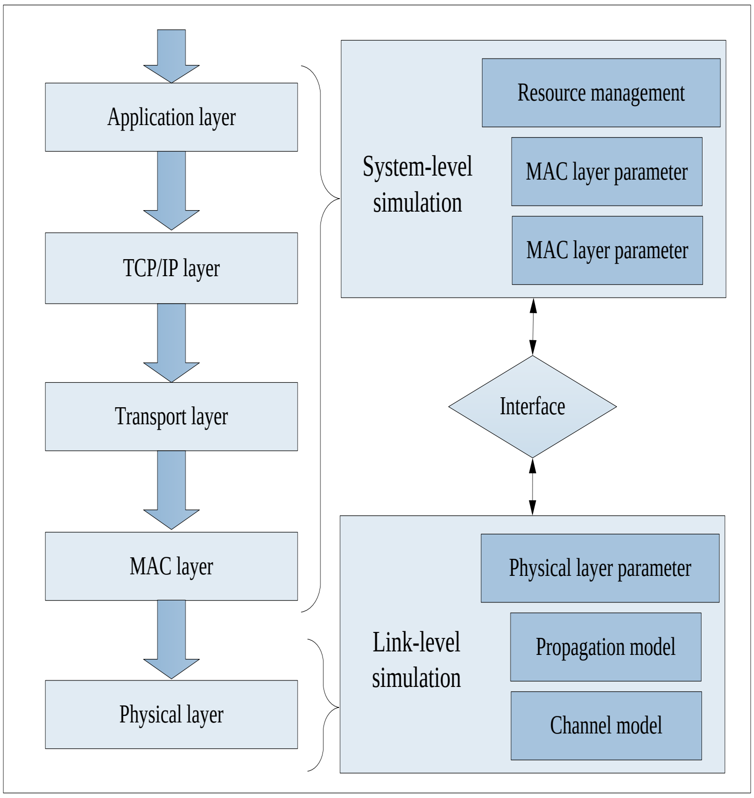

Figure 3-1: General Layers of Link-Level and System-Level Simulators [123]

Investigations therefore are concerned with higher layers including the MAC layer (MAC parameters), transport layer, TCP/IP layer, and application layer [126]. To perform realistic system-level investigations with high degree of accuracy and confidence of the simulation results, the link-level functionalities are traditionally abstracted executing at the end link-level to system-level mapping (L2SM) [126]. This allows the SLS model to simulate the network accounting for the required link-level parameters and their values.

The system level simulation of hundreds of radio links operating in parallel, as would be expected in a practical scenario is particularly challenging to implement due to the vast amount of computational power required. To perform modulation and coding in SLS, the scheduler at the eNodeB needs to know the channel conditions for each user, hence the appropriate modulation scheme and coding rate are assigned. Therefore introduction of a special mathematical model used for accurate Block Error Rate (BLER) prediction in the given signal propagation conditions [124] has been implemented to overcome such difficulties. The channel conditions are estimated from the received uplink sounding reference signals (SRS). The calculated BLER value from the link level model is then passed on to the SLS to calculate the specified probability to model transport block reception success in the system [125, 126]. There are different approaches of implementing a SLSs, but the common approach of achieving an efficient L2SM is by developing two major models which are the Link Quality Model (LQM) and the Link Performance Model (LPM) [126, 128, 129]. In this study, the LQM abstracts the measurement for link adaptability and resource allocation with less complexity. It then outputs a metric (SINR in this instance) quantifying the quality of the received signal after reception and equalisation. Figure 3-2 shows the BLER curve for 5000 iterations regenerated in this research investigation.

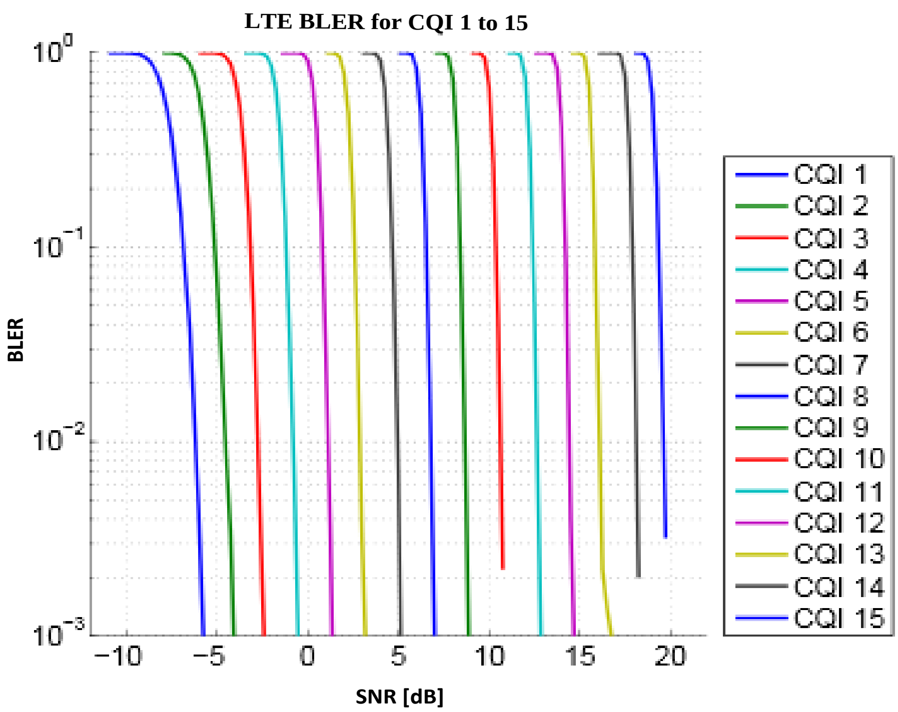

Figure 3-2: BLER curve generated from LLS for 5000 sub-frames

This BLER curve was regenerated using the LTE uplink LLS, developed by the university of Vienna [123], for the use of developing the new state-of-the-art uplink SLS. The link performance model determines the BLER at the receiver given a certain resource allocation and Modulation and Coding Scheme (MCS). For LTE, 15 different MCSs are defined, driven by 15 Channel Quality Indicator (CQI) values. The metric is then mapped into the BLER and throughput based on the code rate, MCS at the LPM. The LTE standard specifies that the MCS scheme has to maintain a BLER of less than 10% (BLER ≤ 10%). For each CQI value the minimum required SNR to achieve this target is obtained by accessing the curves with BLER = 10%. The SNR to CQI mapping function compares the SNR_{fading} calculated for the user, with the CQI-SNR 10% BLER and the first SNR value that is less than or equal to the SNR_{fading} is chosen for the user. The CQI is then used to access the CQI-MCS to obtain the modulation scheme and coding rate to be assigned [130].

The SLS model for the purpose of this research study is based on the framework in [124, 129]. An initial version (2010) of a state-of-the-art UL LTE LLS model with fundamental functionalities provided by the University of Vienna [124, 131] was accessed and used as reference models. Developed comprehensive uplink SLS model includes smart adaptive antennas to perform CoMP techniques in both macro and small-cell environments and D2D communication for the purpose of this research.

The SLS [127, 131] models which were used as reference simulation platforms when developing the new model has no freedom of performing CoMP techniques such as beamforming or joint reception to mitigate inter cell interference which was added to the developed simulator. Results which are obtained by simulations using different algorithms can be compared with the minimum performance requirements (e.g: cell average and cell-edge spectral efficiency) depending on the case and also with the results produced by [124, 127, 132].

3.2.1 Link Quality Measurement in System Level Simulator Model

The key metric used to abstract the measured link quality in the SLS is the post-equalization SINR as discussed in the section above. This can be obtained by modelling the macroscopic path-loss, shadow fading which is position dependent and the fast-fading which is time variant (for the user). The macroscopic path-loss map models the propagation losses (due to distance) between the UE (omni directional antenna) and its serving eNodeB.

The aforementioned position dependent variables are created on a map referred to as Region of Interest (RoI), where all the physical properties/entities of the network are confined (such as eNodeB, UE). The graph represents path-loss of a single sector in a RoI and a single UE in uplink. An illustration of the microscopic path-loss map generated from the developed SLS is shown in Figure 3-3, which can be compared to other available SLS platforms [133, 134] to further validate the results generated in this thesis.

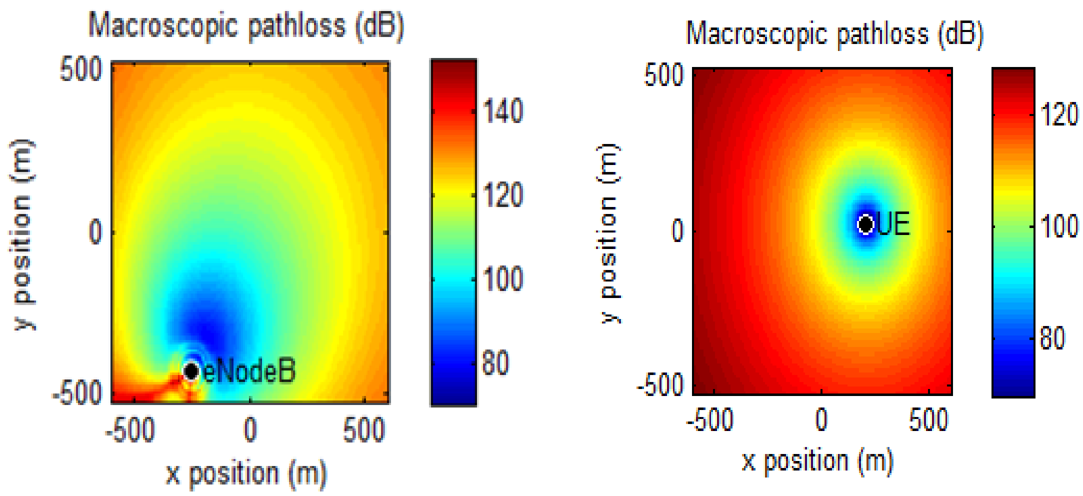

Figure 3-3: Macroscopic path-loss for an UE and an eNodeB with 30 degrees azimuth in a ROI

As depicted in the figure each eNodeB sector has a directional antenna with an azimuth angle of 30 degrees and the UE with an omnidirectional antenna as shown in the graph which has reciprocal properties in uplink and downlink. It can be realised that the path-loss (in dB) is significantly lower (dark blue to light blue area) closest to the eNodeB (or UE), particularly in the direction of the antenna. As it can be seen depending whether the antenna is directive or omni-directional, the gain will be higher in one direction or equal in all directions respectively. Shadow fading is another property modelled in order to obtain the correct link budget input to the SLS platform. This is modelled to represent obstacles/obstruction (i.e. buildings, trees, hills, etc.) in the propagation path between a UE and the eNodeB. It is commonly modelled as a zero-mean log-normal distribution with correlation of 0.5 between eNodeB sites [15]. A correlation factor of 1 is assumed for an urban environment cell layout with three sectors per site, since they occupy the same geographical location [129]. Figure 3-4 presents the correlated shadow fading map of 7 sites in a ROI (one tier network). For each site, a cluster of pixels (geographical positions – explained in the next section) represents the geographical surface of the different sectors within the sites. As illustrated in Figure 3-4 the pixels vary in colour depending on the shadow fading value (in dB) for each pixel.

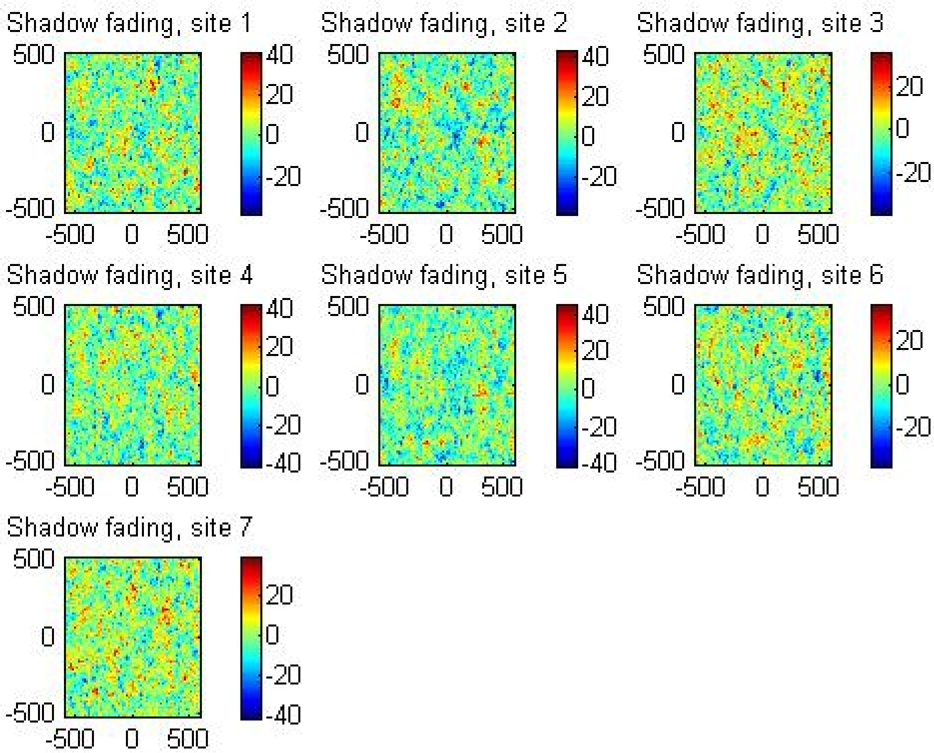

Figure 3-4: Correlated shadow fading map for 7 eNodeB sites (Tier 1 network)

3.2.2 Network Architecture and Cell Layout

At the initial stage of developing the simulation platform, a cell layout consisting of 3 hexagonal sectors was created. Inside each sector, points were created in order to use them as geographical positions where a mobile terminal/UE can be located as shown in Figure 3-5. Each 'x' (pixel) denotes a geographical position (lower resolution is used for illustration) where an UE can appear. In the developed simulator, in comparison with other SLS platforms which use a set of pre-generated positions [124, 131], the resolution of these geographical positions can be increased or decreased depending on user requirements to simulate rural or urban environments.

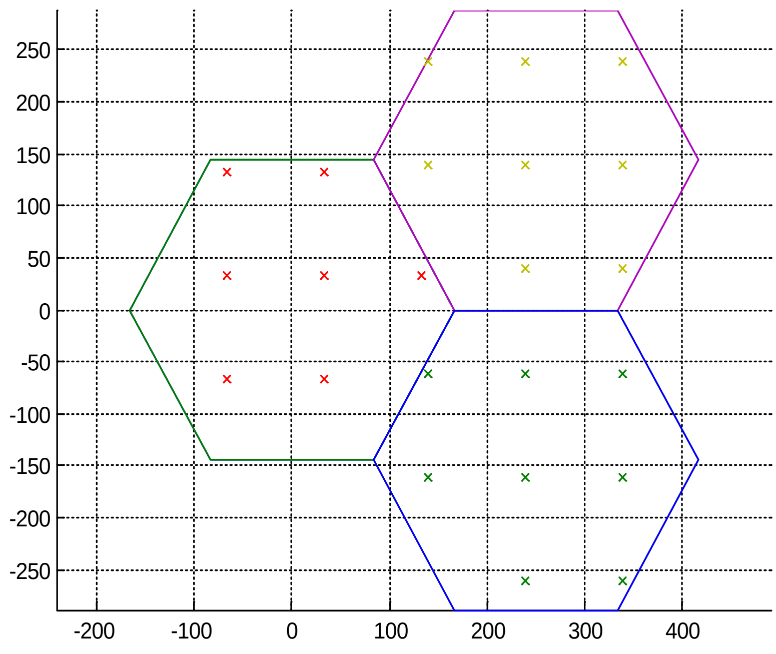

Figure 3-5: Cell layout consisting 3 hexagonal sectors

Geographical positions are equally distributed among sectors with an equal distance and all the position coordinates are stored in a matrix. Hexagonal grids are used to represent the cell sites or sectors, differentiating the cellular scenarios (e.g. macro and micro cells) by the size and distance between the sites [135]. This was done with accurate modelling of entities such as gain pattern and antenna heights. Therefore the implemented SLS topology in the initial stages of work represented a typical macro-cell layout, with hexagonal grids representing eNodeB sectors (indexed for clarity in Figure 3-6).

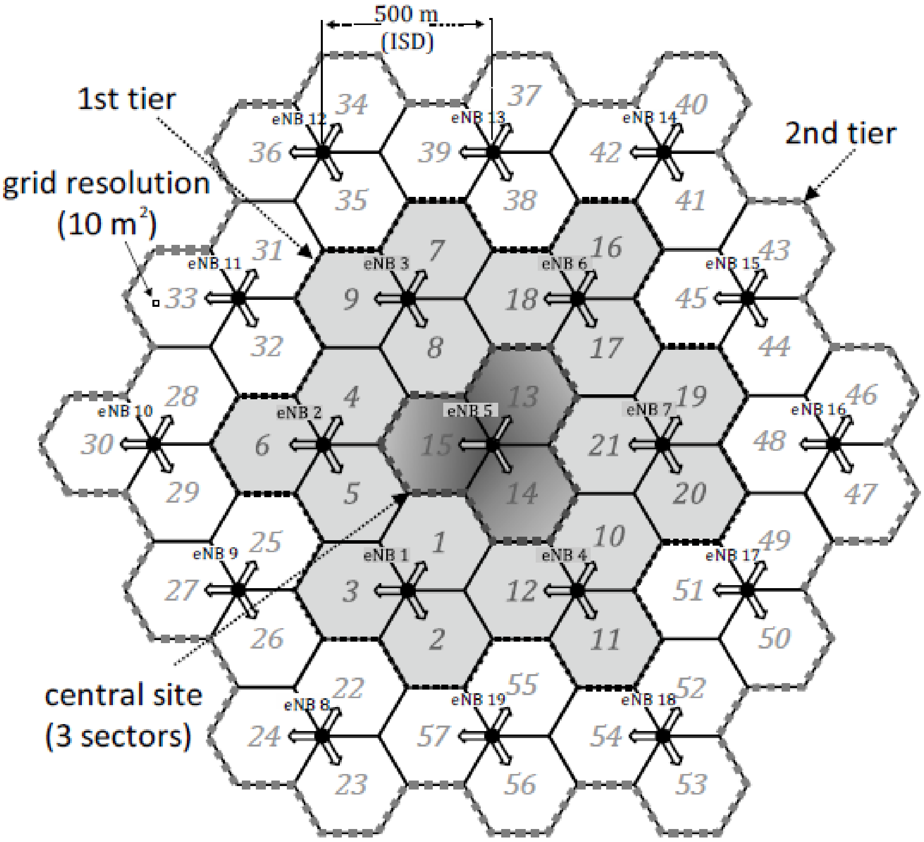

Figure 3-6: Typical 2-tier macro-cell layout with 500m ISD

Figure 3-6 illustrates a 2 tier network where the number of eNodeB cell sites is 19 (N= 19) and a total number of 57 sectors (each site comprises of 3 sectors). The eNodeBs are separated by an inter side distance of 500m. Directional antennas of 120 degrees are used to separate the sectors where the azimuth of each sector is 30 degrees, 180 degrees and 210 degrees respectively with a fixed antenna pattern of [136]:

$$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right], where -180 \le \theta \le 180$$

Eq. 3-1

In the equation above $A(\theta)$ = 2D is the radiation pattern where A is a dependant on azimuth θ, θ_{3dB} is the 3dB (half-power) beam-width which corresponds to 65 degrees and A_m is the maximum attenuation between the main lobe and the highest side lobe with an antenna gain of 20 dB [135, 137]. The simulator uses the standard TS36.942 [136] antenna model to generate the antenna gain patterns. They are shown, for a 3-sector cell in Figure 3-7 below, matching the standard [136].

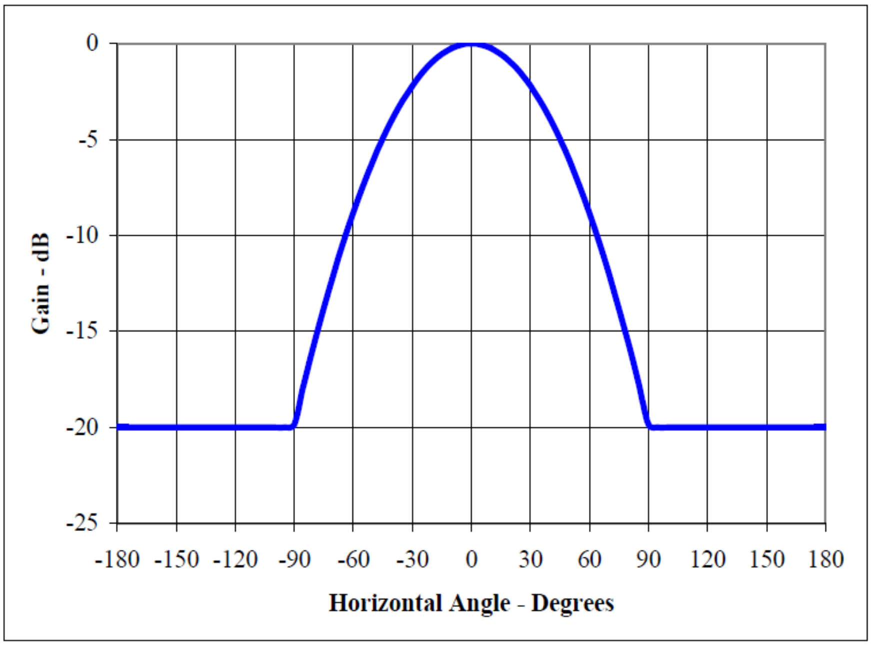

Figure 3-7: Antenna gain pattern for 3-sector cell

The Minimum Coupling Loss (MCL) or minimum distance loss including antenna gains measured between connectors [137] is another important parameter. It describes the minimum signal loss between cellular entities such as eNodeB-to-UE or UE-to-UE.

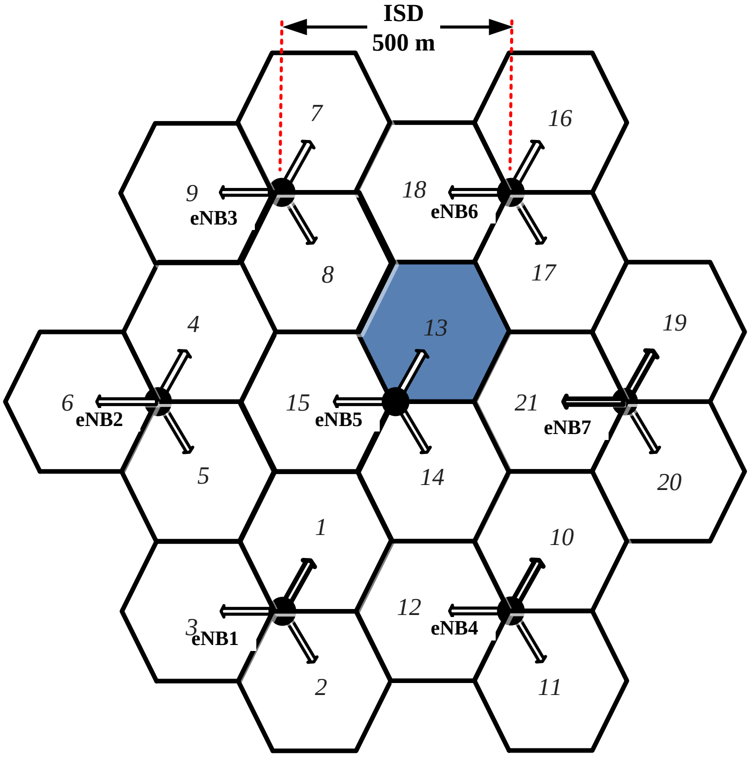

Figure 3-8: Cell-layout used for the performance investigation (Target sector: sector 13 where simulation results were obtained)

For performance investigations a single tier consisting of 7 sites (with 3 sectors each) as shown in Figure 3-8 was simulated to represent a typical urban scenario. Shown in Figure 3-8, eNodeBs have an inter site distance (ISD) of 500m, defined as the distance from the centre of one cell site (eNodeB) to another.

Each sector has 10 UEs. The performance metric of the UEs in sector 13 in eNodeB 5 (i.e. the target sector) are represented in the following results. Sector 13 was chosen because it is in the middle of the layout, and experiences interference from all surrounding eNodeB sites, representing a worst case scenario particularly for those UEs at the edge of the sector.

The UE generation is done randomly to achieve more practical and realistic results. Depending on the number of UEs to be generated, the simulator will randomly select geographical positions (set of random coordinates from the stored positions matrix) from each sector from the positions matrix.

Each simulation iteration will generate a random set of UEs (small circles in Figure 3-9) in each sector.

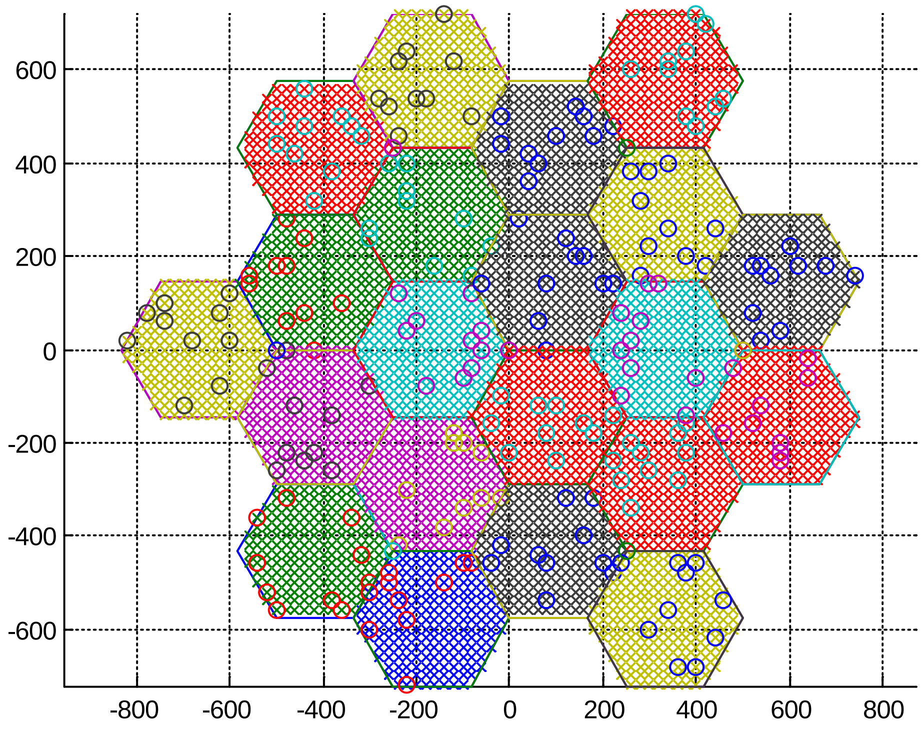

Figure 3-9: Random UE generation in a single tier cell-layout

The simulation assumes in average 10 users per sector (210 UEs in total) as expected in typical deployments. The model also utilises a full buffer traffic which means that a user has an unlimited amount of data to transmit. Various antenna configurations are also simulated and presented in order to evaluate the effect of beam width with the increase number of eNodeB antennas.

As already mentioned the UEs are generated randomly and distributed equally among all the sectors. Since the cell layout represents a typical macro-cell, shadow fading is modelled based on log-normal distributed random variable with zero-mean usually caused by large structures such as hills and large buildings [135] as discussed in section 3.2.1. It is a position dependent feature and a function of the UE location in the cell site. Hence, it is modelled to be space correlated, as the fading experienced by UEs around the same surrounding area would be interrelated.

Table 3-1 summarises the simulation parameters.

Table 3-1: Simulation parameters

Parameter	Assumption
Cellular layout	Hexagonal grid, 19 or 7 cell sites, 3 sectors per site
Inter-site distance	500 m
Cell sectors	120 deg.
Antenna pattern (horizontal)	$A(\theta) = -\min[12(\theta/ \theta_{3dB})2, A_m]$, θ = 65 degrees, Am = 20 dB
Channel model	Urban, Winner II type
Shadow fading	Log-normal, space correlated, zero mean σ = 10 dB
BS height/ antenna gain	20m/ 15 dBi Tx power: 43 dBm
UE antenna height / gain	1.5m/ 0 dBi Tx power: 23 dBm
Frequency	2 GHz (Frequency reuse of 1)
Bandwidth (MHz)	5, 10, and 20
Number of UEs	10
UEs distribution	Homogenous; random positions
TTI (ms)	100

The system level simulator can be used to simulate the network using either one tier (21 sectors) or two tiers (57 sectors). For the 1-tier simulation layout, the performance of UEs in the central sectors is considered (i.e. 30 UEs, considering 10 UEs per sector) and the rest is discarded. For the 2-tier simulation layout only the performance of UEs in the 1st tier are considered (i.e. 210 UEs) and the rest are discarded. This is to ensure all the UEs experience the same interference level and to avoid attaining non-realistic performance from the UEs at the border sectors (such as sectors 3, 6, and 11) in the cell layout. The user and eNodeB height are 1.5m and 20m respectively inside the macro-grid with an inter-site distance of 500m. The UE performance such as throughput is recorded after every TTI. This is then averaged to determine the UE performance after several TTIs.

3.3 Channel Modelling

According to 3GPP, radio wave propagation, in a mobile environment, can be described by multi-paths which arise from reflections and scattering, causing in turn fading and channel time dispersion [138]. Indoor office, indoor-to-outdoor pedestrian and vehicular environments are the most commonly used test environments. According to [139] the attenuation of path-loss in an indoor office environment due to obstacles like walls, floors and furniture is modelled with a lognormal shadow fading with σ = 12dB. A simplified model given by 3GPP to model the test environments' path-loss (PL) is shown in Equation 3-2 [139];

$$PL = 37 + 30\log_{10}(d) + 18.3n^{((n+2)/(n+1)-0.46)} \qquad \text{Eq. 3-2}$$

where *PL* represents the path-loss, *n* is the number of floors between the receivers and *d* is the distance between the transceiver.

As proposed in [140], indoor-to-outdoor pedestrian environments include low antenna height base stations that are located outside, thus covering pedestrian UEs (with an average speed of 3km/h) located on the streets and inside buildings (residential/offices). For accurate modelling in this case, the path-loss is divided into Line-of-site (LOS) and non-LOS lognormal shadow fading with σ = 10 for the pedestrian UEs and σ = 12 for the indoor UEs.

Equations 3-3 and 3-4 represent the path-loss model for the non-LOS and both LOS and non-LOS respectively.

$$L = 40\log_{10}(d) + 30\log_{10}(f_c) + 49 \qquad \text{Eq. 3-3}$$

$$L = 20\log_{10}\frac{4\pi f d_n}{c} \qquad \text{Eq. 3-4}$$

where f_c is the carrier frequency, and d_n is the sum of n street segments.

The path-loss of the vehicular test environment can be expressed as follows,

$$L = 40(1 - 0.004 \times \Delta h_b)\log_{10}(R) - 18\log_{10}(\Delta h_b) + 21\log_{10}(f_c) + 80 \qquad \text{Eq. 3-5}$$

where Δh_b is the height of the base station in meters form an average rooftop height with $0 < \Delta h_\mathrm{b} < 50$ [139]. The vehicular test environment is alternatively characterised by large cells (macro-cells), high transmit power, and high cell capacity (assuming limited spectrum). The signal strength diminishes with increasing distance from the transceiver, and is typically used to represent urban and suburban environments with UE speed from 30 to 350km [138]. For an environment where Δh_b = 15m and f_c= 2GHz, the path-loss model is then represented as follows,

$$L = 128.1 + 37.6\log_{10}(d) \qquad \text{Eq. 3-6}$$

The Wireless-World-Initiative-New-Radio II (WINNER II) model was considered in this thesis since it is able to describe numerous propagation environments for single and multiple radio links for all scenarios outlined above [141]. It is worth noting that WINNER II was modelled to cover a vast amount of propagation scenarios including indoor office, large indoor hall, rural macro-cell, urban macro-cells, suburban macro-cell and micro-cell etc.

amongst many. It also supports multi-antennas technologies, polarisation, multi-user and multi-cell networks [142].

3.4 Beamforming and Generating Beam Patterns

The cell layout used for the purpose of this research consists of 7 eNodeBs (single tier network) as depicted in Figure 3-8, with an ISD of 500 m. The simulation is performed by defining a RoI (target sector) in which the eNodeBs and UEs are positioned and it is only in this area where UE movement is performed. Each sector has 10 UEs, and the performance metric of the UEs in sector 13 (target sector) are taken in to account. This is because the sector is in the middle of the layout, and receives interference from all surrounding eNodeB sites, therefore avoiding optimistic results at the cell-edge. It has to be taken into account that the figures (Figure 3-10 to Figure 3-12) illustrated throughout the section have a lower resolution for illustration purposes.

Received power to each of the geographical position in each sector from its respective eNodeB is calculated depending on the distance, path-loss and shadow fading from the eNodeB and logged in a matrix. This matrix was generated to support the TS36.942 [136] antenna model.

To determine the geographical areas with bad channel conditions, the calculated received power (power received by an UE from the relevant eNodeB) values at each point are used. The received power is calculated using the Equation 3-7 and logged in a matrix:

$$W(\theta,\phi) = \left[G(\theta,\phi) \Big/ 4\pi r^2 \right] P_t \qquad \text{Eq. 3-7}$$

For the transmitting antenna, G the radiation power density at a distance r from the antenna is W. Here, the arguments θ and ϕ indicate a dependence on direction from the antenna, and P_t stands for the power the transmitter would deliver into a matched load (receiver).

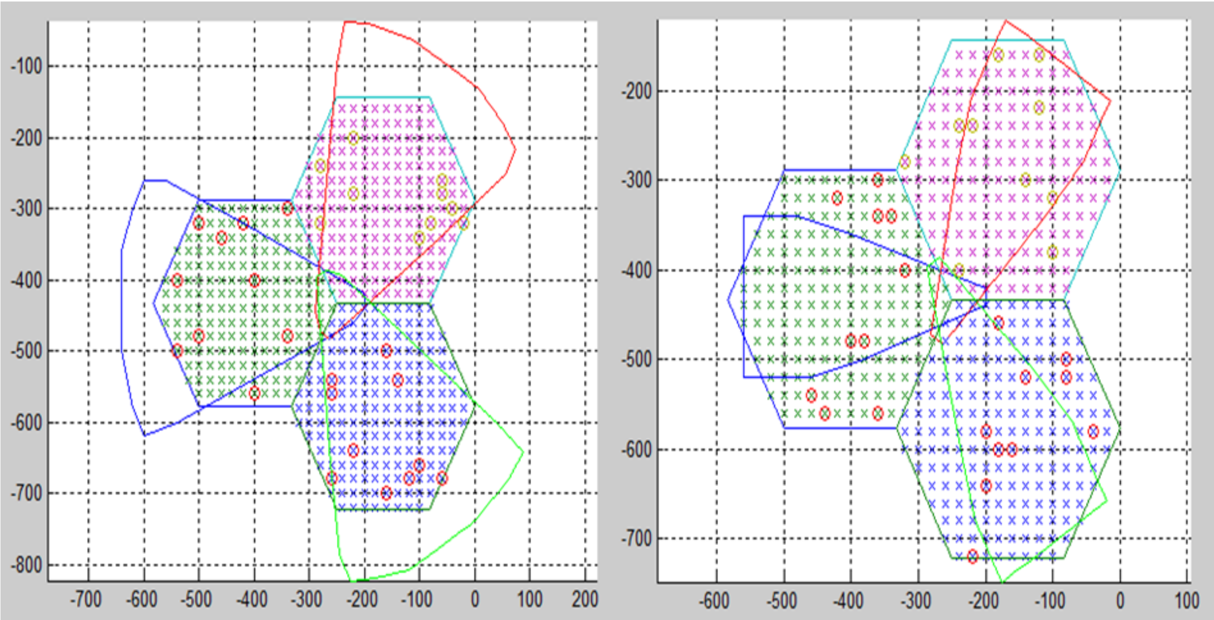

Figure 3-10: Antenna beam pattern for positions inside 120dB and 80dB

This matrix which includes the received power value for each position depending on the distance from the eNodeB can be used to generate receiver beam patterns using different power levels at the eNodeB to investigate the coverage, or to determine the power needed to cover a certain area (e.g. cover the UEs in the range of < 120dB) as shown in Figure 3-10 (lower resolution has been used for illustration purposes).

These patterns are generated using the fixed beam antennas covering the geographical positions which are inside the given received power range. It can be observed that most of the radiation power is fallow and it extends beyond the cell-edge boundary, causing interference at the next cell sector.

As an example, Figure 3-11 describes the fixed beam pattern generated using a 4 x 4 antenna which covers the geographical positions inside the receiver power range of < 80dB.

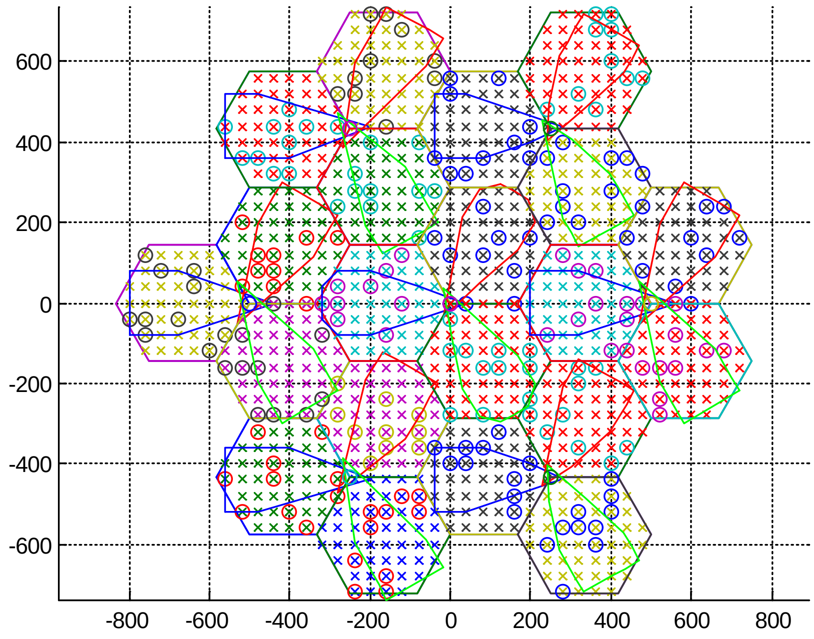

Figure 3-11: Antenna beam pattern inside the range of < 80dB

Figure 3-12 illustrates how the average coverage and interference changes when the number of UEs is increased, in order to check the consistency of the simulator. In total 50 iterations were performed and the results were averaged for the fixed beam radiation pattern. Users are generated randomly and a range of 10 up to a maximum of 25 UEs inside a sector was considered. The 'x' denotes a geographical position and a 'o' represents a UE. Using the antenna receiver radiation power at each geographical position the simulator can change the antenna radiation pattern to cover a specific area as shown in the figure. From Figure 3-12 can be observed that in average 85% of the UEs are covered by the generated fixed beam patterns (CoMP not required).

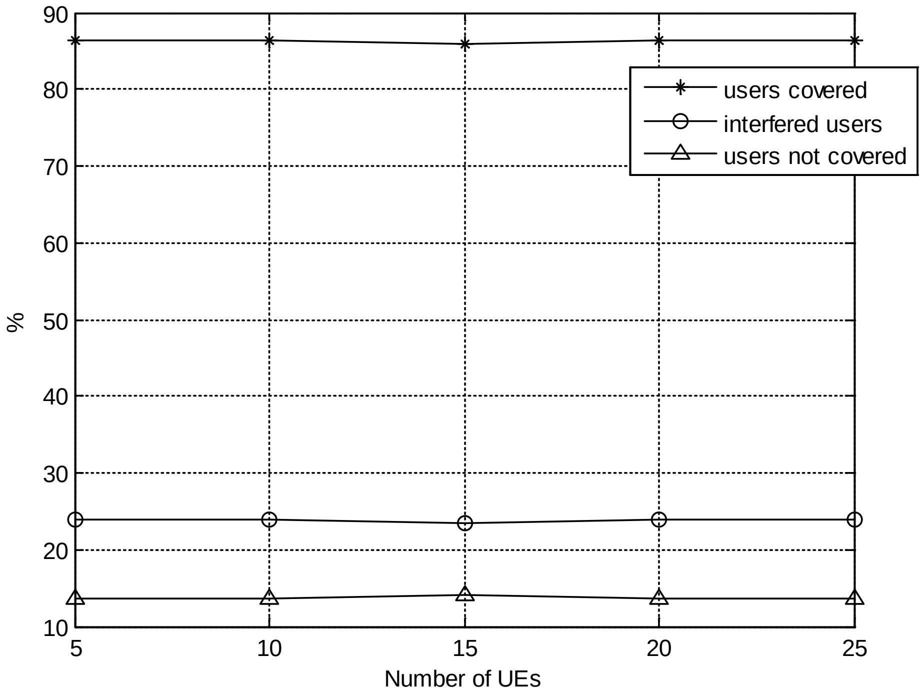

Figure 3-12: Coverage consistency check for the fixed beams

To perform coordinated multipoint, beamforming techniques were taken into consideration based on which new antenna receiver beam patterns are generated, for specified UE locations (positions) in each sector. It was assumed that the direction (angle) and the UEs' distance to are known to the eNodeB (eNodeB is aware how UEs are distributed across the network). In addition, the Direction of arrival (DoA) from all randomly generated UEs is calculated and the average angle is taken in to consideration when the eNodeB generate the gain pattern.

There are several methods discussed in the LTE Rel. 9 [86] standard that can be used to acquire the position of UE. From these techniques the Enhanced Cell ID (E-CID) method [86] provides several benefits since it calculates the angle and the distance to an UE, by using timing measurements (based on round trip time) to calculate how far a mobile terminal for example is from the eNodeB [17, 74]. When connected, both the serving cell and the UE measure the timing difference between Rx sub-frames and Tx sub-frames. The UE reports the measured values to the eNodeB and the eNodeB calculates the round trip time (RTT) required for determining the position.

Since the eNodeB's coordinates and antenna height are also known the position of the UE can be calculated. This method can be further improved with the addition of a feature known as Angle of Arrival (AoA). There are several methods such as ESPRIT and MUSIC [143, 144] discussed in literature for the calculation of AoA. The eNodeB estimates the direction from which the UE is transmitting using a linear array of equally spaced antenna elements. Reference signals received from the UE at any two adjacent elements are phase rotated by an amount which depends on the AoA.

By increasing the number of antenna elements in the eNodeB the generated beam pattern can be narrowed to a specific UE or an area only. Therefore a smart antenna system needs to differentiate the desired signal from co-channel interference and normally requires either the knowledge of a reference signal (or training signal), or the direction of the desired signal source which can be calculated using any of the above methods mentioned above [145].

Even though the direction and angle of arrival were calculated by taking the average of all angles to all UEs from an eNodeB, the receiver beam pattern generated with a fixed antenna configuration is not able to cover all positions in a sector in the absence of CoMP techniques. Since the simulator has the knowledge of the received power value of each geographical position, the antenna radiation pattern to be used for each sector in 3 – sector cell site is plotted using the matrix generated by using Equation 3-1.

Figure 3-13 shows how each antenna radiation pattern covers the geographical positions which are within their given received power (dB) range. Since the received power value at each geographical position is known, it can be used as a reference point for developing power control algorithms at eNodeBs and UEs, to combat cases of high power consumption.

Combining algorithms for reducing radiation power at specific directions with receiver beamforming techniques, as will be described in following sections, can minimise interference. Currently Figure 3-13 displays the fixed antenna beam patterns of a single tiered network in the absence of any beamforming techniques used and with fixed beam antenna (SISO) configuration.

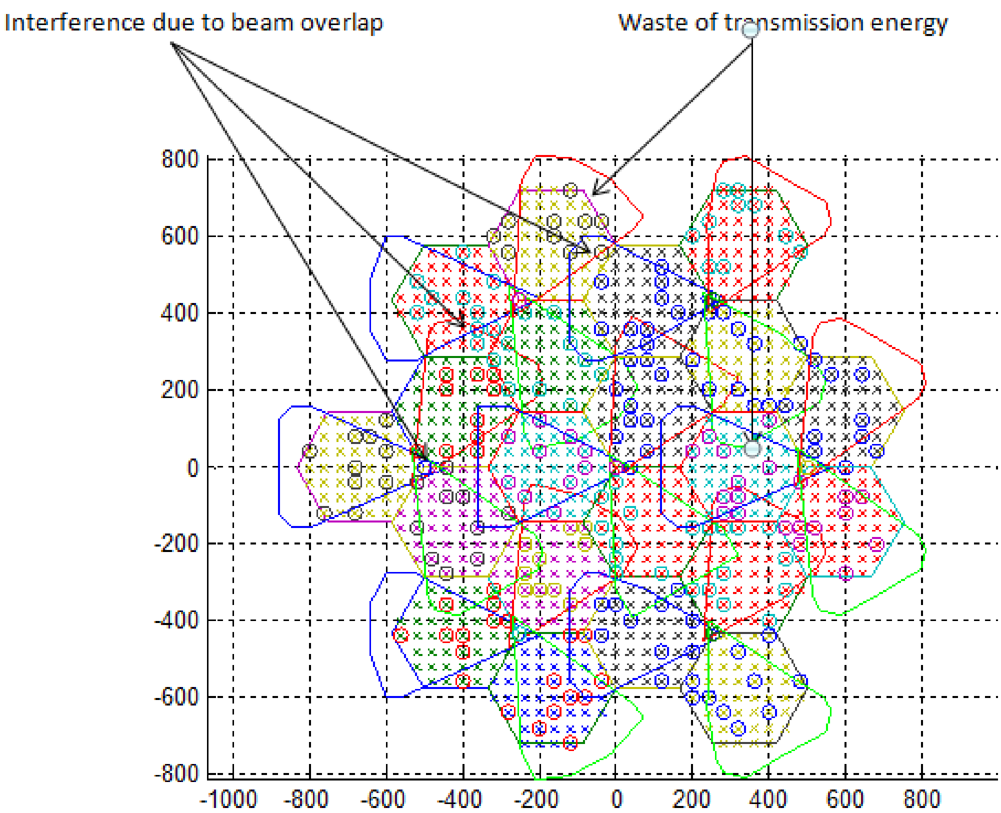

Figure 3-13: Single tier network with fixed beam antenna configuration

In use of fixed antennas the interference due to constant radiation power which is made worse by beam overlap is significantly higher compared to an adaptive smart antenna scenario. Therefore to overcome this problem the receiver beamforming technique using smart antennas is introduced. Receiver beamforming will be demonstrated and evaluated in detail in chapter 4, for transmission in the uplink of a cellular network in order to focus energy at a specific UE or cluster of UEs providing in cooperation with other techniques interference mitigation.

3.5 Transmission Modes in LTE and LTE-A Uplink

Since CoMP techniques are considered in this research, the use of Multiple-Input-Multiple-Output (MIMO) technology is naturally considered. MIMO in this thesis in particular involves the configuration of multiple antennas at the transmitter and/or receiver to achieve diversity or spatial multiplexing in the spatial domain. This is an alternative to Single-Input-Single-Output (SISO) transmission which requires a single antenna at both transmitter and receiver. To keep complexity at UEs low, Rel.8/9 do not specify an exact MIMO in the uplink for LTE [146]. Receive beamforming in the uplink can be carried in consideration of the base station implementation.

In contrast, LTE-A supports uplink MIMO with up to four layers. The standard therefore defines a new transmission mode in the uplink in support of up to four antennas. LTE Rel.12 for examples specifies two main transmission modes in the uplink. One for single antenna operation and the Closed-Loop-Spatial-Multiplexing (CLSM) mode with 2 or 4 antennas [146]. Spatial multiplexing is used in LTE-A as a technique to increase the transmission data rate whereby data is divided into separate streams, which are then transmitted simultaneously over the same air interface resources. The transmission includes special pilots or reference signals which are known to the receiver. By using these signals the receiver can perform channel estimation for each transmit antenna's stream. In the closed-loop (CLSM) method, the receiver reports the channel status to the transmitter via a special feedback channel which enables it to respond quickly to changing channel circumstances [146, 147].

Spatial multiplexing achieves spatial diversity by transmitting multiple independent streams from multiple antennas. Therefore with appropriate Channel State Information (CSI) feedback from UEs, the eNodeBs can choose the optimum Precoding Matrix Index (PMI) to maximise network capacity. To reduce the added complexity to UEs signalling (i.e. PMI feedback), the matrix is chosen from a predefined codebook [147] for the different antenna configurations (2 or 4 transmit antennas).

The transmission modes have been simulated, followed by their performance to provide the background for the development in subsequent chapters of cooperative interference mitigation. Varying channel conditions were used to evaluate and analyse the modes, including a sudden increase in UE speed, leading to the implementation of two scenarios [147]. UEs are modelled in a ‘random walk’ speed of 5km/h as the first scenario, and a much higher UE moving speed of 120km/h emulating high speed users (vehicles, trains). The same network and channel conditions were implemented for the two scenarios, apart from the UE speed, to be able to compare and contrast between them. Figure 3-14 illustrates the throughput performance metric of UEs in the target sector for a single tier network consisting of 7 sites (with 3 sectors each) cell layout (as shown in Figure 3-8) with 10 UEs per sector representing a typical urban scenario with an ISD of 500 m. UE performance was averaged over 50 TTIs and aggregated to obtain accurate results for the throughput evaluation.

The performance gains of different antenna schemes for SISO and CLSM were compared against the uplink throughput in the target sector using a normalized cumulative distribution function (CDF) from 500 samples (50 TTIs times 10UEs). A channel bandwidth of 10MHz was used. Figure 3-14 provides a comparison between SISO and CLSM with both 2 x 2 and 4 x 4 antenna configurations.

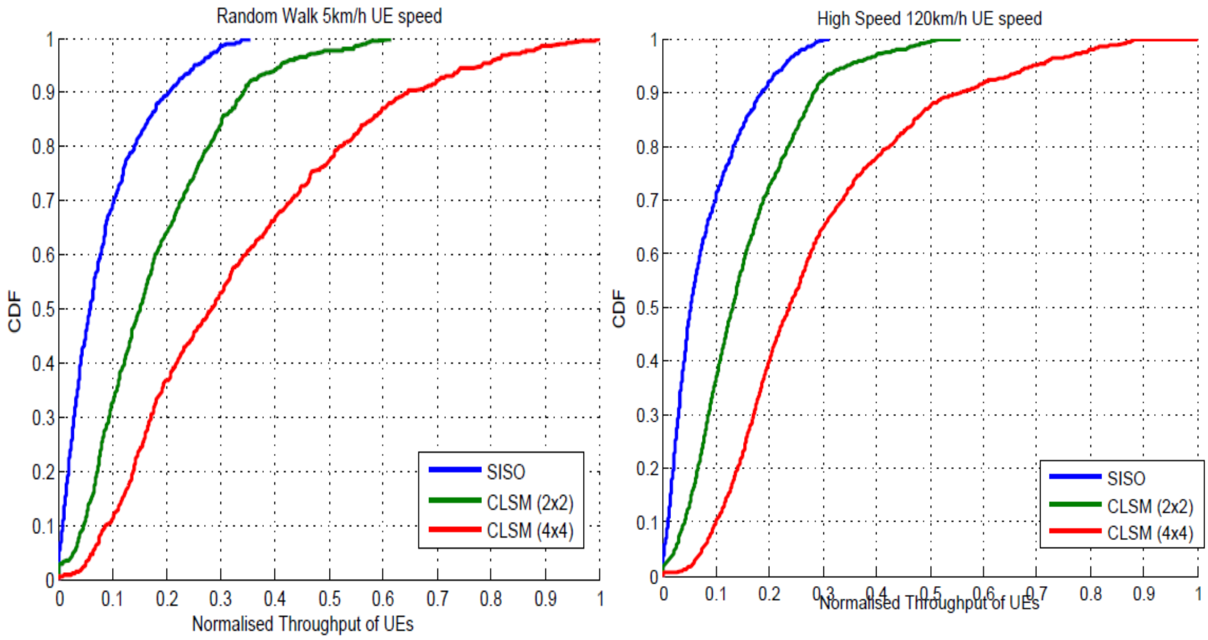

Figure 3-14: Transmission mode comparison between SISO and CLSM with 2 x 2 and 4 x 4 antenna configurations for different UE speeds

As a point of reference the 50th percentile (average throughput) was used. The normalized throughputs for SISO, 2 x 2 and 4 x 4 CLSM antenna configurations are 0.05, 0.15 and 0.29 respectively at an UE speed of 5 km/h (random walk). For the high speed scenario the normalized throughputs at the point of reference (50th percentile) are 0.04, 0.12 and 0.23 respectively. However it can be seen that with both UE speed of 5km/h and 120km/h, the throughputs at the point of reference compared to the SISO, CLSM for 2 x 2 antenna configuration and 4 x 4 configuration throughputs are approximately 3 times and 6 times higher respectively. The CLSM mode performs significantly better with low and high speed UEs, which is due to the more detailed UE feedback obtained when compared to SISO mode.

3.6 Resource Allocation Algorithms

The key to achieve optimal eNodeB performance is dynamically scheduling limited resources like power and bandwidth to offer the best service for terminals/ UEs with the lowest cost.

Therefore this section provides initially a brief theoretical overview of the common resource allocation algorithms in LTE uplink, known as the Round Robin (RR) and Proportional Fair (PF). The later part of this section will present the simulation design and performance metrics of UEs for both resource allocation algorithms. Since the LTE physical resources are represented as a time-frequency resource grid, which consists of a number of resource elements, resources are allocated to UEs in the form of resource blocks (RBs). This is primarily dependent on the channel bandwidth and channel condition of the UE (depending on the resource allocation scheme used) [148].

From the scheduling algorithms mentioned above, the RR scheduler is most widely used in literature for performance evaluation and comparison due to its simplicity in implementation and uniformity in resource allocation [148]. It uses a 'round robin' format where to start with all UEs are put in a queue and served one after the other equally. It is obvious this algorithm fails to account for UEs with poor channel conditions (usually UEs at the cell edge) needing more resources to carry out equally high transmission rates with the ones benefiting from good channel conditions, resulting to lower recorded throughput for the network in general.

Proportional Fair (PF) scheduling in general aims to maintain simplicity and maximum network/UE throughput, by exhibiting increased fairness to UEs with poorer channel condition. To achieve this UEs are categorized based on a priority function. Then PF algorithm assigns resources to UEs with the highest priority first, repeating the allocation to least priority UEs until all resources are used up or all resources requirements are satisfied.

Compared to RR which considers individual UEs at a time, the PF scheduler considers all UEs in order of priority over a certain period of time, within which is taking scheduling decisions. Hence, the eNodeB firstly obtains the instantaneous CQI for each UE, k, in a time slot, t, with reference to a requested data rate $R_{k,n}(t)$. Then it keeps track of the varying average throughput $T_{kn}(t)$, for each of the UEs, on n RBs within a past time window length t_c. Therefore the priority function for each UE k^*, in the t^{th} time slot and RB n that satisfies the maximum relative channel condition in PF [149] is given by:

$$k^* = \arg\max \frac{[R_{k,n}(t)]^{\alpha}}{[T_{k,n}(t)]^{\beta}} \quad , k = 1, 2, ... \qquad \text{Eq. 3-8}$$

Where $\alpha = 1, \beta = 1$, the PF algorithm is in use. If $\alpha = 0, \beta = 1$ the RR algorithm is in force and if $\alpha = 1, \beta = 0$ the Best CQI (BCQI) which is out of the scope of this thesis since it only assign resource blocks to the user with the best radio link conditions which does not provide fairness for comparison. Figure 3-15 is plotted to draw the performances of the two schedulers.

A single tier cell layout (again as shown in Figure 3-8) consisting of 7 sites (with 3 sectors each) with an ISD of 500m is used to emulate the network for the performance comparison and establishing a comprehensive simulation platform fit for purpose. The UEs are modelled to exhibit random walk (5km/h speed of movement), with a 10MHz bandwidth channel operating in the CLSM transmission mode. The measured UE throughput distribution between the scheduling algorithms discussed is compared using a normalised CDF as in the previous section.

The performance gains of the two antenna schemes were compared against the uplink throughput in the target sector over from 500 samples (50 TTIs times 10UEs). The 95th percentile (UEs with a best channel quality or UEs closest to the eNodeBs) and 5th percentile (cell edge) are used for comparison. The 95th percentile, as expected, provides the best achievable UE throughput, whereas the 5th a worst case scenario.

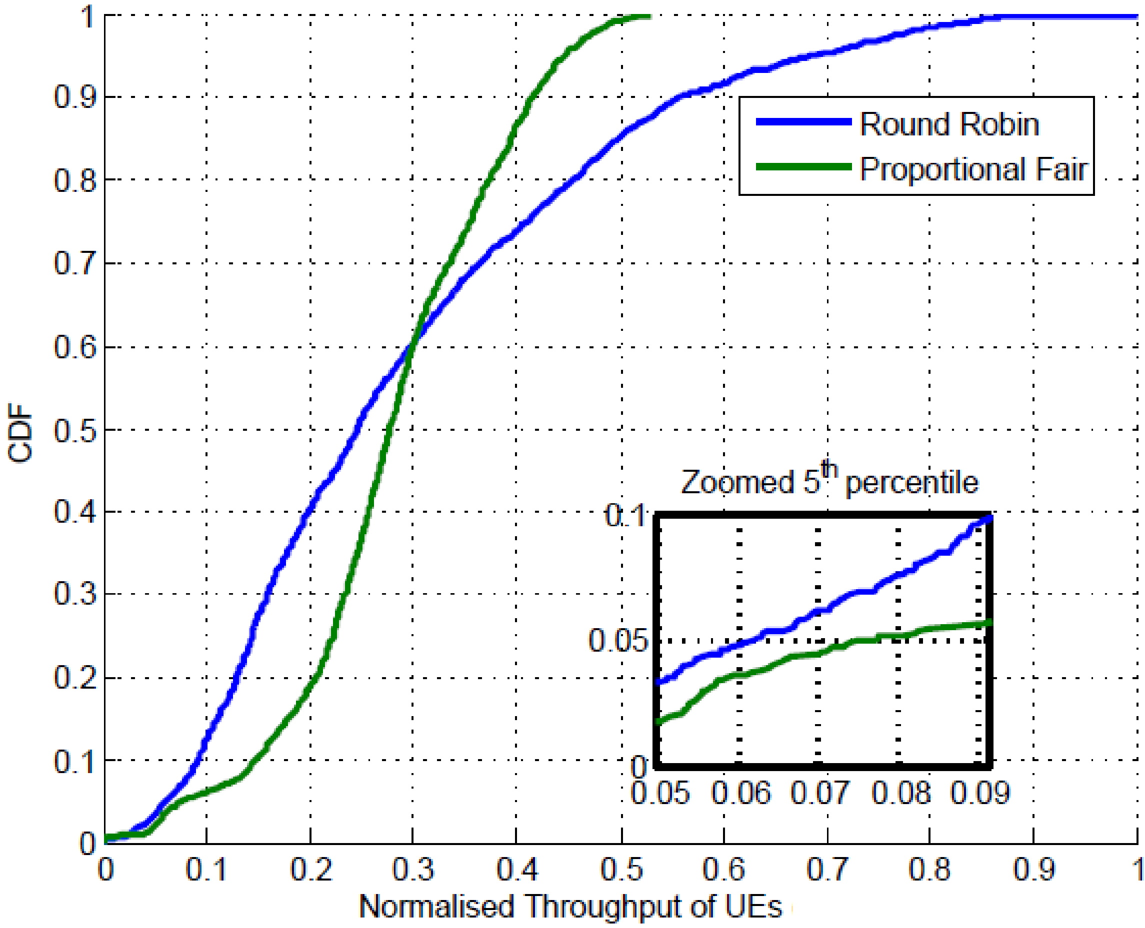

Figure 3-15: Normalized throughput CDF with the two scheduling algorithms for UEs in target sector

At the 5th percentile the normalized CDF displays, approximately 0.077 and 0.061 UE throughputs for the PF and RR schedulers respectively. At the 95th percentile the same values are 0.446 and 0.684. It can be concluded that the PF scheduler performs slightly better (by 25%) at the cell-edge (5th percentile) compared to RR, while the RR scheduler performs significantly better (by 55%) at the 95th percentile compared to PF. At to some extent the performance achieved is expected considering the PF scheduler provides increased fairness to cell-edge UEs while the RR scheduler is focused on simplicity of implementation, regardless of the channel quality of each UE by exhibiting uniform scheduling. Since the RR scheduler has significantly less computational complexity in its implementation and has exhibited not huge different performance at the worst case, cell edge scenario, it is the primary scheduler used in this thesis to evaluate network performance in following chapters.

3.7 Performance Evaluation

UE uplink performance evaluation discussed in this section considers the achieved throughput metric, for different LTE channel bandwidths (i.e. 5 MHz, 10 MHz and 20 MHz) by drawing the cell-edge UE performance degradation relative to UEs closer to eNodeBs, and the observed transmission gain. Inter-cell interference in addition to other limiting factors such as propagation distance and fading, are particularly investigated to define their level of contribution to the overall network throughout degradation experienced. A single tier cell layout shown in Figure 3-16 consisting of 7 sites (with 3 sectors each) with an ISD of 500m is used to simulate the network as before. The network was evaluated using the CLSM transmission mode and RR scheduler for all three different LTE channel bandwidths. A total of 50 iterations were performed and a normalized CDF of the target sector UEs throughput is taken for the 5th, 50th, and 95th percentiles which commonly represents the cell edge throughput, median throughput, and best UE throughput respectively in a cellular network.

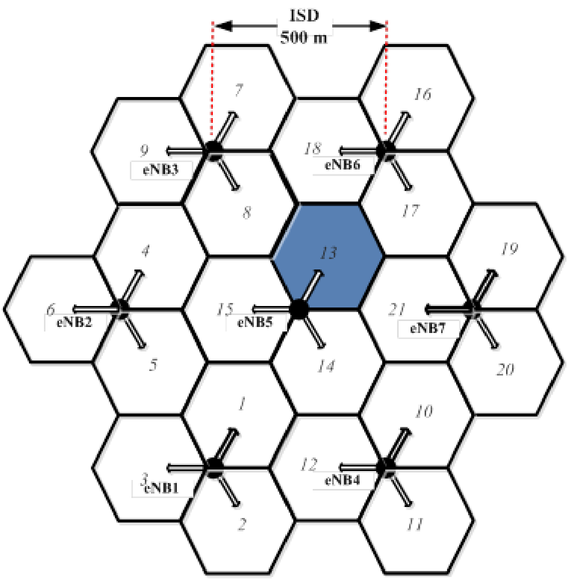

Figure 3-16: Single tier cell layout with the target sector (13)

The achieved uplink normalized throughput for different bandwidths are shown in Figure 3-17. It can be first observed that the cell-edge (5th percentile) and best throughputs have increased significantly when the bandwidth is increasing.

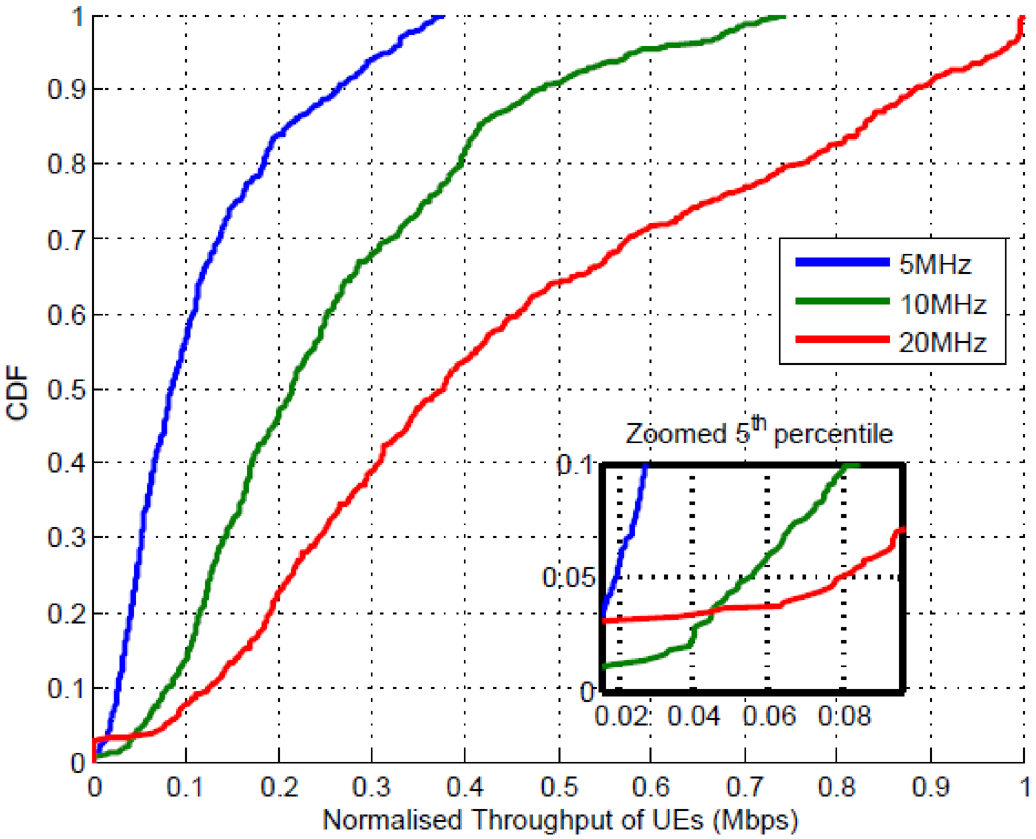

Figure 3-17: Uplink normalized throughput for different bandwidths

The antenna reciprocity feature is adopted from antenna theory stating that the antenna properties such as gain and radiation pattern are symmetrical for transmitting and receiving. The simulation is performed by defining a RoI (target sector) in which the eNodeBs and UEs are positioned and it is only in this area UE movement is performed. Each sector has 10 UEs, and the performance metric of UEs in sector 13 (target sector) is taken in to account. This is because the target sector is in the middle of the layout, and receives interference from all surrounding eNodeB sites, therefore providing a worst-case scenario performance at the cell-edge. The coverage and interference of each cell sector was taken into consideration with and without beamforming techniques applied as presented in the following box plots. Figure 3-18 box plot illustrates coverage demonstrating the effect of beamforming as a percentage compared to fixed beams.

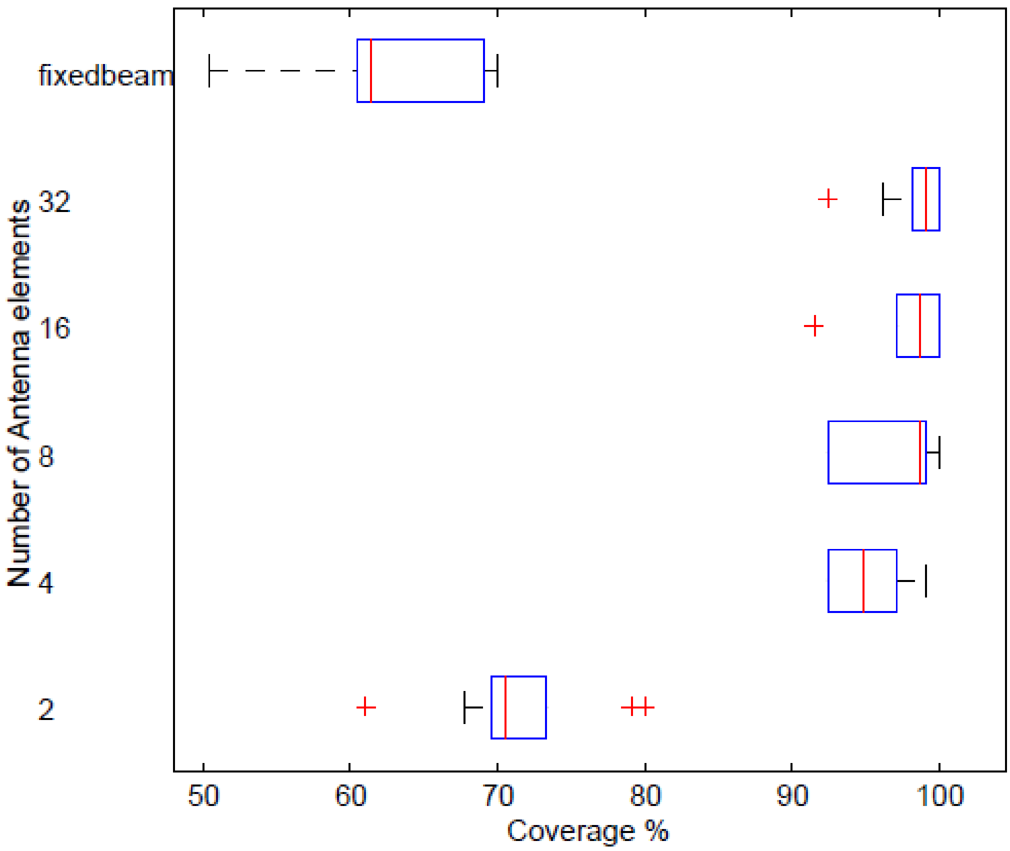

Figure 3-18: Coverage% performance

The box represents the interquartile range (IQR), which is the 25th (Q1) to 75th (Q3) percentile. The vertical line inside the box is the median. The whiskers (+ marks) indicate the lower (Q1 – 1.5(IQR)) and upper (Q1 + 1.5(IQR)) fences, while the plus signs denote the outliers.

By increasing the number of antennas the overall coverage of a cell site is improved. The average receiver beam coverage of a fixed beam, 4x4 antennas is around 68.3%. By using the smart antenna configuration, even for 2x2 the coverage can be further improved up to 70.7% showing an improvement in coverage compared to fixed beams.

By increasing the number of antenna elements to 4 (4x4 antenna) the coverage can be considerably improved to 94.9% since it becomes easier to steer the beam or to make the beam narrower. Table 3-2 below presents the relationship between antenna elements and average coverage for both fixed beam and smart antenna configurations, produced by the system level simulator, up to 32 antenna elements, achieving the highest SINR at the eNodeB.

Table 3-2: Coverage results and antenna elements

Number of elements at the receiver	Coverage%
Fixed beam (with 4 elements)	68.3
2	70.7
4	94.9
8	95.6
16	98.0
32	99.4

It can be seen, by using 8 elements antenna configuration 95.6% of the UEs can be covered. More antennas the transmitter/receiver (transceivers) equipped with, more the possible signal paths, the better the performance in terms of data rate and link reliability [150]. Increased number of antenna elements are used in Massive MIMO [151] (also known as Large-Scale Antenna Systems) which using a large excess of service-antennas over active terminals and time division duplex operation which are beyond the scope of this research.

Following from the previous result the box plot in Figure 3-19 presents the average interference in the cell site towards neighbouring UEs. What can be observed is that by using beamforming technique interference is reduced significantly compared to operation with fixed beams.

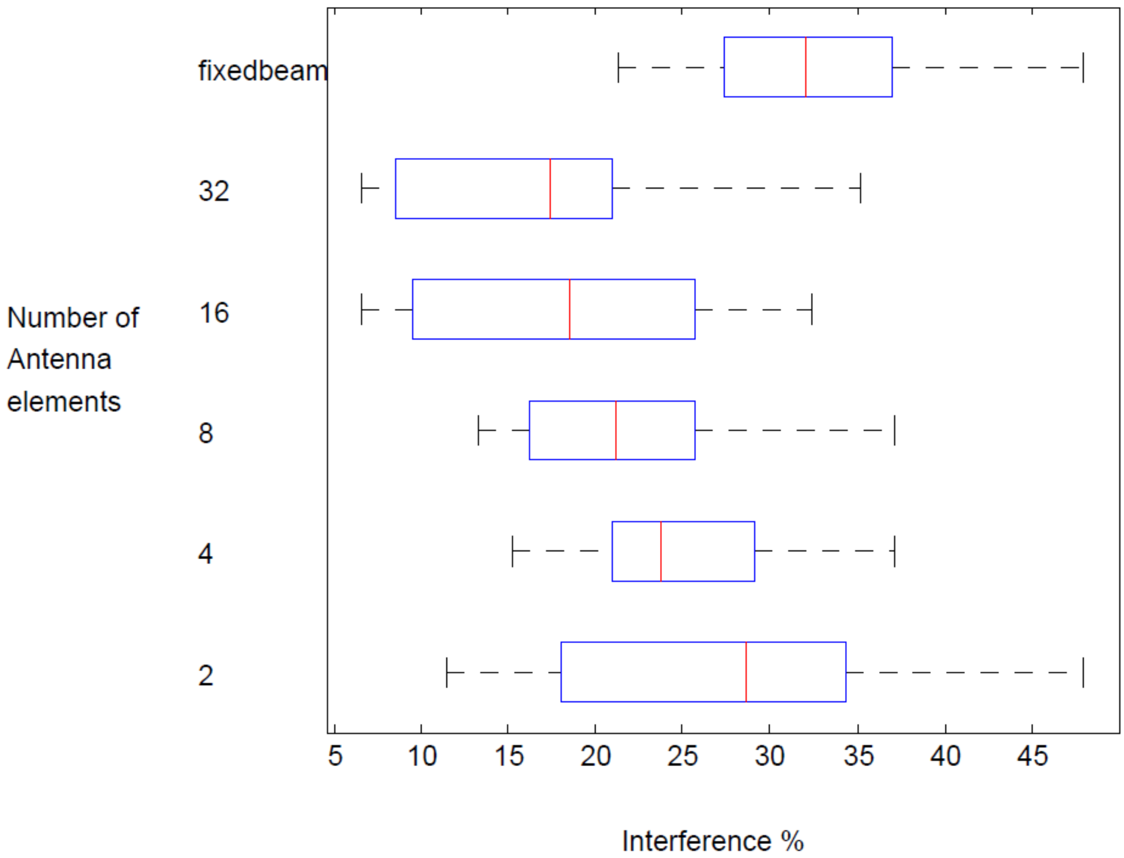

Figure 3-19: Interference % towards neighbouring UEs

When using the fixed beam 4 element antenna system the average interference is 32.6%. By using the 2x2 smart antenna systems, interference is reduced to 27.7% and by increasing the number of antenna elements to 4, it is further reduced to 25.2%. These results were obtained using the number of geographical positions covered when the specific antenna configuration is used in the target sector in a single tier cell layout.

Table 3-3 presents the average interference achieved by beamforming antennas compared to fixed beam antenna systems demonstrating clearly the mitigation of interference achieved with increased antenna elements as these with high level MIMO.

Table 3-3: Interference towards neighbouring UEs

Number of elements	Interference towards neighbouring UEs
Fixed beam (with 4 elements)	32.5
2	27.7
4	25.2
8	21.5
16	18.3
32	16.2

3.8 Summary

This chapter presented the implementation of an uplink LTE/ LTE-A system level simulator based on MATLAB programming to be used for performance evaluation of original concepts and ideas generated by this research. Uplink LTE link level simulator, best in its domain at the start of the research, provided by the University of Vienna was used to benchmark the new system level simulator and establish initially the correct operation of the fundamental network features of a LTE/LTE-Advanced network with emphasis on uplink transmission being the core focus of this research.

The link level simulator model was used to abstract the link level functionalities of the network entities to obtain a metric, which is then used to assess the performance of the network. This was achieved by using the link quality model and link performance models as described earlier for the design of the simulation mode. Typical LLS models simulate a single communication link between a UE and an eNodeB, which take excessive simulation time and parameters to depict the process in a single simulation model since there are many functionalities that need to be simulated and taken into consideration. For a system level simulator exhibiting several eNodeBs and UEs in a large network configuration, the computational time and resources will be further increase, making it impractical to use. By using the LLS metrics to generate the post-equalisation SINR, which was mapped to CQI to achieve a BLER probability of less than 0.1, led to a practical implementation of the simulator able to simulate all required parameters and vital network properties with efficiency.

A typical macro-cell environment using three sectors (hexagonal grids were used to characterise the sectors) were assumed as the network layout of the SLS model. General antenna gain patterns (for non-CoMP) of the individual sectors were generated to support the TS 36.942 antenna model. Different test environments were taken into consideration in the simulator model, including indoor office, rural macro-cell, urban macro-cells, and urban microcell. WINNER II channel model was described for its merits and used in the implementation to abstract the different propagation models for different network evaluations. Smart adaptive antennas were also introduced to support multiple antenna configurations which is well suited for higher channel bandwidth modelling expected with next generation cellular networks (with channel bandwidth of up to 100 MHz and above).

Two transmission modes, single-input-single-output and close-loop-spatial-multiplexing were analysed for uplink LTE to implement the SLS for random walk (5km/h) and high speed (120km/h) environments. Compared to the SISO mode which has no diversity since it uses single antenna for transmission, CLSM provides multiple antenna transmission modes of operation to achieve diversity in the spatial domain. The CLSM mode has shown to perform significantly better with both low and high speed UEs, due to the more detailed UE feedback (PMI feedback from the UE) obtained when compared to single antenna systems. It also increases the transmission rate by transmitting and receiving different streams from multiple antennas. Results suggest that at both UE speeds of 5km/h and 120km/h, the achieved throughput at the point of reference for 2 x 2 and 4 x 4 CLSM is approximately 2 times and 4 times higher compared to SISO respectively.

Round-robin and proportional-fair resource allocation algorithms were also examined and implemented in the simulator to analyse the performance disparity between cell edge UEs and UEs closest to eNodeBs. RR is the most commonly used algorithm due to its simplicity while PF is expected to demonstrate more efficient scheduling even to UEs at the cell-edge with poor channel conditions. A normalised CDF of the aggregated throughput metric of UEs was used to draw the performance of both algorithms. It was observed that the PF scheduler performed better at the cell-edge but marginally, suggesting at this stage of the research that the RR scheduler with its significantly less computational complexity in implementation would be suitable for further investigations. Simulations were performed towards the end of the chapter to compare the achievable throughputs with different channel bandwidths available in the LTE network.

Chapter 4

4. *Smart Antennas and Receiver Beamforming for Future Generation Networks*

4.1 Introduction

Currently, network providers have delivered sufficient bandwidth and services within the downlink communications by using different technologies. This has allowed an increasing number of subscribers to be supported. But with the emergence of Internet of Things (IoT), smart grids, and Machine-to-Machine (M2M) communication to mention a few, more bandwidth is required in the uplink since users are demanding more and more bandwidth for internet services. A comprehensive literature review of the key requirements and challenges for next generation networks was presented in Chapter 2. A major limiting factor in current 4G networks is cell-edge user performance degradation (in both DL and UL) due to the inter-cell interference. CoMP has been proposed as a solution to such limitations.

As mentioned in the previous sections, major research has been produced in recent five to six years on downlink CoMP algorithms to improve the cell-edge performance. However, in the present, the user behaviour in uplink is equally important as the downlink. Yet there are limited references on similar work taking place in uplink cell-edge interference mitigation. Radio flexibility is one of the main aspects in current and future 5G networks [108], including inter-cell interference coordination, beamforming, dynamic clustering and cell shaping. Therefore this chapter will provide solutions towards the enhancements for 4G and 5G features such as CoMP and smart antennas in order to enable interference reduction or mitigation.

A novel solution based on smart antenna systems is proposed to overcome uplink inter cell interference using a novel eNodeB receiver beamforming technique with a target to provide solutions to both currently deployed and also future 5G networks uplink. The target is to improve the uplink signal-to-interference-noise-ratio (SINR) of particularly, as already mentioned, cell-edge users. Smart antennas and adaptive antenna array technology have been introduced gradually over the past years together with the development of other technologies including Software Defined Radio (SDR), Cognitive Radio (CR), and MIMO to mention the most relevant. Smart antenna or adaptive antenna array technology allows antennas to adapt quickly to changing conditions in the cellular network using beamforming techniques to achieve better reception. Signal processing is utilised to perform tasks such as the analysis of the Direction of Arrival (DoA) or Angle of Arrival (AoA) of a signal. The proposed technique is complemented by the presence of switched antenna beamforming which is applicable to selective cluster UEs, therefore saving on processing power at the eNodeB. The state-of-the-art SLS presented in Chapter 3 is used in order to investigate the performance of the proposed novel receiver beamforming technique.

4.2 Motivation for Uplink CoMP and Interference Mitigation/ Cancellation

With the rapid development of smart portable devices and increase in broadband services offered by the service providers, more bandwidth is required to accommodate these services and the increasing number of users. Long Term Evolution Advanced (LTE-A) an Orthogonal Frequency Division Multiplexing (OFDM) based network utilize a frequency re-use of one (denoted by N = 1). A frequency reuse of N = 1 implies that the base stations in cells transmit on all available time frequency resource blocks (RBs) simultaneously which increases the inter-cell interference [152, 153]. This results the interference limited system for N = 1 deployment to not to achieve the full potential capacity that the LTE/ LTE-A standard can support. This has to be overcome by the implementation of one or more viable interference mitigation and/or cancellation techniques at the base station and mobile terminals. Due to transmit power limitations in mobile terminals, the constraint on the uplink link budget will necessitate the need for smaller cell sizes, better interference mitigation techniques or both. This requirement is driven by the need to meet targeted higher data rate throughputs for users not only near the base station, but also for cell-edge users. The trend of increasing demand for high quality of service at the user terminal or user equipment (UE) in 5G networks, coupled with the shortage of wireless spectrum, requires more advanced wireless communication techniques to mitigate inter cell interference and increase the cell-edge throughput [152]. Theoretical work has shown that uplink CoMP offers the potential to increase throughput significantly, in particular at the cell-edge, which leads to enhanced fairness overall [43, 154]. Uplink CoMP promises average cell throughput gains on the order of 80 percent, and roughly a threefold cell-edge throughput improvement [20].

A higher transmission rate for uplink is a main research area in most of the main telecoms providers worldwide. Research initiatives such as the METIS project among other as described in chapter 2 [41], aims at reaching world-wide consensus on the future global mobile and wireless communications system where the overall technical goal is to provide a system concept that supports 1000 times higher mobile spectral efficiency as compared with current LTE deployments [40]. Some of the research initiatives [155],which are based on cooperative communications interference management techniques to achieve such higher spectral efficiency are 5GNOW [42], Advanced Radio Interface Technologies for 4G Systems (ARTIST4G) [156], METIS 2020 and METIS II [40, 41], 4G++ [157] and COMBO [43, 158].

To achieve such higher spectral efficiency and throughput in the uplink there are several techniques suggested in the literature. Here a solution based on the concept of CoMP and smart antennas in eNodeB side is proposed since it is difficult to employ many antennas in the user equipment considering the power consumption, cost and size. Multi-User Multi-Input Multi-Output (MU-MIMO) in uplink is adopted in LTE-Advanced to improve system throughput making use of spatial multiplexing. MIMO has become one of the most promising solutions to enhance the system spectral efficiency [150]. MU-MIMO allows two or more users to transmit data on the same time frequency resource, independently. However, the signals from user equipment of different base stations cause obvious inter cell interference and it becomes a bottleneck of the system performance, especially for the network design with high base station density [159]. In the future heterogeneous network deployment, by introducing small-cells into the LTE macro cell grid, interference between macro and small cells becomes a critical issue [82],[160].

Uplink CoMP has been suggested in several research initiatives. In the 4G++ project [157] the main objective is to explore various technical challenges beyond 3.5G and 4G wireless systems. These include providing innovative schemes for capacity boosting in LTE and LTE-Advanced systems in the areas like inter-cell interference coordination and channel-aware radio resource management and scheduling focusing in LTE uplink CoMP. 4G++ signifies uplink CoMP in LTE-Advanced to be considered as one of the key enablers for capacity boosting [157]. In 5GNOW [42], one of the main considerations are collaborative schemes to boost capacity and coverage (CoMP), and wireless networks to provide solutions to heterogeneous networks following the non-uniform distribution of users [42].

ARTIST4G: Advanced Radio Interface Technologies for 4G Systems is one of the main research initiatives mainly focused on improving the ubiquitous user experience of cellular mobile radio communications systems [156]. It is focused on achieving high spectral efficiency and user data rate across the whole coverage area, fairness between users and low latency based on smart antennas and CoMP beamforming techniques [156]. ADEL (Advanced Dynamic Spectrum 5G mobile networks Employing Licensed shared access) which proposes technology enablers towards magnitude gains in terms of overall spectral and radio efficiency envisioned for 2020 wireless access, using advanced collaborative sensing between the cooperating wireless networks, individual nodes for better network coordination and advanced transceiver techniques (smart antenna based systems). These are key examples which prove that the uplink data transmission in future networks is critical and an area to be researched on.

4.2.1 Current Advances in Uplink CoMP Techniques

The available literature on proposed uplink CoMP techniques is not extensive which allows for new ideas to be generated and contribute to the development of research in this area. In [161] a joint scheduling scheme is proposed, at about the same time this research project started, for optimally employing CoMP and MU-MIMO for uplink LTE-A systems based on two network topologies. The performance of single user (SU) adaptive CoMP is simulated and analysed compared with SU-CoMP without adaptive antennas. Multiple receiving antenna configurations (e.g. 1×8) were also demonstrated to increase LTE coverage.

In [162], a combined switched beamforming and adaptive beamforming algorithm is proposed for orthogonal frequency division multiplexing (OFDM) systems with antenna arrays in multi-path fading channels. The technique used is to generate multiple beams by using a set of known weight vectors to cover the direction of arrival (DoA) range from 0 to 360 degrees. Secondly, two adjacent beams, which contain the same delayed multi-path with the largest power, can be selected by calculating the correlation of each beam with a reference signal. Thirdly, the two selected beams are optimally combined by using adaptive beamforming algorithms such as sample matrix inversion (SMI), etc.

In [154] uplink joint processing technique to improve interference both in the macro grid cell-edge and in a heterogeneous network scenarios is presented. In the paper it was discussed how interference rejection may be further improved by combining the received signals from more antennas and nodes. Uplink CoMP joint processing, however, needs real time signals, a great amount of data exchange between eNodeBs and centralized data processing. The benefits of centralized and coordinated baseband processing among eNodeBs were particularly accounted for to show the feasibility of, uplink joint processing [116, 163].

In [150], an orthogonality based proportional fair (OPF) scheduling algorithm was proposed. Following the implementation of OPF, the paper subsequently provides an analysis and comparisons on LTE uplink spectral efficiency for SIMO, Virtual-MIMO and CoMP. The impact of the number of the coordinated BSs on the uplink spectral efficiency was analysed in [164, 165].

There are also a couple of patents which display, only in part, similarities to the proposed receiver beamforming technique in this study. In [166] an adaptive beam-forming system is proposed using hierarchical weight banks for antenna arrays. The banks contain weights that are pre-calculated based on pre-set beam, look directions. By comparing the measured signal quality metrics for pre-set look directions, the best weights, and thus the best beam look direction, can be selected from the weight banks.

An antenna array was proposed in [167], to be used in base stations. The antenna array is initially configured to display beamforming in uplink and subsequently in downlink, exhibiting in each case different beam characteristics.

For added clarity on available techniques in literature and an attempt to provide a clear distinction in the section following of the contributions of the proposal of this thesis, Table 4-1 summarizes the key concept and pros and cons of key uplink CoMP techniques.

Table 4-1: Comparison of available uplink CoMP and interference reduction / cancellation techniques

Method	Year	Description	Cons	Pros
Interference cancellation in uplink [161, 168]	2012 2013	Regenerate and subtract interfering signal from desired signal.	Requires exchange of information in real time between base stations. High cost of implementation will likely limit application to the UL.	Can potentially improve channel performance if accurate channel estimation is available.
MU-MIMO [161, 169]	2012	UL technique to assign the same RB to multiple mobiles in the same cell	Scheduling algorithms to select MU mobiles are still developing since it's a new technology.	Scales exponentially with number of mobiles simultaneously processed.
Dirty Paper decoding		Precoding of signal mapped into a known code space	Depending on the size of the search space and code-word size complexity increases exponentially. High cost of processing.	Significant spectral efficiency gains
Adaptive FFR [170]	2007	FFR assignment is adaptively updated based on the SINR in each sub-band	Requires exchange of SINR based metric between base stations. Scales linearly with the number of mobiles served at the base station.	Significant spectral efficiency gains
Power control [171, 172]	2008 2012	Regular power control and fractional power	Scales linearly with increase in number of resource blocks available.	Improvements of aggregate throughputs and for cell-edge users.

		control		
Opportunistic Spectrum Access [173]	2007	eNodeBs assign resources only to sub-channels with low power spectral density	High complexity.	Suited to mitigate interference levels and strong interferers.
Receiver beamforming (adaptive antenna) [162, 174-176]	2007 1998	eNodeB focuses the receiver beam directed at the desired UE	Uses smart antenna technology. Complexity can be minimized since DSP technology is used to steer the beam using complex weights.	Can be used in both rural and urban areas when enhanced with power controlling technique. Can be used with joint reception to achieve better interference cancellation and spectral efficiency. Significant spectral efficiency gains and better performance in small-cell environments.

4.3 Novel Adaptive Antenna System for Interference Mitigation in Uplink

It has already been deduced that in order to support the new paradigm shift in 5G mobile communications, in providing significant capacity increase compared to any current cellular solutions [152], radically new solutions need to be developed for the air interface.

Cooperative scheduling has only recently been promoted as a possible solution for interference mitigation by supporting major cell densification which in turn can lead to required 10-fold increase in spectral efficiency [152] [153].

Investigations into new fibre-wireless (FiWi) networks and CoMP techniques such as adaptive antennas [154], to avoid inter-antenna communication and significantly enhance cooperative transmission have also emerged [43, 156].

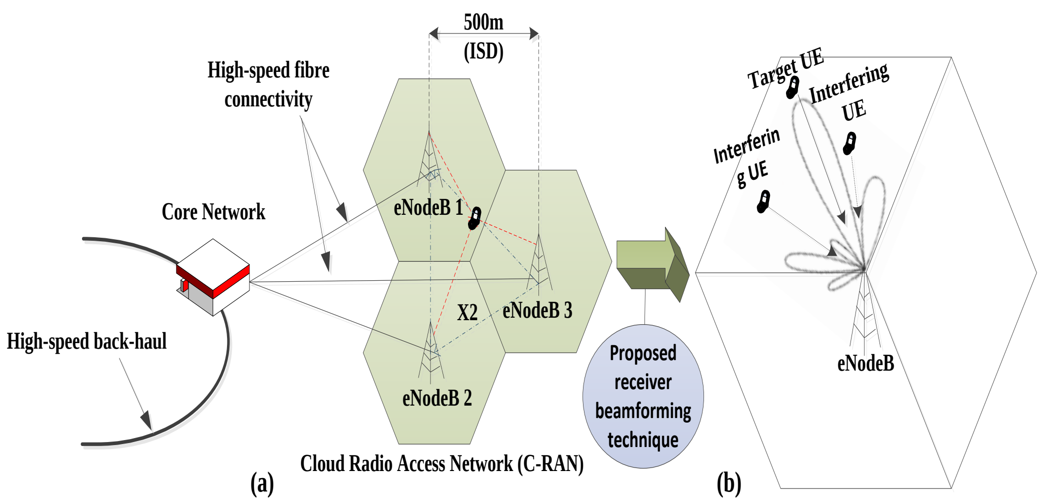

Figure 4-1: (a) FiWi system architecture with (b) the proposed receiver beamforming technique

In contrast to the above proposals a receiver beamforming technique is conceived through comparing and contrasting literature, implemented and evaluated, with a focus on interference mitigation.

As described in Figure 4-1(a), the network eNodeBs are connected to the central office via a high speed optical fibre infrastructure which has not been critical in the justification, performance evaluation and significance of the forthcoming ideas of this thesis but puts a mark on the inspirations for the network coming next. eNodeBs are connected using the X2 interface where inter base station communication becomes possible. A point to point connectivity has been described however other topologies, such as tree based passive optical networks [43], are also highly possible. Inter-antenna communication for the cooperative transmission is established using the X2 interface thus reducing significantly the latency of the proposed algorithm, since it does not have to go through the central office [43].

Furthermore, Figure 4-1(a) demonstrates a typical cellular deployment with the inter-site distance (ISD) of 500m. However the proposed techniques are also applicable for smaller ISDs typically encountered in dense urban environments. As also described in the figure, user signals transmitted in uplink can reach neighbouring cells reducing significantly the signal-to-interference-noise ratio (SINR) of that cell.

The proposed receiver beamforming technique to minimise this effect is described in Figure 4-1(b). Compared to typical beamforming transmission techniques applied in downstream, the proposed receiver beamforming uses the antenna reciprocity properties to steer the antenna receiver pattern towards the intended user thus increasing the uplink SINR. The antenna reciprocity feature is adopted from the antenna theory stating that the antenna properties such as gain and radiation pattern are symmetrical for transmitting and receiving. Therefore, as shown in Figure 4-1(b), eNodeB adjusts the receiver radiation pattern towards the targeted user while nulling the pattern at the interfering user equipment. This means that the main beam is put in the direction of the desired signal while nulls are in the direction of the interference. Each eNodeB is aware of the overall distribution of all UEs across the network thus effectively scheduling the transmission without additional delays.

Therefore, exploiting the aforementioned antenna symmetry, the individual receiving antenna elements at the eNodeBs are weighted using complex weights to create the desired receiver antenna pattern. The weights are computed by an adaptive algorithm at the eNodeB. Depending on the calculated weights, the eNodeB then selects the most appropriate receiver beam from the pre-defined beam pattern matrix. The receiver beams in the direction of the desired UEs are added constructively whereas they are nullified in the directions of interfering UEs (i.e. null steering) as described in Figure 4-1(b). Since the proposed technique uses Closed Loop Spatial Multiplexing (CLSM) [177] that relies on channel feedback, the eNodeB can inform UEs for the preferred transmit antenna based on an established receiver pattern.

Figure 4-2 [178] illustrates the main elements of the receiving part of a smart antenna. The antenna array contains of N (e.g. N = 4) elements. The smart antenna reception part consists of four units which include the antenna array, radio unit, beam forming (DoA) and signal processing unit [12].

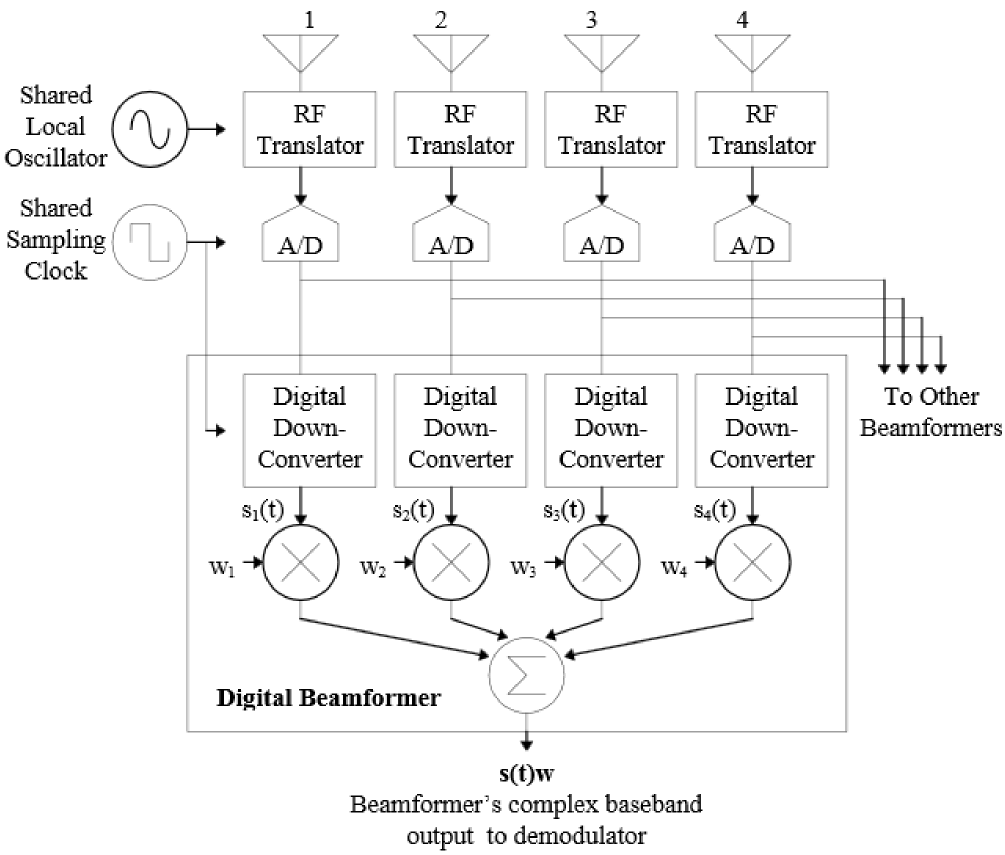

Figure 4-2: Digital beamforming receiver (receiver beamformer) [173]

Normally the array (antenna) will have a low number of elements in order to avoid unnecessarily high complexity when it comes to signal processing. The radio unit consists of analogue-to-digital converters (A/D) and also N down-conversion chains (digital down converters), one for each array element.

The adaptive algorithm/ signal processing unit will, calculate the complex weights ($W_1,\ldots,W_N$) based on the received signal from the UEs, with which the received signal from each of the array elements is multiplied. These weights will then give rise to the antenna gain pattern in the uplink direction. The weights could then be slowly adapted to steer the beam until maximum signal strength occurs. In beamforming, the weights are chosen to give a radiation pattern that maximizes the quality of the received signal. However in switched beam technique the weights are optimized to maximise the received signal from the desired user. In adaptive array technique it will suppress the signals from interference sources to maximise the SINR. With N antenna elements, smart antenna can "null out" N-1 interference sources [179], but due to multipath propagation this number is typically lower.

There are different methods for calculating the weights depending on the type of optimisation criterion. In the switched beam technique, the receiver tests all pre-defined weight vectors (corresponding to the beam set) and choose the one giving the strongest received signal level. If the adaptive approach is used, which directs the receiver beam to attain a maximum gain towards the strongest signal component, the DoA is first estimated and then the weights are calculated. As mentioned in Chapter 3 the DoA and AoA can be estimated by one of many methods. When the beam forming is done digitally (after the A/D), the DoA and adaptive algorithm units can be integrated normally in the same unit (Digital Signal Processor).

The algorithm proposed in this thesis is based on the novel concepts of switched and adaptive antenna receiver beamforming. In switched beam the receiver antenna beam patterns are fixed in time and users are switching from one beam to another depending on their location within the cell. This technique is beneficial to deployment scenarios where channel conditions do not change frequently. Alternately, the receiver beam pattern can be adapted according to channel conditions and users locations. Therefore, enhanced performance with respect to SINR is expected with increased implementation complexity compared to switched beamforming. A hybrid approach is also possible and is further investigated, contributing one of the novelties of the research.

4.4 Methodology and Simulation Investigations

The system level simulator built to exploit receiver beamforming, among other innovations was described in chapter 3. The increase of the entropy in this scenario is needed in order to closely approach ‘real-life’ scenarios and take into account different environments including heterogeneous, rural and urban. Multiple iterations were therefore run (100 to be exact) whereby UE performance results from different simulated environments were aggregated taking the average as the indicative evaluation figure. The key simulation parameters used to demonstrate receiver beamforming are summarised in Table 4-3. A 20MHz bandwidth is assumed however it should be noted that wider bandwidths can be equally considered with comparable results allowing to safely concluding on the applicability of the proposed concepts to 4^{th} and 5^{th} generation. It would also be useful stressing on a certain degree of freedom allowed in simulations. For example, the shadow fading map is produced using a lognormal space-correlated function, the UEs movement is simulated based on ‘random walk’ (5km/h) models and their positions are picked in a uniform fashion across each sector.

Interference was modelled in conformance to the well-known wrap-around interference modelling technique where UE performance metric, such as throughput, is taken from a single cell/sector surrounded by a number of equidistant eNodeB sites [180]. UEs are accordingly handed over to the assigned sector in the event where they move out of the simulation region of interest (e.g. out of the 3 cells in Figure 4-1(a)).

The simulation is performed by initially defining a region of interest in which eNodeBs and UEs are positioned and it is only in this area where UE movement is performed. A typical cell layout setup consists of 7 eNodeBs with each eNodeB comprising 3 hexagonal cell sectors forming a site as shown in Figure 4-3.

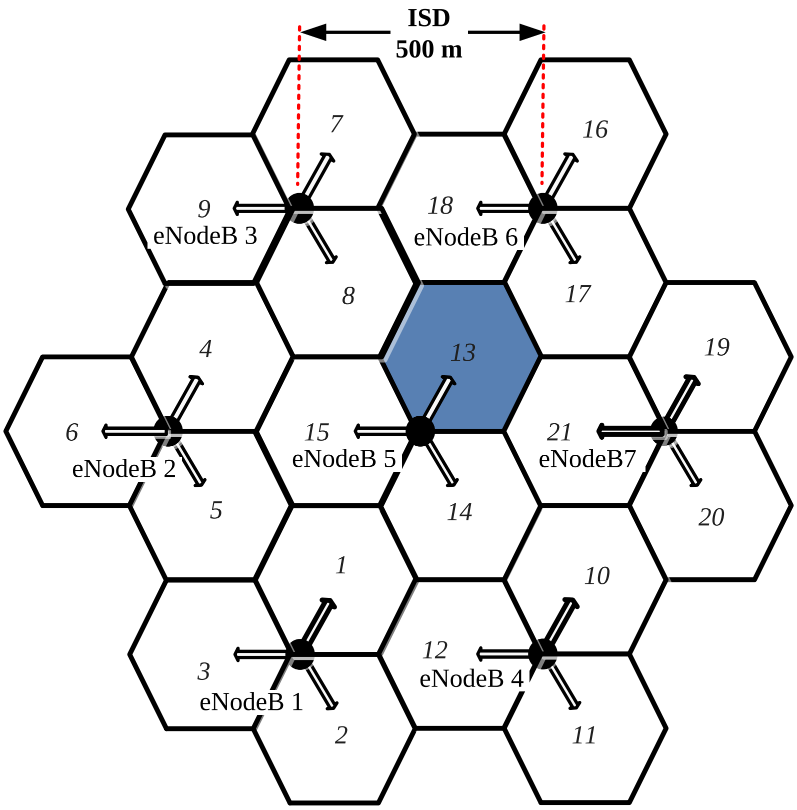

Figure 4-3: Cell layout setup consists of 7 eNodeBs

For the purpose of investigating cell-edge interference, the simulated setup demonstrates conflict of service originated by 2 cells (belonging to different sites) sharing a common border (i.e. cell edge) in a single tier cell layout. As shown in Figure 4-4, the eNodeB 5 and eNodeB 7 sectors, (sectors 13 and 21 in Figure 4-3) have a common border (conflicting border in this case) since it is between different sites.

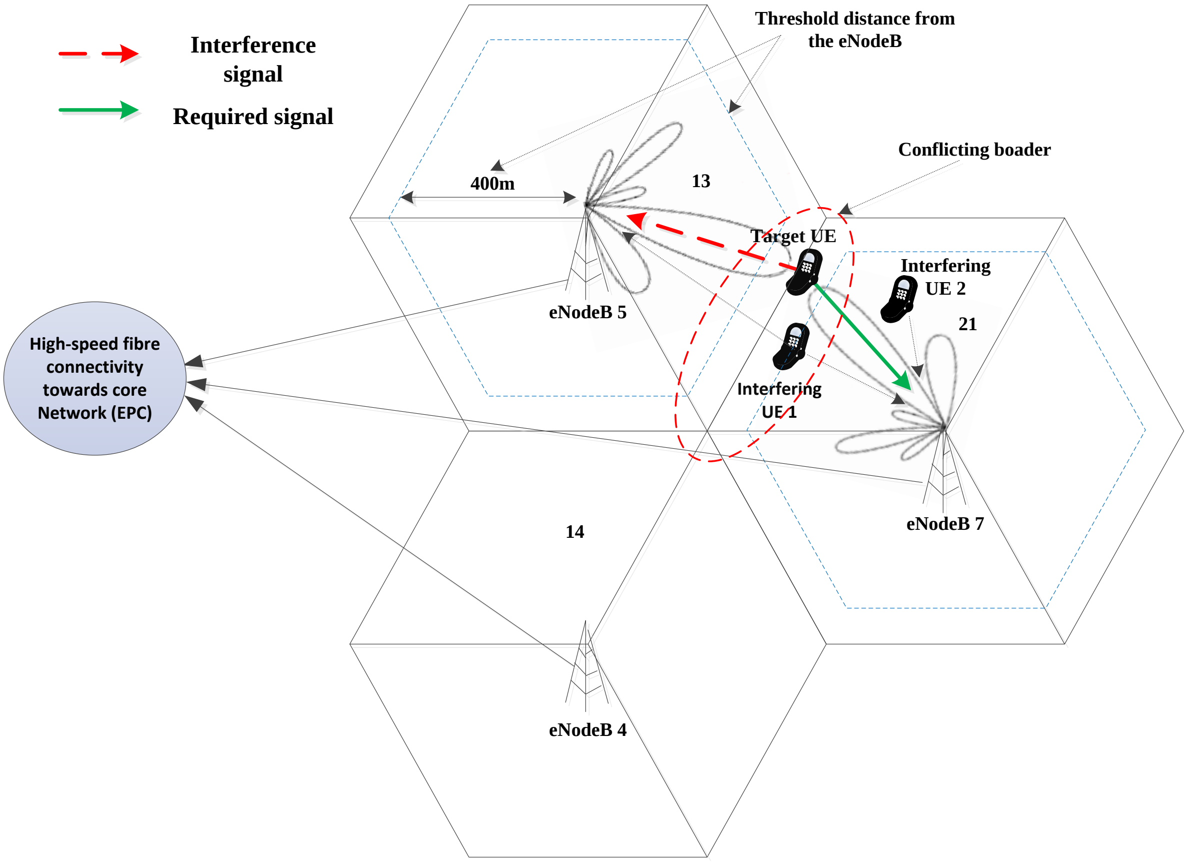

Figure 4-4: Cooperating cells and conflicting boarder between sector 13 and 21

As already defined in Chapter 3, in developing the algorithm it was assumed that the UE positions are known or in a real scenario are determined by the eNodeB as a prerequisite for mitigating interference. Such assumption is based on the argument that increasing and more accurate information of UE positions could be readily available in future networks following the advancements in centralised processing through SDN and Network Function Virtualization (NFV) [181].

The significance of making such assumption when developing the system level simulator, is significantly reducing the channel state information (CSI) requirement on UEs, leaving only the need for sharing the instantaneous location of the cell-edge UEs between adjacent cooperating cells. This will overcome the common limitation, the backhauling capacity due to explicit CSI to be shared between cooperating cells. Table 4-2 presents the pseudo code for the algorithm designed to provide receiver beamforming in the uplink of cellular networks. Some parameters were defined to establish a platform where specific conditions in the algorithm could be varied such as the threshold distance (*ThD*) to the cell-edge from their respective cell centre and, the angle/direction (θ_1 and θ_2) of the "conflicting border" of the cooperating cells in the respective cells. Parameters *UEs* and *UEm* are used to differentiate between static and moving UEs respectively and indexes *I1* and *I2* are defined to indicate the presence or absence of cell-edge UEs in respective cells for each TTI.

When a UE in sector 13 is further away than *ThD* (distance of UE from cell centre >*ThD*) and this UE is in the direction of propagation of the eNodeB in sector 21 with a direction angle, θ_1 , in relation to the corresponding eNodeB, this UE is defined to be a cell-edge UE. The same applies to sector 21 with θ_2 towards sector 13. Indexes *I1* and *I2* are set to 1 if UEs provided with connectivity from different eNodeBs/cells are located at the conflicting borders in the same TTI. Time of the proposed algorithm spans over two TTIs in this scenario. In TTI 1, if the cell-edge is populated by UEs provided with connectivity from different cells/ eNodeBs, the receiving beam from one of the cells/ eNodeBs is steered away from the cell-edge, and vice versa in the TTI 2.

To generate the receiving beam pattern the algorithm applies a complex weight to the signal from each antenna element, as described right below, and then sums all signals into one that exhibit the desired directional pattern. The combined relative amplitude a_k and phase shift θ for each antenna is called a "complex weight" and is represented by a complex constant w_k (for the kth antenna). The quadrature baseband *i* and *q* components can be used to represent a radio signal as a complex vector (phasor) with real and imaginary parts. Two components are used to represent both positive and negative frequencies relative to the channel centre frequency.

$$s(t) = x(t) + jy(t) \quad \text{Eq. 4-1}$$

The complex baseband signal is represented by *s(t)*, *x(t) = i(t)* is the real part, *y(t) = -q(t)* is the imaginary part, and *'j'* is √ *(-1)*. For beamforming, the complex baseband signals are multiplied by the complex weights to apply the phase shift and amplitude scaling required for each antenna element. For beamforming, the complex baseband signals are multiplied with the complex weights to apply the phase shift and amplitude scaling required for each antenna element.

$$w_k = a_k e^{j\sin(\theta_k)} \quad \text{Eq. 4-2}$$

$$w_k = a_k \cos(\theta_k) + ja_k \sin(\theta_k) \quad \text{Eq. 4-3}$$

w_k is the complex weight for the k^{th} antenna element, a_k is the relative amplitude of the weight and θ_k is the phase shift of the weight. Therefore a general-purpose DSP can implement the complex multiplication for each antenna element.

$$s_k(t)w_k = a_k \left\{ \left[x_k(t)\cos(\theta_k) - y_k(t)\sin(\theta_k) \right] + j\left[x_k(t)\sin(\theta_k) + y_k(t)\cos(\theta_k) \right] \right\} \quad \text{Eq. 4-4}$$

By calculating the correlation of each beam's signal with respect to each other, two adjacent beams which contain the same delayed-path, the signal with the largest power are selected. Then an adaptive algorithm is used at the eNodeB to combine the selected two adjacent beams. There are some commonly used methods to do that. The Minimum Mean-Square Error (MMSE) assumes that the desired received signal waveform is known by the receiver. Complex weights are adjusted to minimize the mean-square error between the beam-former output and the expected signal waveform. The Maximum Signal-to-Interference Ratio method estimates the strengths of the desired signal and of an interfering signal at the receiver and weights are adjusted to maximize the ratio. The maximum signal to interference ratio is therefore implemented in the adaptive algorithm such that the spacial filter can improve the input SINR and overall network performance for the adaptive algorithm by suppressing other delayed paths. In another method when the signal shape and source direction are both known, minimum variance method can be used to choose the weights to minimize the noise on the beam-former output. For static UEs the switched beam technique is applied. The signal at each element of the array is multiplied with a complex weight, where the weight vector is fixed. Since the receiver beam is concentrated towards a single cell-edge UE when there's number of cell-edge UEs are present, the SINR at the eNodeB at each TTI can be maximised relative to each respective UE being served in each TTI.

Table 4-2: Receiver beam steering conditions for cooperating cells in target sector

---

Algorithm Receiver beam steering conditions for cooperating cells in target sector

---

Initializing

At the beginning of each TTI the eNodeB updates its distance and angle matrix for each UE in the target sector.

Step 1

(1) *ThD*: Threshold distance to the cell-edge from the cell centre
(2) θ_1 : angle of conflicting border for cell 1
(3) θ_2 : angle of conflicting border for cell 2
(4) UEs : static UEs
(5) UEm : moving UEs
(6) Inter-cell coordination = 0
(7) $I_1 = I_2 = 0$ (*reset interference index log*)

Step 2

(8) **for** each TTI
(9)   ***if*** inter-cell coordination = 0
(10)   **for** $UE_i \rightarrow UE_n$ in coordinating cells/ target sector
(11) $UE_i\,pos$ = position of the i^{th} UE relative to serving eNodeB
(12) $UE_i\theta$ = angle of the i^{th} UE relative to serving eNodeB
(13)   ***if*** UE_i is attached to cell 1
(14)   ***if*** $UE_i\,pos >= ThD \,\&\, UE_i\theta >= \theta_1$
(15) $I_1 = 1$
(16)   ***else if*** UE_i is attached to cell 2
(17)   ***if*** $UE_i\,pos >= ThD \,\&\, UE_i\theta >= \theta_2$
(18) $I_2 = 1$
(19)   ***end*** **for**
(20)   ***if*** $UE_i = UEs$
(21)   ***if*** inter-cell coordination = 0 & $I_1 = I_2 = 1$
(22)   *use switched beam technique with pre-defined beam pattern matrix*
(23)   ***else if*** $UE_i = UEm$
(24)   ***if*** inter-cell coordination = 0 & $I_1 = I_2 = 1$
(25)   *steer beam of cell 1 in this TT1*
(26)   *inter-cell coordination = 1 (set inter-cell coordination index)*
(27)   ***if*** inter-cell coordination = 1
(28)   *Steer beam of cell 2 in this TT1*
(29)   *inter-cell coordination = 0 (reset coordination index)*
(30)   **else** *transmit normally* (I_1 *or* $I_2 \neq 1$ *i.e. no interference)*
(31)   *inter-cell coordination = 0 (reset coordination index)*
(32) ***end*** **for**

The simulation assumes in average 10 users per sector as expected in typical deployments. To provide a realistic simulation platform UE placement is done randomly. The model also utilises full buffer traffic which means that a user has an unlimited amount of data to transmit. Various antenna configurations are also simulated and presented in order to evaluate the effect of beam width at an increased number of eNodeB antennas.

Table 4-3: Simulation parameters

Parameter	Assumption
Cellular layout	Hexagonal grid, 7 eNodeBs, 3 sectors per eNodeB
Inter-site distance/ Cell sectors	500 m/120 deg.
Antenna pattern (horizontal)	$A(\theta) = -\min[12(\theta/ \theta_{3dB})^2, A_m]$ θ = 65 degrees, Am = 20 dB
Antenna spacing	$\Delta = 0.5\lambda$
BS height /antenna gain	20m /15 dBi
UE antenna height /antenna gain	1.5m /0 dBi
Number of UEs per sector	10
UEs distribution	Homogeneous random positions
Transmission modes	CLSM
Frequency / Bandwidth	2GHz (reuse factor 1) / 20MHz
Number of iterations	100

The following Figure 4-5 illustrates (lower resolutions is used for illustration purposes) the (a) 2x2 and (b) 4x4 smart antenna receiver radiation patterns from each eNodeB using the introduced receiver beamforming technique. Each 'x' denotes the positions covered by the receiving beam from the eNodeB and 'o' the position of UEs. It can be generally observed that by using the new algorithm to steer the beam the interference can be minimized as depicted in Figure 4-5. The radiation power is utilized by steering the main lobe towards the UEs and also by using a technique to reduce the power at eNodeB, the consumption of the radiation can be further minimized.

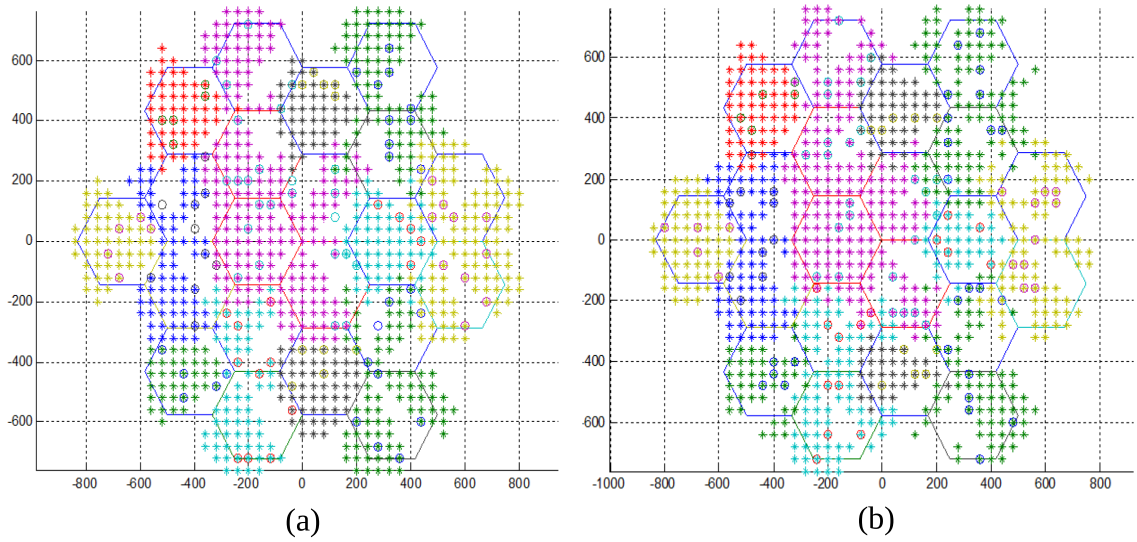

Figure 4-5: Smart antenna system with receiver beamforming (a) 2 elements (b) 4 elements

A beamformer controls the phase and relative amplitude of the signal at each receiver, in order to create a pattern of constructive and destructive interference in the wave-front when receiving, information from different sensors is combined in a way where the expected pattern of radiation is preferentially observed. By increasing the number of antenna elements the coverage can be improved and the interference can be mitigated as shown in Figure 4-5 (b), showing the use of a 4 element smart antenna array with the applied receiver beamforming. Also important to mention is that the algorithm in this case generates narrower beams compared to the 2x2 implementation directing more accurately the main lobe towards the target UEs. To continue from above, Figure 4-6 shows the statistical results obtained for the network coverage metric, for different MIMO antenna configurations compared to the standard deployment with no beamforming. The box represents the interquartile range (IQR), defined by the 25th (Q1) to the 75th (Q3) percentiles. The vertical line inside the box is the median. The whiskers indicate the lower (Q1 – 1.5(IQR)) and upper (Q1 + 1.5(IQR)) fences, while the plus signs denote the outliers. To reduce the performance fluctuation the same shadow fading map was used during all iterations which allow for more accurate, direct comparison between various configurations. Figure 4-6 clearly demonstrates that the proposed receiver beamforming with 2x4 and 2x8 antenna configurations achieves 26% and 30% performance improvement respectively compared to typical non beamforming scenarios. A moderate enhancement only of 3% is measured with 2x2 MIMO, agreeing with the observed trend.

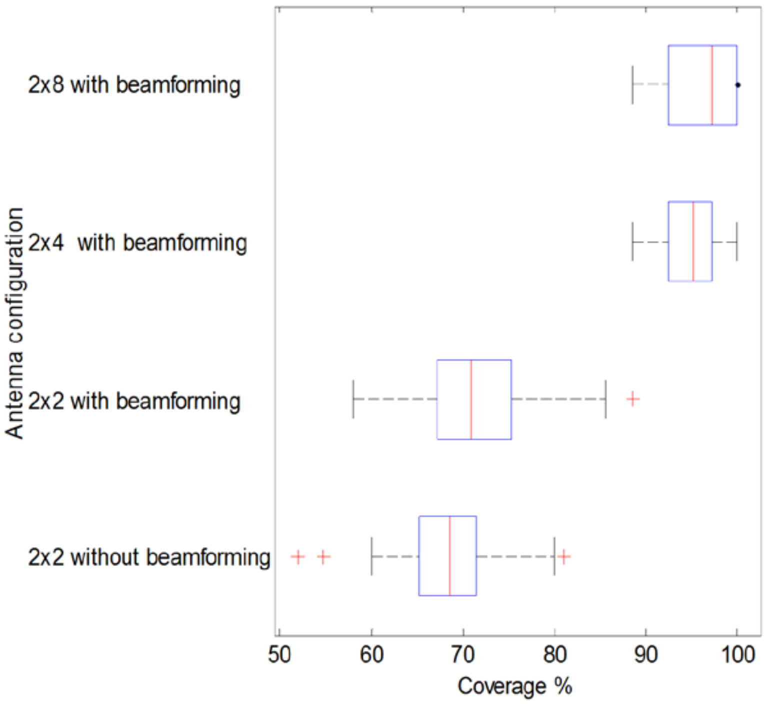

Figure 4-6: Cell coverage with and without beamforming for different antenna

In addition, the performance gain of the considered antenna schemes were observed and compared with respect to the uplink throughput in the target sector versus the cumulative distribution function (CDF) as illustrated in Figure 4-7. The graph shows the comparison between hybrid beam steering (i.e. combination of switched and adaptive receiver beamforming) versus only the switched or only the adaptive techniques for a 1x2 antenna configuration.

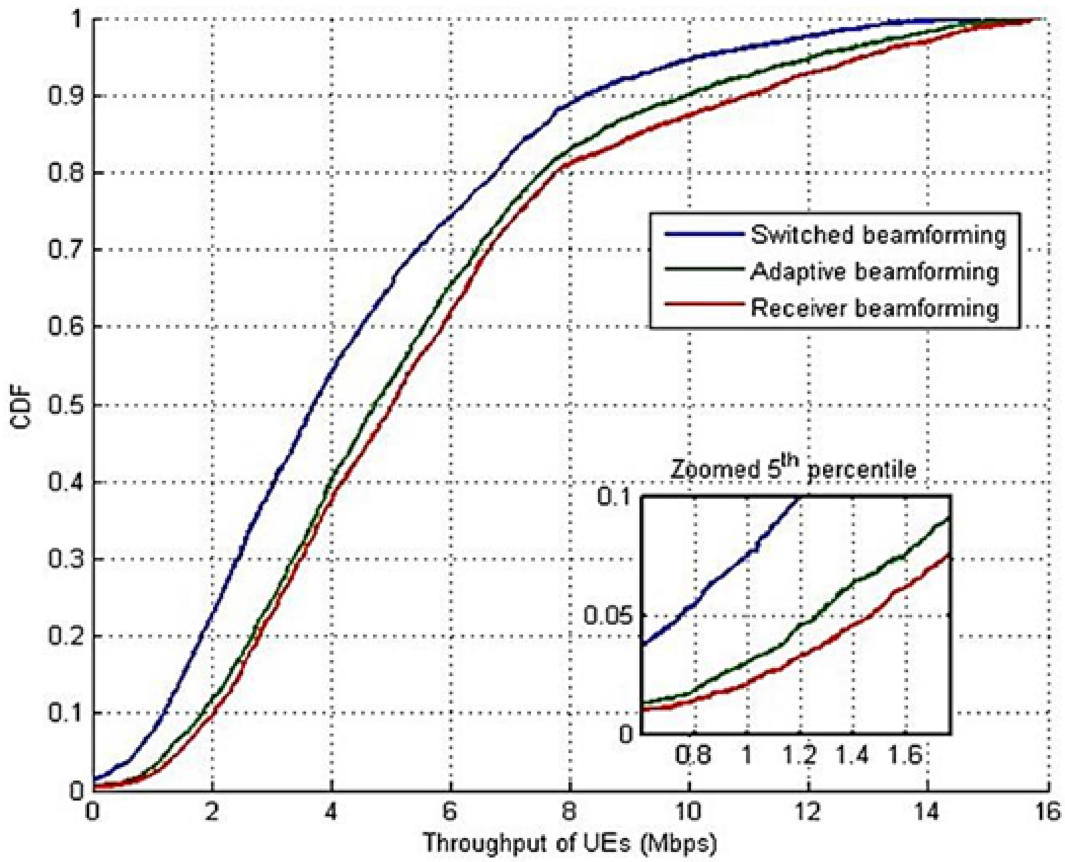

Figure 4-7: Throughput for different beamforming techniques for 1×2 antenna configuration

The inset significantly presents the 5th percentile specifying the throughput of cellular users at the network cell-edge. The evaluation of the drawn responses can lead to the conclusion that by using hybrid receiver beamforming, as proposed in this thesis, the throughput measured at the cell-edge is increased by 60% and 43% compared to only switched beamforming and only adaptive beamforming respectively. The result seems to indicate that although adaptive beamforming, based on previous analysis, seemed to provide an obvious solution for optimum performance, the combination of the two techniques could potentially significantly increase the cell-edge interference mitigation. It should be noted that while the referred data rates are only in the Mbps range, since a 20 MHz transmission bandwidth was considered, the performance enhancements are expected with confidence to become more significant, in the few hundreds of Mbps rates if 100 MHz bandwidths and above were to be considered as would be expected to for 5G .

Finally, four scenarios have been simulated, as before, to demonstrate the performance trend following the various possible antenna configurations with and without receiver beamforming. The obtained throughput values for these scenarios are presented in Figure 4-8.

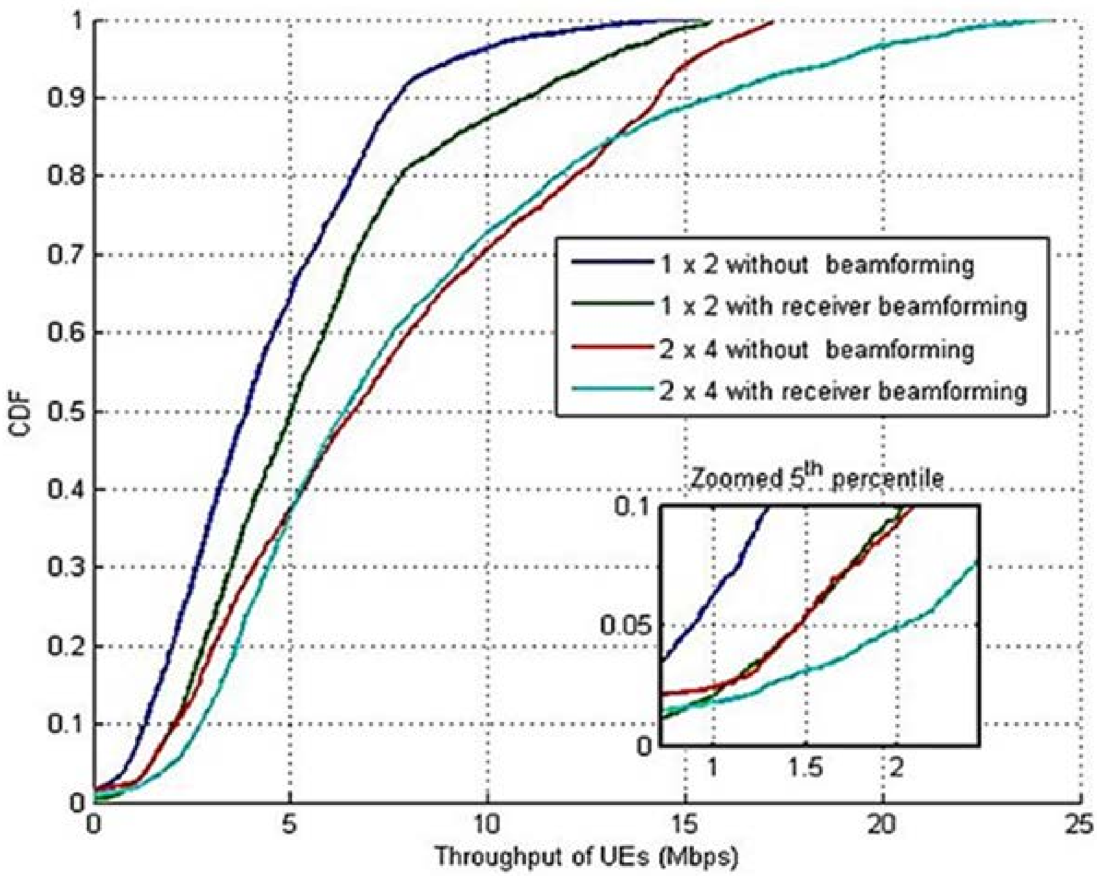

Figure 4-8: Throughput with and without receiver beamforming for different number of antenna elements

As it may be observed, for 1x2 and 2x4 antenna configurations the receiver beamforming outperforms the non-beamforming scenario by 66% and 40% respectively. This substantial improvement was achieved since the receiver beamforming provides high beam directivity towards targeted users and as a result significant increase in SINR.

In terms of spectral efficiency, the inset in Figure 4-8 demonstrates 65%, 53% and 40% receiver beamforming improvements for 1x2, 2x2 and 2x4 antenna configurations respectively. Therefore, the proposed scheme increases the cell-edge throughput in average by 50%. As indicated before, the obtained results demonstrate that significant gains can be obtained for future 5G (e.g. 50% improvements with high data rates could result in gain of several hundred Mbps). Following Table 4-4 exhibits the improved spectral efficiencies achieved using the receiver beamforming compared to LTE-Advanced targets.

Table 4-4: Spectral efficiency comparison

Antenna configuration	**LTE-Advanced Cell-edge Target (b/s/Hz)**	**Achieved without receiver beamforming (Cell-edge 5%)**	**Achieved with receiver beamforming (Cell-edge 5%)**
1 x 2 (SIMO)	0.04	0.044	0.073 (+65%)
2 x 4 (MIMO)	0.07	0.072	0.101 (+40%)
	LTE-Advanced peak Target (b/s/Hz)	**Achieved without receiver beamforming (Peak 95%)**	**Achieved with receiver beamforming (Peak 95%)**
1 x 2 (SIMO)	1.2	0.45	0.65 (+45%)
2 x 4 (MIMO)	2.0	0.76	0.95 (+25%)

4.5 Summary

Following the deliberation in the previous chapter of the new system level simulator (SLS) model and its unique features to be able to simulate comprehensively uplink cooperative processing, the current chapter elaborated on original CoMP algorithms based on the principal of receiver beamforming using smart antennas (combination of adaptive and switched beam antennas) to reduce/ mitigate interference in uplink 4G and potentially in the future 5G networks.

The concept of smart receiver antennas, using antenna reciprocity, is adopted to adjust the receiver beam pattern and thus increase SINR of the intended set of users. The eNodeB global view at the central office is exploited to effectively allocate transmission across the whole network. The applied receiver beamforming scheme uses switched and adaptive antenna techniques to increase performance and save on processing power at eNodeBs. Compared to the most profound CoMP techniques available in uplink which generally require complex pre-processing between the coordinated cells and CSI from the UEs involved, the proposed requires the location (direction of UEs from their serving eNodeBs) of the targeted UEs which was assumed to be efficiently acquired by available techniques (e.g.: E-CID).

The algorithm is based on the assumption users are switching from one beam to another depending on their location within the cell when the switched beam technique is used. In that scenario the receiver antenna beam patterns are fixed and are applicable to deployment scenarios where channel conditions do not change frequently and UEs are static. If UEs are moving frequently the adaptive technique is used where the eNodeB adjust their receiver radiation pattern towards the targeted user while nulling the pattern at the interfering user equipment. This means that the main beam is put in the direction of the desired signal while nulls are in the direction of the interference.

System level simulations of a complete cellular network have demonstrated in average 50% increase in spectral efficiency at the cell-edges compared to a scenario where beamforming is not applied. More importantly, results have shown 66% and 40% throughput increase with the application of beamforming compared to without any beamforming for 1×2 and 2×4 antenna configuration respectively. Utilising the four antenna elements a significant 26% improvement in cell-edge coverage was also observed.

Chapter 5

5. Joint Processing / Reception using Receiver Beamforming in Heterogeneous Network

5.1 Introduction

Following from chapter 4, this chapter elaborates on the design, system level implementation and performance evaluation of new uplink joint reception techniques for uplink interference mitigation using receiver beamforming. Similarly to downlink, uplink CoMP cooperative scheduling and joint reception is also important from a 3GPP specification and NGMN Alliance point of view [182, 183]. It could be directly applied to LTE Release 8 UEs considering uplink CoMP does not necessarily require any changes to be implemented to the radio specifications [182] but only on the eNodeB side. CoMP reception requires that the signals from several antennas in the network are routed to a central baseband receiver, where they can be combined and used in the detection process for every user. In this thesis joint reception is adopted to improve inter-cell interference mitigation based on the novel receiver beamforming of Chapter 4.

Cooperative Scheduling/ Beam Forming (CS/BF) and joint reception using smart antennas have recently appeared to be a potential solution for interference mitigation based on inter-base station communication [153, 184]. This is typically enhanced by exploiting base station equipment (x2 interface) in a HetNet scenario to reduce the traffic exchange, latency and significantly enhance cooperative transmission [43, 185].

Joint reception/ processing is performed in eNodeBs which allows for joint scheduling decisions of individual mobile users to be made based on the information received from different cells. This information together with the application of an advanced receiver beamforming technique is used to schedule uplink transmission. Subsequently, the performance gain of the proposed joint reception and receiver beamforming techniques is analysed for both macro and small cell environments. The performance evaluation figures produced include detailed system level simulation results of uplink throughput and spectral efficiency compared to with and without CoMP receiver beamforming techniques.

5.2 Interference Mitigation using Joint Reception and Coordinated Scheduling

As discussed in chapter 2 interference in cellular networks can be explored by applying CoMP transmission and reception, where different base stations act together as a distributed antenna system, sharing data and control information [186]. CoMP techniques are used to orchestrate the transmission/reception of cells in cooperating groups (clusters) coordinating to improve the link quality but significantly at the same time to mitigate inter cell interference. With respect to the latter, the literature review in chapter 2 has focused on the most prominent CoMP methods, namely Coordinated Scheduling/Beamforming (CS/BF) and Joint Processing/Reception (JP/JR) [184].

Figure 5-1 illustrates the initial direction of the beams at the start of the simulation for non-CoMP scenarios. It displays a typical macro-cell scenario with eNodeB antennas operating at maximum power of up to 43dBm (approx. 20W), quite possibly extending their beams to neighbouring cells.

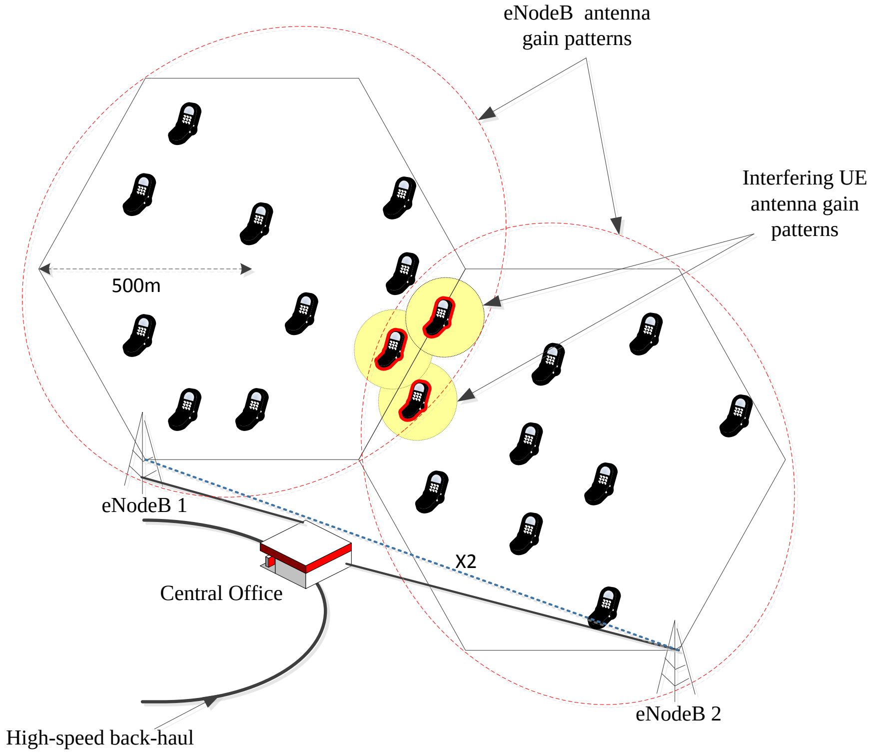

Figure 5-1: Normal/fixed direction of the antenna beams for the non-adaptive antennas in eNodeBs

Figure 5-1 illustrates a normal/fixed direction of the antenna beams for the non-adaptive antennas in eNodeBs. It can be seen that the signal coverage (antenna beams) from these sector antennas are not perfectly restricted within their cells. Similarly UEs at the cell-edges transmitting uplink with a maximum antenna power of up to 23dBm can interfere with each other. In the absence of CoMP, interference at eNodeBs will become more severe, due to the antenna reciprocity. For the cell-edge UEs transmitting in uplink, the receiver beams form the eNodeBs extend over to the neighbouring cells will increase the interference at the receiving end reducing the SINR.

CS/BF reduces inter-cell co-channel interference by avoiding scheduling users on the same direction of one or more eNodeBs from different cells (corresponding eNodeBs) at the same time through coordinated scheduling or using precoding to spatially separate transmission signal between the cooperating cells in order to control and/or reduce the interference between different transmissions by sharing received data via backhaul. Uplink coordinated multi-point reception implies reception of UE transmitted signals at multiple geographically separated points particularly at the cell-edge. In the uplink since the signal can be received by multiple cell sites, if the scheduling is coordinated from the different cell sites, the system can take advantage of this multiple reception to significantly improve the link performance.

Hence in uplink JP/JR makes use of the interference signals which are naturally received at the eNodeBs, other than the intended signals to mitigate multiuser and inter-cell interference in order to increase the signal to noise ratio [187]. Joint reception in uplink allows signals with very low strength or masked by interference in some areas to be received at the eNodeB with few errors.

Uplink CoMP needs great amount of data/ control signals exchange among eNodeBs. However it can be reliably overcome by fast exchange of additional control signals between coordinating eNodeBs by X2 interface. By using the X2 interface, scheduling decisions can be coordinated among cells (different eNodeBs) to control interference with minimum latency. In a heterogeneous environment the cooperating units can be separate eNodeBs' or RRUs in different instances.

5.3 Modelling and Evaluation of Proposed Algorithms

Implementing coordinated scheduling/ beamforming and joint reception with receiver beamforming, new models had to be designed with additional functionalities incorporated to the already comprehensive system level simulator designed for this work and described in chapter 3. To summarise, the benchmark system-level-simulator consists of eNodeBs and UEs within a RoI, which are created as a map and includes all the fundamental properties/ characteristics included in chapter 3. Figure 5-2 illustrates the basic single tier cell layout simulated, consisting of 7 sites (with 3 sectors each) with an ISD of 500m.

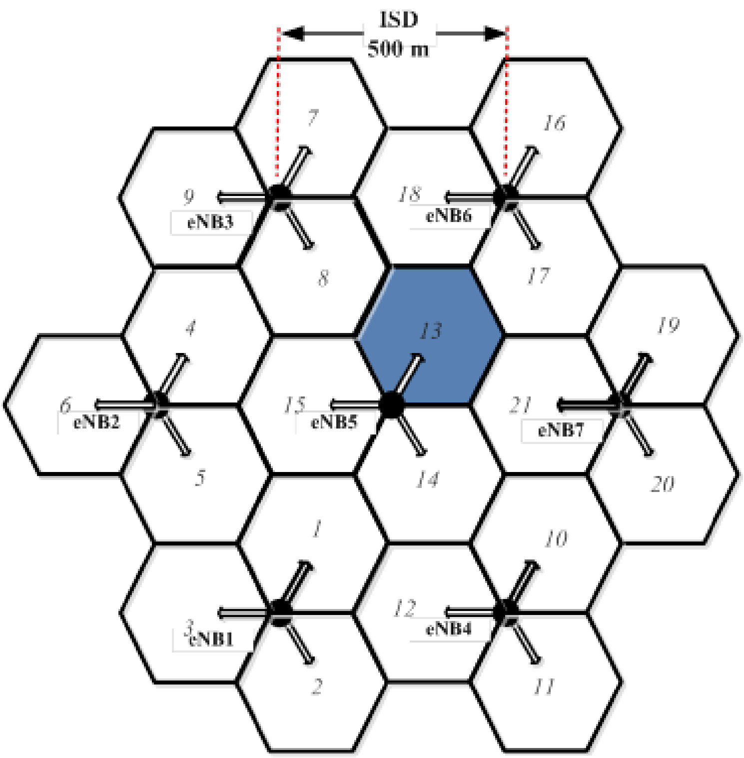

Figure 5-2: Single tier cell layout consisting of 7 sites (with 3 sectors each) with an ISD of 500m

Figure 5-3 demonstrates the network architecture investigated, where eNodeBs are connected using the X2 interface in an urban deployment with an inter-site distance (ISD) of 500m [43, 175]. As illustrated in Figure 5-3, the cell edge UEs, UE1 and UE4 will interfere with each other in the absence of CoMP scheduling. In uplink this is one of the main reasons for spectral efficiency degradation. To overcome this issue eNodeBs should schedule UEs at the conflicting boarder in different time slots. As an example, assuming that each UE is connected to a single eNodeB, during the Transmission Time Interval (TTI) 1, eNodeB 1 and eNodeB 2 are serving UE1 and UE3 respectively (Figure 5-3).

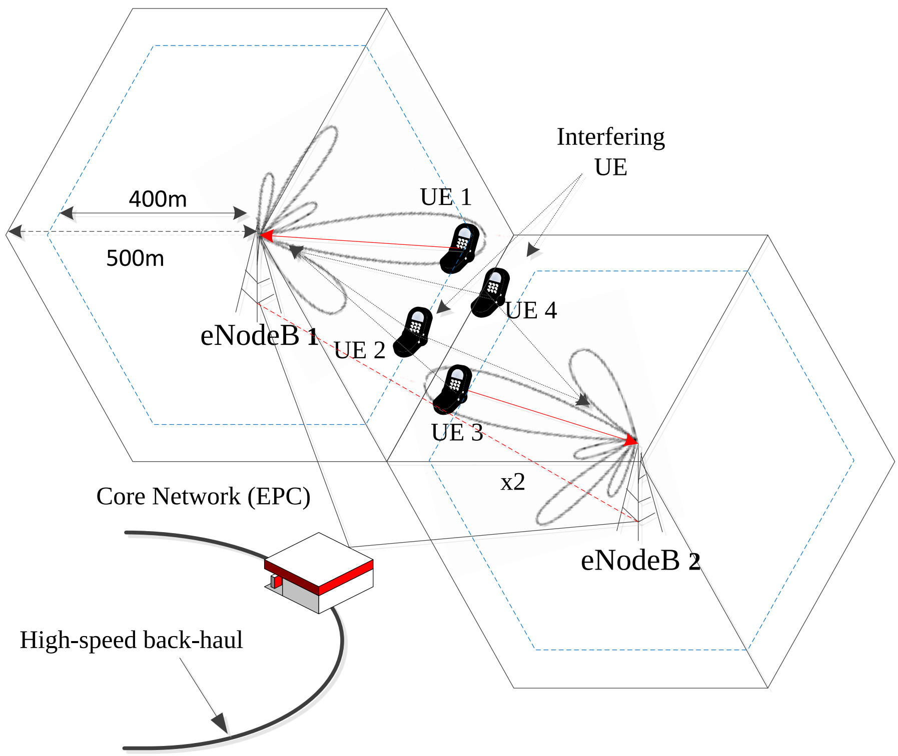

Figure 5-3: FiWi system architecture with cooperative scheduling/beamforming at TTI 1

At TTI2 (Figure 5-4) the eNodeBs adjust their transmission beams in the direction of other users based on their locations in order to minimise interference.

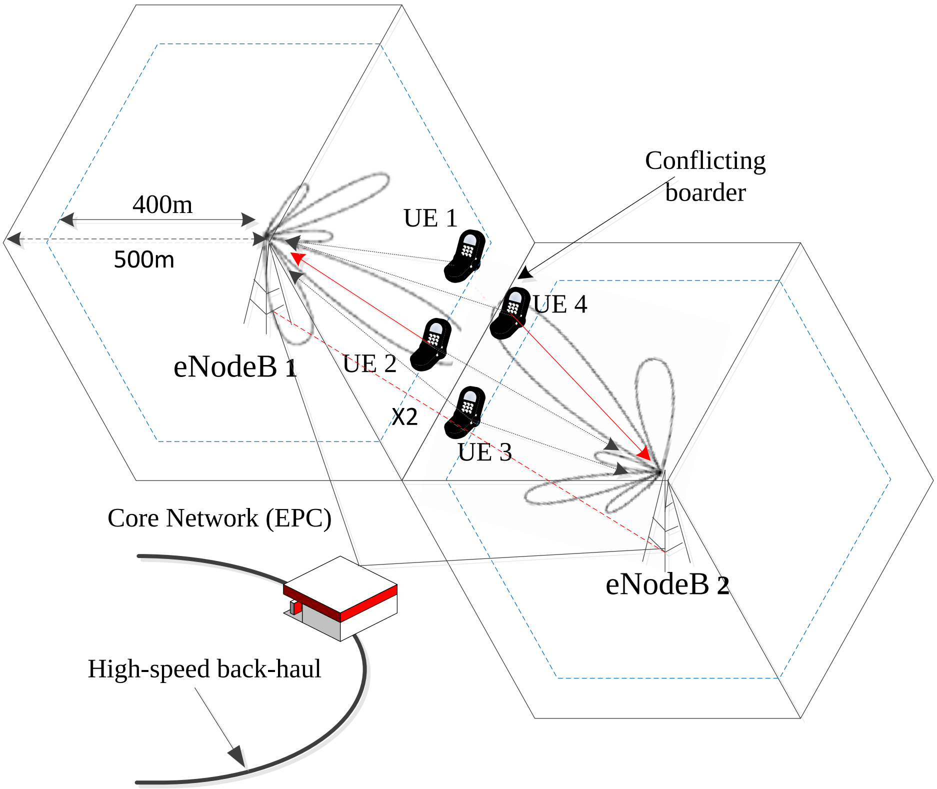

Figure 5-4: FiWi system architecture with cooperative scheduling/beamforming at TTI 2

The concept of steering the transmit beam pattern is typically known as CS/BF [40, 175]. CS/BF is an effective scheme for increasing the overall users' throughput especially at the cell-edge. As shown in Figure 5-4, it is assumed that users that are more than 400m away from the eNodeB represent cell-edge users. Distance is calculated based on channel feedback since the Closed Loop Spatial Multiplexing (CLSM) algorithm is used at the eNodeB [175]. Considering, it is assumed that each eNodeB is aware of the overall distribution of all UEs across the network, therefore uplink user transmission is scheduled accordingly to minimise the overall uplink interference. Exploiting the antenna reciprocity properties (i.e. same antenna characteristics in downlink and uplink) the receive beam pattern can also be adjusted in order to minimise the interference in uplink [175]. As a result, the receive pattern/ beam at eNodeB antenna is steered in the direction of the desired UE whereas it is nullified in the direction of interfering UEs. The algorithm used to implement the CS/BF receiver beamformer is shown in Table 5-1.

Table 5-1: Coordinated scheduling with receiver beamforming conditions for cooperating cells in target sector

Algorithm Coordinated scheduling with receiver beamforming conditions

Initializing
At the beginning of each TTI the eNodeB updates the distance and angle matrix for each UE in the target sector.

Step 1: Finding the cell-edge UEs and the conflicting boarders for each eNodeB

for $N = eNodeB_{1\ldots n}$
    for $M = UE_{1\ldots m}$ ($Threshold_{EdgeDistance=}$ 400m)
        if (distance between UE_M and $eNodeB_N$) ≥ $Threshold_{EdgeDistance}$
            else-if (Maximum allowed path-loss) ≥ 123.9dB
                Add UE_M to List $Edge_N$
                Add Angle of UE_M with respect to $eNodeB_N$ to List $Edge_N$
            end
        end
    end
end
for $N = eNodeB_{1\ldots n}$
    for $P = eNodeB_{1\ldots 6\ (neighbouring\ eNodeBs)}$
        for $M = UE_{1\ldots m}$
            if $UE_M(Angle)$ in List $Edge_N$ match any Angles in List $Edge_P$
                Add UE_M to List $Conflict_{N,P}$
            end
        end
    end
end
for $N = eNodeB_{1\ldots n}$
    for $P = eNodeB_{1\ldots 6\ (Neighbouring\ eNodeBs)}$
        for *ConflictingUEsN* = $Conflict_{N,P}$
            for *ConflictingUEsP* = $Conflict_{P,N}$
                for Angle = 5:10:55 ($Threshold_{Angle}$ = 5 degrees)
                    if (*ConflictingUEsN* == *Angle* ± $Threshold_{Angle}$)
                        AND
                    (*ConflictingUEsP* == *Angle* ± $Threshold_{Angle}$)
                        Add matching UE to List $Scheduling_{N,P,Angle}$
                    end
                end
            end
        end

```
    end
end
```

Step 2: Coordinated **s**cheduling for the cell-edge UEs at conflicting boarders

for $N = eNodeB_{1\ldots n}$
  for $P = eNodeB_{1\ldots 6\ (Neighbouring\ eNodeBs)}$
    for Angle = 5:10:55
      if UEs in $Scheduling_{N,P,Angle}$ Matches UEs in $Scheduling_{P,N,Angle}$
        Add UE from $Scheduling_{N,P,Angle}$ to List TTI_N (First TTI Available)
        Add UE from $Scheduling_{P,N,Angle}$ to List TTI_P (Second TTI Available)
      end
    end
  end
end

For each $TTI_{(1\ldots k)}$:

for *Iteration = 1: Length(List TTI)*
  for $N = eNodeB_{1\ldots n}$
    Connect $eNodeB_N$ to UE listed in TTI_N(Iteration)
  end
end

At the beginning of each TTI the eNodeB updates its distance and angle matrix for each UE in the target sector. As described in step 1, each eNodeB will select the cell-edge UEs depending on the distance from their serving eNodeB or the maximum allowed path-loss. Then each eNodeB will determine its conflicting boarders (boarder between two hexagonal sectors belonging to different eNodeBs) towards neighbouring eNodeBs.

Individual cell-edge UEs angle determined by one of the DoA or AoA techniques will then be added to a list depending on which conflicting boarder, the particular UE is belonging to. Then these UEs depending on their angles, from each eNodeB will be matched to see whether any of the UEs interfere with each other. For this a threshold angle of ±5 degrees (assuming that a UE within this area can interfere with the intended UE) were taken into consideration. If any of the UEs are in the conflicting boarder within the mentioned threshold angle, will be taken as an interfering UE and will be scheduled for the second available TTI. This will ensure that the coordinating eNodeBs will not schedule any of the selected interfering UEs (with each other) at the conflicting boarder to be served on the same TTI reducing the interference. Following the application in the system level simulator of the above process and therefore the implementation of the coordinating scheduling algorithm, beamforming is incorporated by executing the algorithm presented in Table 4-2 of chapter 4.

The concept of uplink CS/BF joint reception is further enhanced by the introduction of the adaptive receiver beamforming, as illustrated in Figure 5-5, in order to further reduce ICI for cell-edge users.

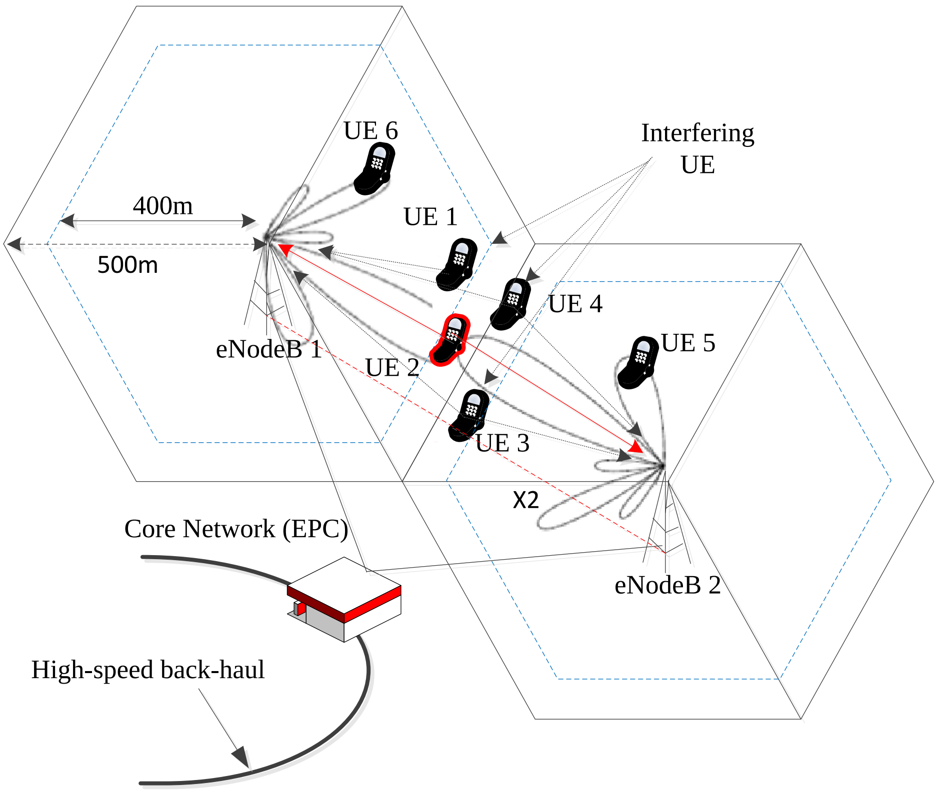

Figure 5-5: System architecture with joint reception with the assistance of receiver adaptive beamforming in TTI 1

In contrast to the typical CS/BF algorithm, two or more eNodeBs (e.g. eNodeB 1 and eNodeB 2 in Figure 5-5) in the proposed algorithm are simultaneously receiving data from a single cell-edge UE. For instance, Figure 5-5 shows, eNodeB 1 and eNodeB 2 receiving data at TTI 1 from UE2 while at TTI 2 from UE4 (Figure 5-6). It can be also observed that the interfering UEs at each instance, e.g. UE4 and UE3 in TTI 1 are in null directions where the interference is mitigated. Signals are then combined at eNodBs so that following the strategy above interference can be turned into useful signal increasing the overall uplink signal to interference noise ratio (SINR).

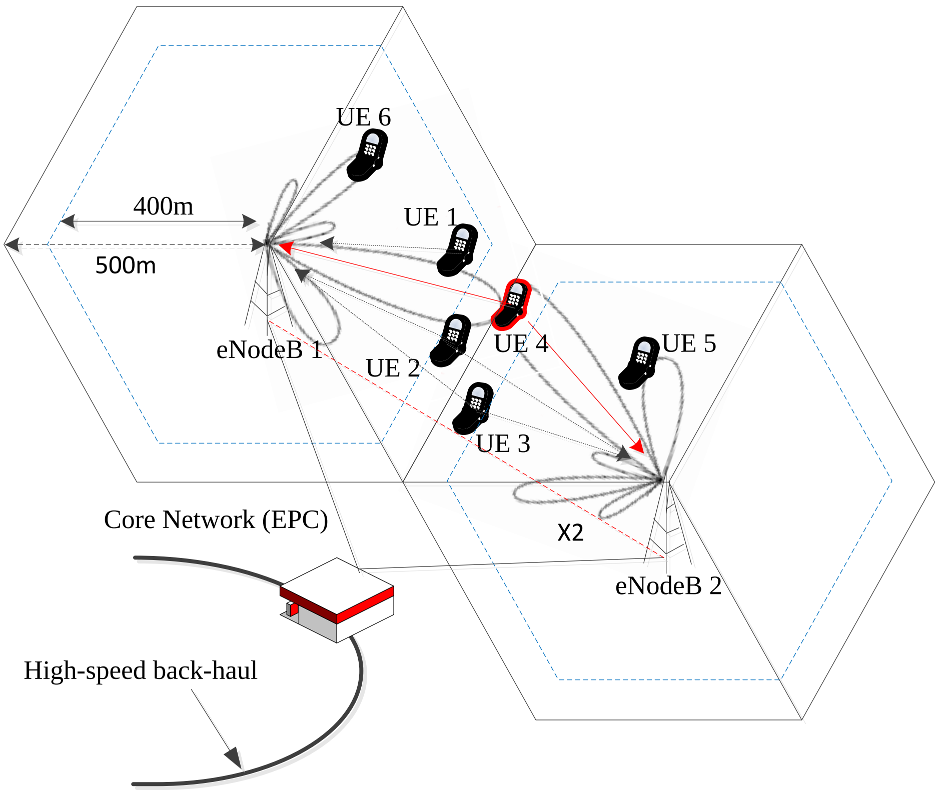

Figure 5-6: System architecture with joint reception with the assistance of receiver adaptive beamforming in TTI 2

Therefore, our proposal makes use of the geographically separated eNodeBs to receive the users' data by coordinating multiple cells. Because of the X2 interface eNodeBs are able to share received data with reduced latency. In a real system the signal processing performs all the above mentioned algorithms, exhibiting as distributed antenna system across a coordinated set of cells. As described in earlier algorithms, at the beginning of each TTI eNodeBs update their distance and angle matrix for each UE in the target sector. This is done in order to determine the cell-edge UEs. As already mentioned, other than the distance and angle matrices the maximum allowed path-loss can be used for these calculations. Again assuming eNodeBs have the knowledge of the distribution of UEs in the network; at the beginning of each TTI the eNodeB updates its distance and angle matrix for each UE in the target sector. eNodeB will then determine the cell-edge using the threshold distance and the angle or maximum allowed path-loss, then measure the path-loss from the cell-edge UE to surrounding cells and estimate the CoMP cluster. After selecting the CoMP cluster, eNodeBs in the CoMP cluster exchange the data about the cell-edge UEs among them. Then the eNodeBs in the CoMP cluster performs the coordinated scheduling depending on the exchanged CSI information among the cluster using the algorithm in Table 5-1. eNodeBs in the CoMP cluster uses the complex weights to steer the receiver beams towards the target cell-edge UEs based on their locations in order to achieve joint reception and minimise interference. At the end of each TTI, eNodeBs in the CoMP cluster share the information among all the cells and do link adaptation at the central office and perform joint reception processing.

The receiver beam pattern can change adaptively according to the channel conditions and users' location. Using a high-speed FiWi configuration the amount of traffic exchange on the X2 interface, as with traditional cellular deployments [53, 154], is significantly reduced since all information required for interference cancellation is exchanged with minimum delay due to high backhaul capacity.

5.4 Performance gains of CS/ BF and Joint Reception with Smart Antennas

The comprehensive MATLAB system level model, used to evaluate the performance of the proposed algorithm, is described in this section. For the system level evaluation of cooperative scheduling/ beamforming the shadow fading map is produced using a lognormal space-correlated function, the UEs movement is simulated based on 'random walk' models and their positions are picked in a uniform fashion across each sector. The network scenario under investigation requires an increase of the entropy in order to closely approximate 'real-life' conditions and take into account different environments, therefore multiple iterations are run (100 times in this scenario) where UE performance is the result of averaging those of each simulated environment. The key simulation parameters are summarised in Table 5-2. A 20MHz bandwidth is assumed currently, however it should be noted that the proposed algorithms can equally benefit technologies with wider bandwidths, expected for the deployment of 5G.

Table 5-2: Simulation parameters

Parameter	Assumption
Cellular layout	Hexagonal grid, 7 eNodeBs, 3 sectors per eNodeB
Inter-site distance/Cell sectors	500 m/120 deg.
Antenna pattern (horizontal)	$A(\theta) = -\min[12(\theta/ \theta_{3dB})^2, A_m]$ θ = 65 degrees, Am = 20 dB
Antenna spacing	$\Delta = 0.5\lambda$
BS height /antenna gain	20m /15dBi

UE antenna height /antenna gain	1.5m /0dBi
Number of UEs per sector	10
UEs distribution	Homogeneous random positions
Transmission modes	CLSM
Frequency / Bandwidth	2GHz (reuse factor 1) / 20MHz
Number of iterations	100

Providing a realistic cellular environment, interference was modelled in conformance to the well-known wrap-around interference modelling technique where an UE performance metric, such as throughput, is taken from a single cell/sector surrounded by a number of equidistant eNodeB sites. UEs are accordingly handed over to their assigned sector in the event where they move out of the simulation region of interest. The simulation is performed by defining a region of interest in which the eNodeBs and UEs are positioned and it is only in this area where UE movement can be performed. The basic simulation cell layout setup consists of 7 eNodeBs with each eNodeB comprising 3 hexagonal cell sectors forming a site.

The simulation assumes in average 10 users per sector as expected in typical deployments. The model also utilises a full buffer traffic which means that a user has an unlimited amount of data to transmit. Various antenna configurations are also simulated and presented in order to evaluate the effect of beam width with the increase in the number of eNodeB antennas.

The performance gain of different antenna schemes has been compared against the uplink throughput in the target sector using a normalized cumulative distribution function (CDF). Figure 5-7 and Figure 5-8 provide a comparison between 1 x 2 and 2 x 4 antenna configurations with CS/BF and joint reception including receiver beamforming respectively.

The performance figures are compared with the non-CS/BF (non-CoMP) scenario. The figure insets represent the 5th percentile showing the normalized throughput of users at the cell-edge.

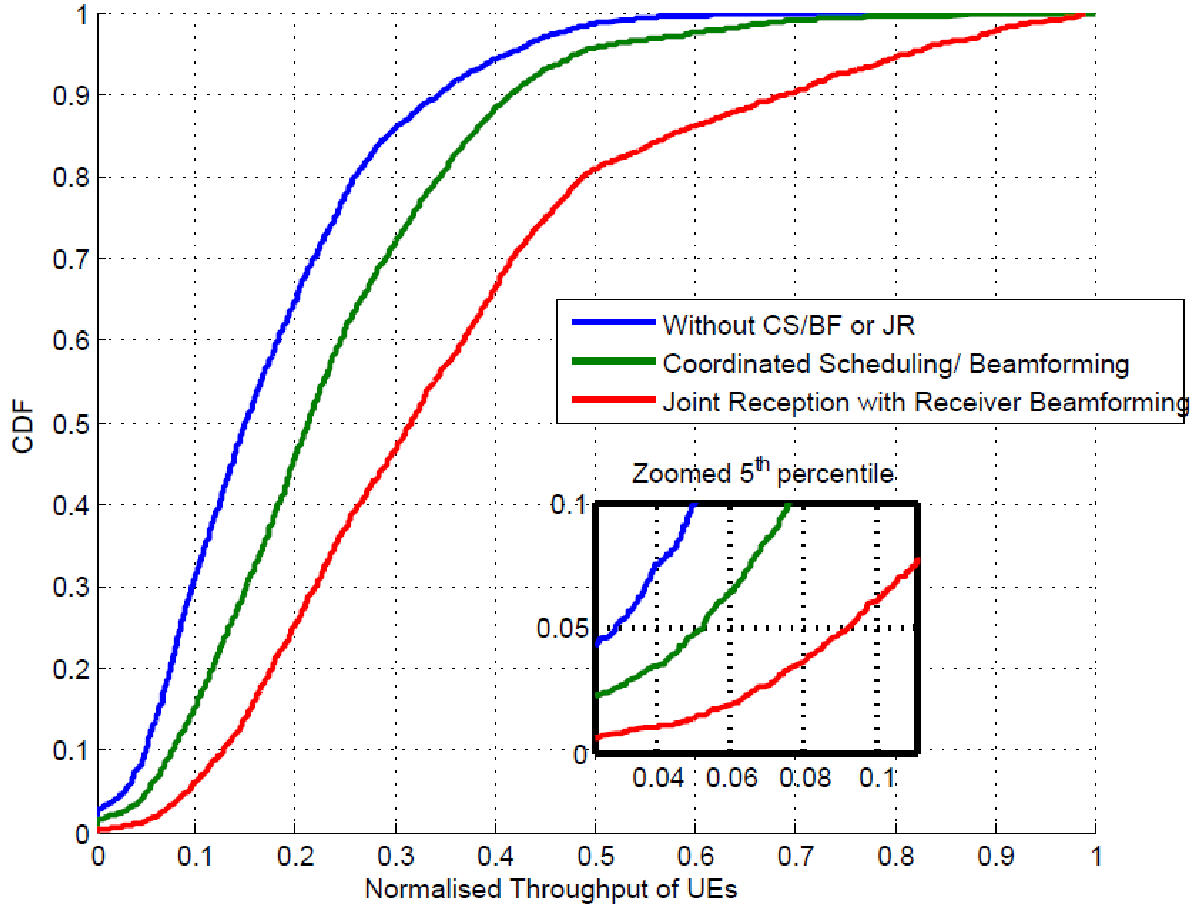

Figure 5-7: Normalized throughput for 1x2 antenna configurations

By observing Figure 5-7 it can be seen, by using coordinated scheduling and receiver beamforming, throughput at the cell-edge is increased by 84% (from 0.0285 to 0.0512) for the 1 x 2 antenna configuration and significant increment of 223% (from 0.0285 to 0.0912) when joint reception is used compared to the single antenna reception scenario which clearly shows that applying the proposed CS/BF with joint reception algorithm the cell-edge normalized throughput has increased when compared to the non-CS/BF scenario.

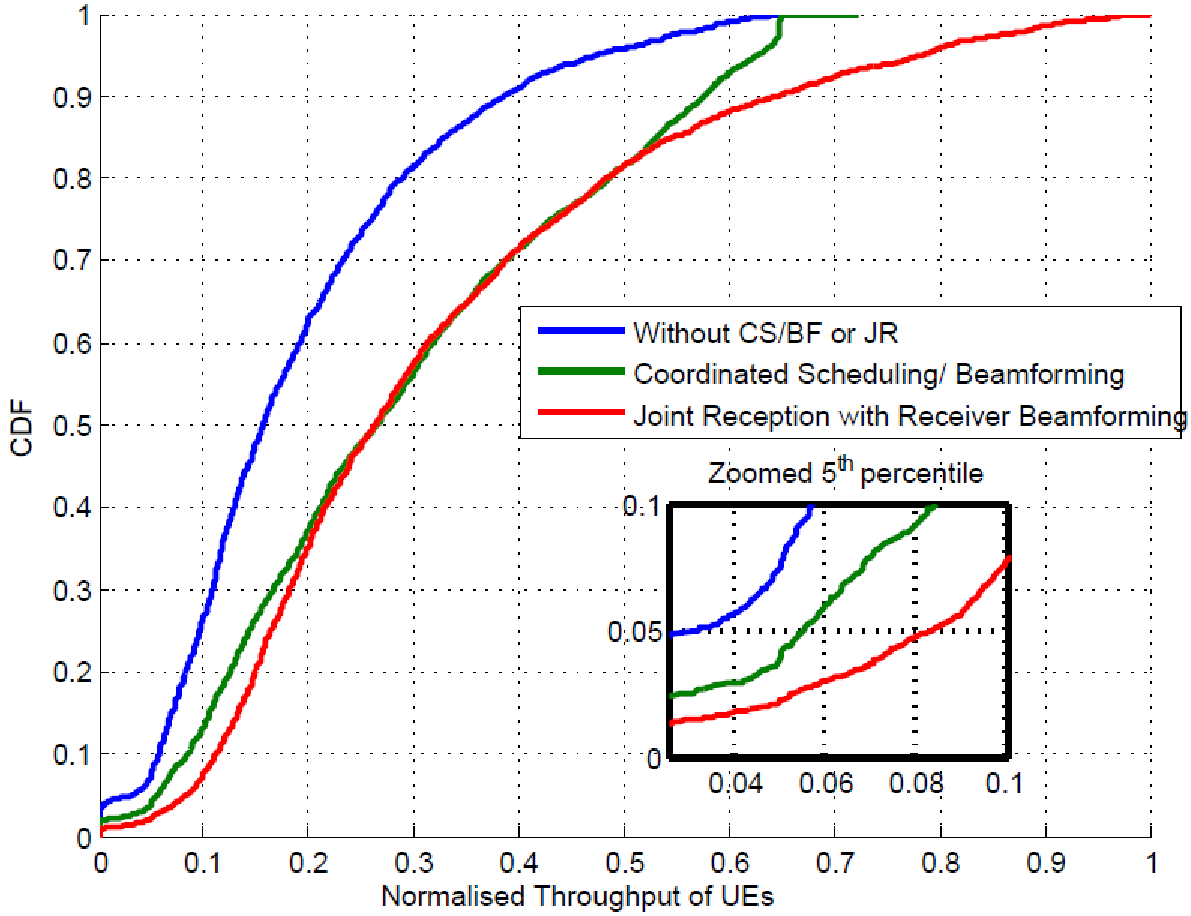

Figure 5-8: Normalized throughput for 2x4 antenna configurations

Respectively for the 2 × 4 configuration the overall cell-edge throughput is increased three times compared to the non-CS/BF scheme. This corresponds to a further increase in throughput compared to 1 x 2 as expected since with 2 x 4 antennas the spectral efficiency is increased (i.e. normalised value of 1 in Figure 5-8 is higher compared to the 1 x 2 scenario). To extent the analysis further and emphasise of the performance enhancement of joint processing with receiver beamforming as implemented in this thesis, compared to coordinated scheduling, it can be observed that for the 1 × 2 and 2 × 4 antenna configurations joint reception outperforms the coordinated scheduling by 0.63 (76%) and 0.69 (52%) respectively. This substantial improvement is achieved since the joint reception algorithm combines the UE signals from neighbouring cells, which effectively increases the overall throughput and reduces the interference by the receiver beamforming technique.

Finally, four scenarios have been compared, as in previous chapters, to demonstrate the performance trend of various possible antenna configurations under the operation of coordinated scheduling on one hand and joint reception with receiver beamforming on the other. The obtained throughput values for this algorithm implementation are presented in Figure 5-9.

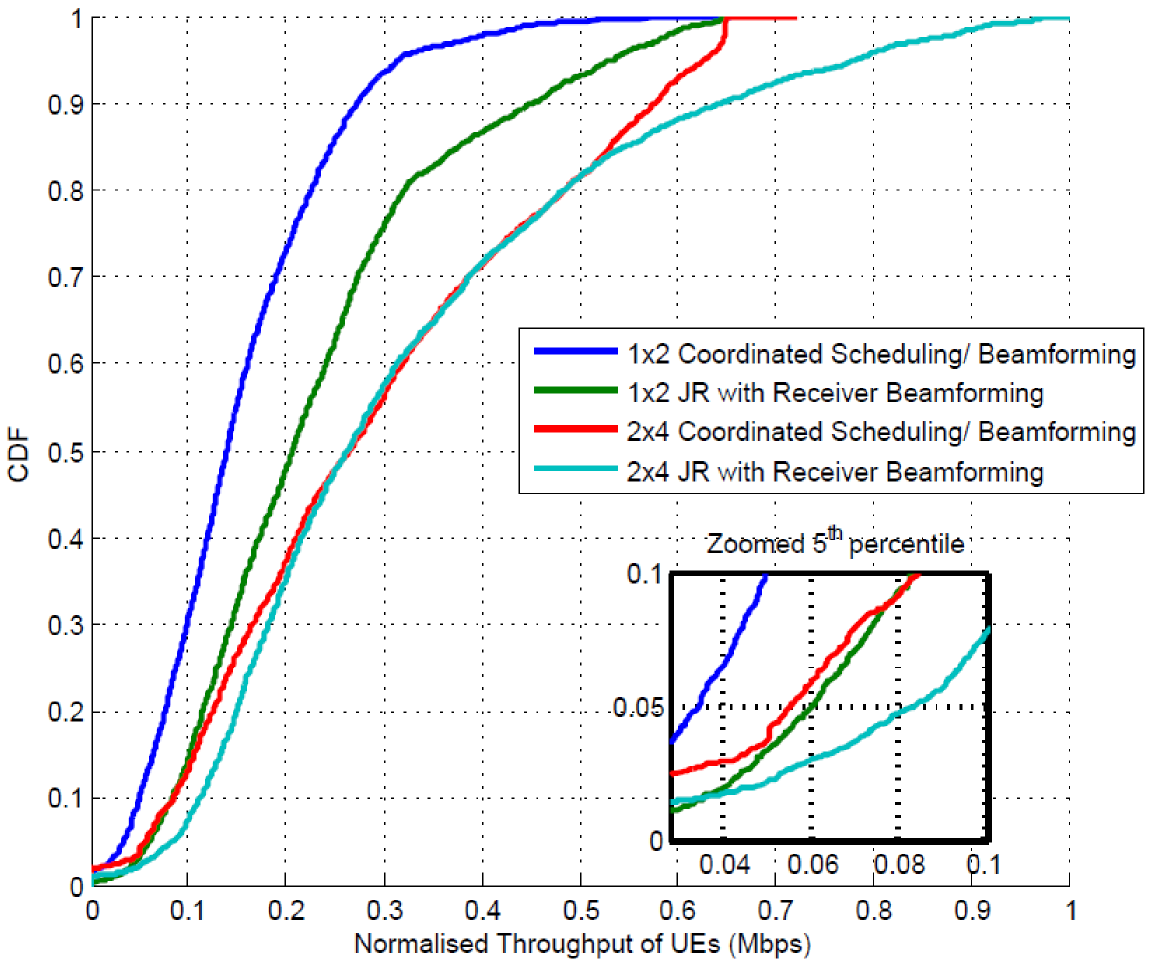

Figure 5-9: Normalized throughput for CS/BF compared to joint reception

As it may be observed, for 1 × 2 and 2 × 4 antenna configurations the joint reception with receiver beamforming outperforms the coordinated scheduling scenario by 76% and 52% respectively. This substantial improvement was achieved since the joint reception combine the UE signals from neighbouring cells where interference can be turned into useful signal and as a result significant increase in SINR.

Following from the figures above Figure 5-10 demonstrates the relationship between the average sector and cell-edge spectral efficiencies for the proposed scheme in comparison with both the non-CS/BF and CS/BF algorithms from paper published on chapter 4[175].

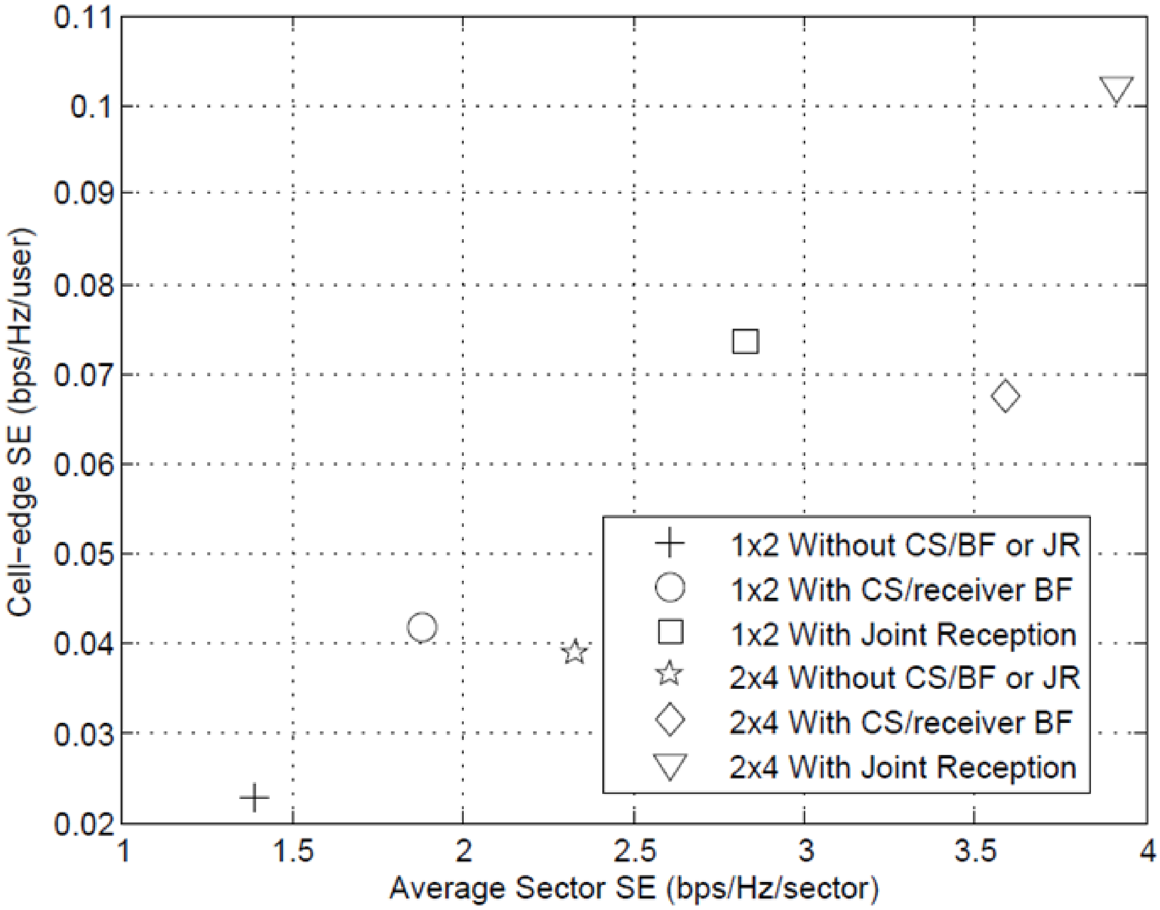

Figure 5-10: Spectral efficiency for CS/BF and JR with receiver beamforming

For both antenna configurations, CS/BF with joint reception exhibits an increase in the overall spectral efficiency compared to CS/BF, by 3.163b/s/Hz (76%) and 3.456b/s/Hz (51%) for 1x2 and 2x4 respectively.

The contribution of the new algorithms to high speed UEs (moving at 120 km/h) in a similar cell configuration was also assessed to account for the increased mobility in 5G networks. Figure 5-11 presents the obtained normalized throughput values for the high speed UEs for both algorithms but only the 2 x 4 antenna configuration, presenting so far the best results.

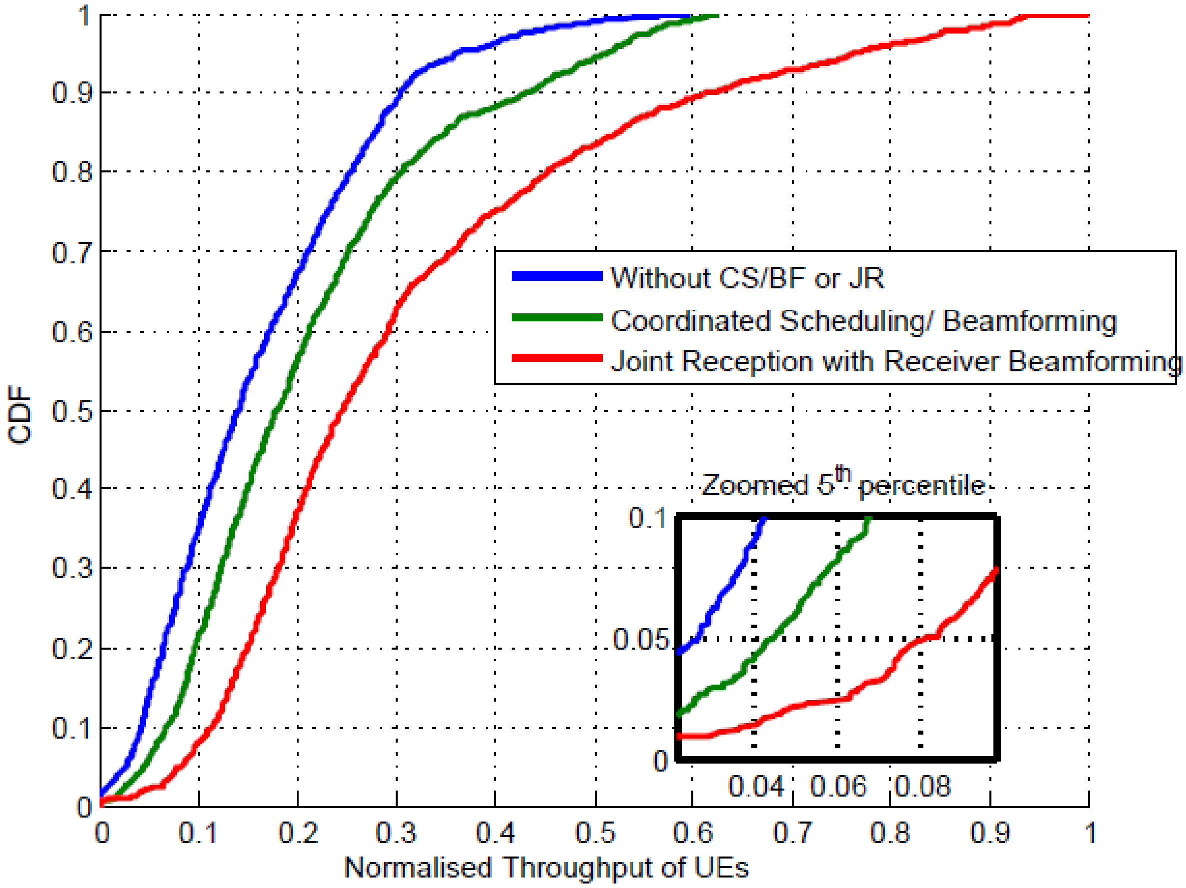

Figure 5-11: Normalized throughput for CS/BF compared to joint reception in high-speed UEs

It can be observed that CS/BF with receiver beamforming increases the overall spectral efficiency by 2.3072b/s/Hz (68%) and joint reception with beamforming by two times (6.919b/s/Hz) compared to non-CS/BF scheme for a 2 x 4 antenna configuration. For a high-speed scenario, use of adaptive antennas for joint reception can provide a better and significant throughput gains at the eNodeBs compared to CS/BF.

5.5 Joint Processing/ Reception in Small-Cell Environment

Low power Remote Radio Units (RRUs), giving rise to low-power small cells, are considered to be one of the key components to increase the capacity of cellular networks in dense areas with high traffic demands, especially in future heterogeneous network deployments [38, 188].

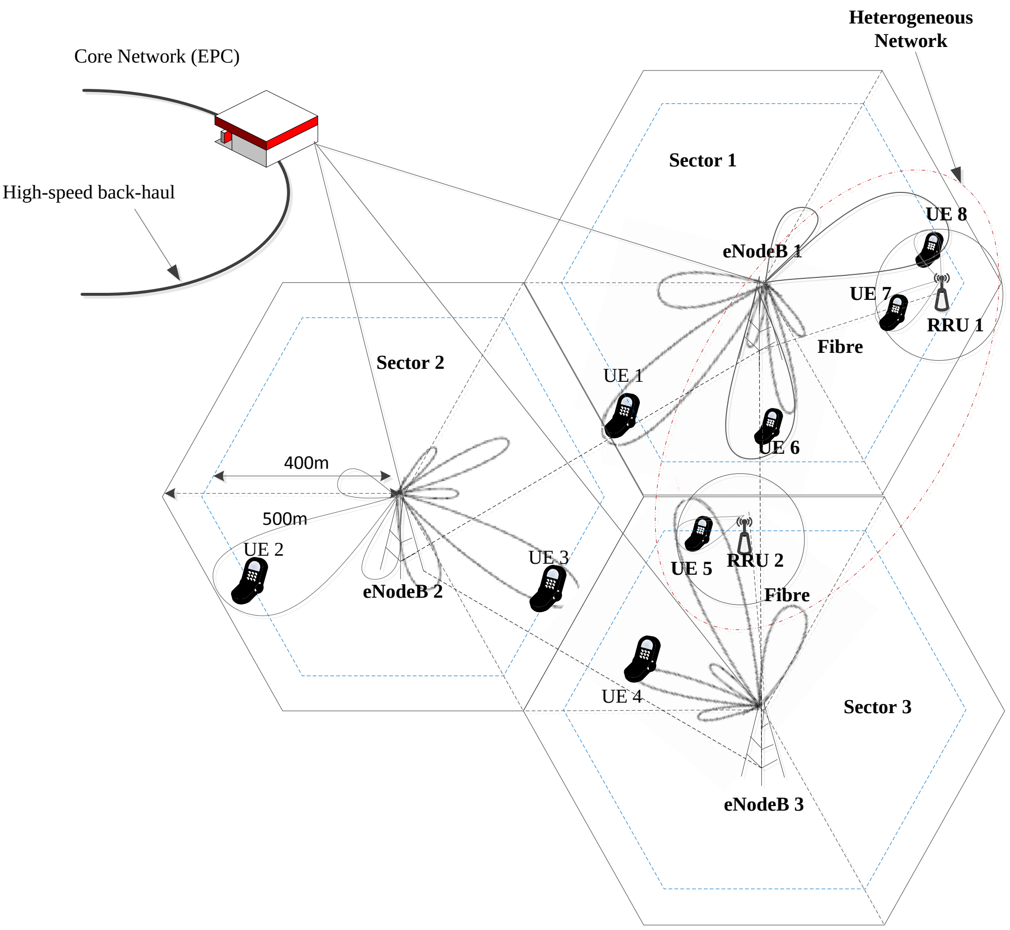

Figure 5-12: Heterogeneous deployment with uplink CoMP

In consolidation with macro-cells, small-cells can improve both the coverage and capacity of cell-edge users, being the focus of this research and hotspots by exploiting the spatial reuse of spectrum [188]. However, massive deployment of small-cells, can lead to significant co-channel interference in HetNets, especially for cell-edge users, interference management of which has been scarcely discussed in literature [188, 189]. Figure 5-12 present a heterogeneous deployment, incorporating uplink CoMP and low power RRUs within the coverage of a high power macro node to achieve intra-site joint reception. In the presence of CoMP, uplink transmission can acquire significant gain from macro reception diversity by coordinating low power RRUs with macro eNodeBs [50]. In particular low power RRUs can be deployed in the cell-edge to form small-cells, providing better reception than an eNodeB in scenarios with poor channel conditions. The coverage of a cell in downlink depends on the downlink transmit power [50], but for the uplink, the best link depends on the lowest path loss, where the cell-edge UEs in uplink transmission will realize a better link when a low power RRUs are available.

Hence at the edge of the low power cell (edge of the small-cell), user always gets better uplink channel conditions when attached to the low power RRU. This is because it is more closer to the low power RRU and thus lower path loss than when attaches to macro eNodeB. As illustrated in Figure 5-12, UE 8 in sector 1 can be served by both eNodeB 1 and RRU 1. Similarly joint reception can be achieved for UE 5 in sector 3 which is served by the cell-edge RRU 2 and at the same time served by its respective eNodeB 3. Therefore when intra-site uplink CoMP is applied, the uplink can be received and combined simultaneously from the macro and the low power RRUs thus increasing the uplink gain from macro reception diversity. Table 5-3 represents the base station specifications in the simulated heterogeneous network.

Table 5-3: Base station configurations in the heterogeneous network

<table>
<tr><th colspan="2"></th><th>Tx. Power</th><th>Antenna configuration</th><th>Height</th></tr>
<tr><td colspan="2">Macro-cell</td><td>46dBm (40W)</td><td>15dBi, Sectored</td><td>25m</td></tr>
<tr><td>Small-cell</td><td>5dBm (0.0031W)</td><td>2dBi, Omni directional</td><td colspan="2">7m</td></tr>
</table>

Two scenarios have been compared, distinguished by the number of small cells deployed inside the target sector to demonstrate the performance trend. In both cases macro eNodeB using joint reception with and without receiver beamforming was used to compare the achieved throughput. The measured characteristics are shown in Figure 5-13 and Figure 5-14.

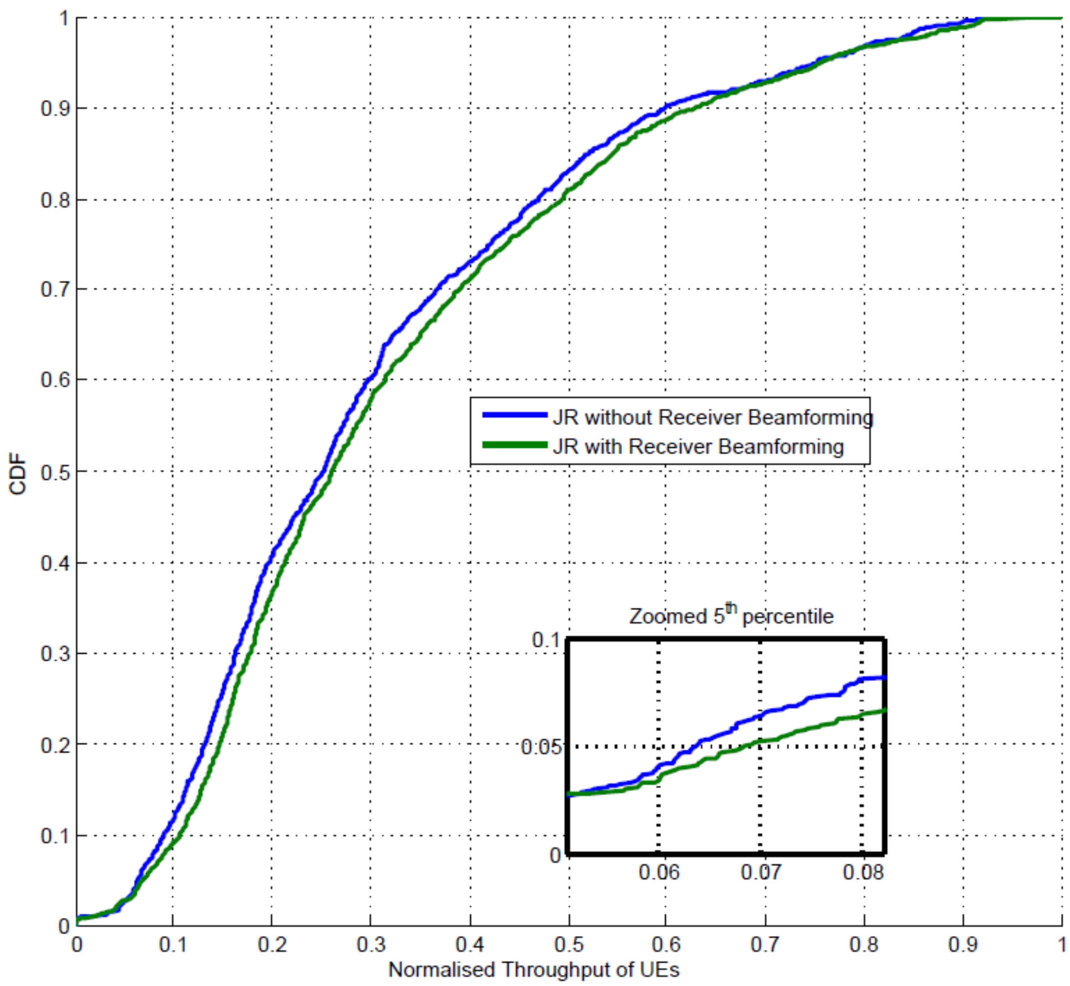

Figure 5-13: JR in Heterogeneous Network (1 small-cell)

The simulation is performed by defining a RoI (target sector) in which the eNodeBs, RRUs and UEs are positioned and it is only in this area where UE movement is performed. The basic simulation cell layout setup consists of 7 eNodeBs with 3 RRUs inside the target sector. The RRUs are deployed in pre-defined positons (locations known) inside the target sector.

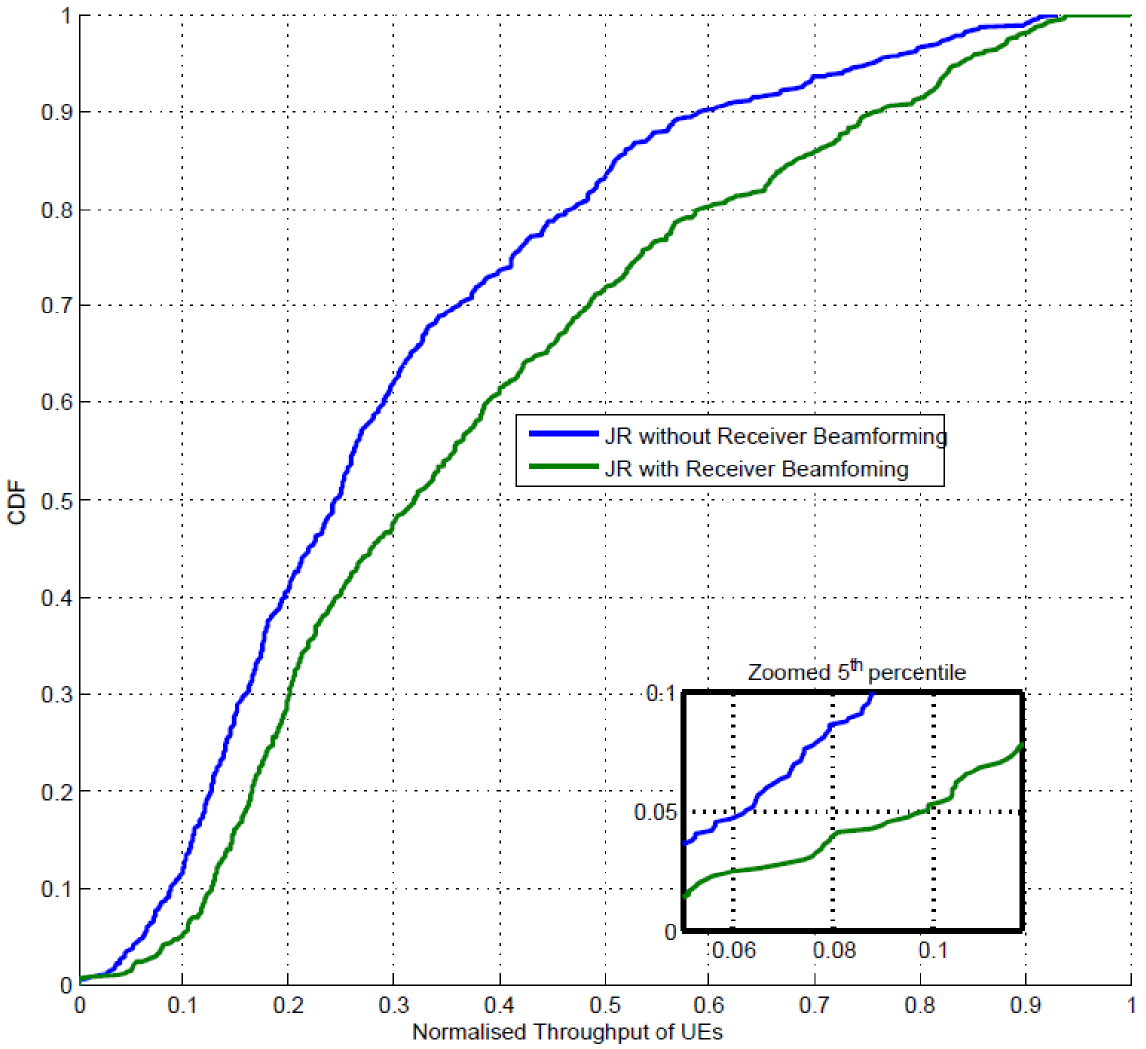

Figure 5-14: JR in Heterogeneous Network (3 small-cells)

The simulation assumes in average 10 users per sector as expected in typical deployments. The model also utilises full buffer traffic which indicates users have an unlimited amount of data to transmit. Figure 5-14 presents the normalized throughput characteristic measured under these conditions for a heterogeneous network with three small cells.

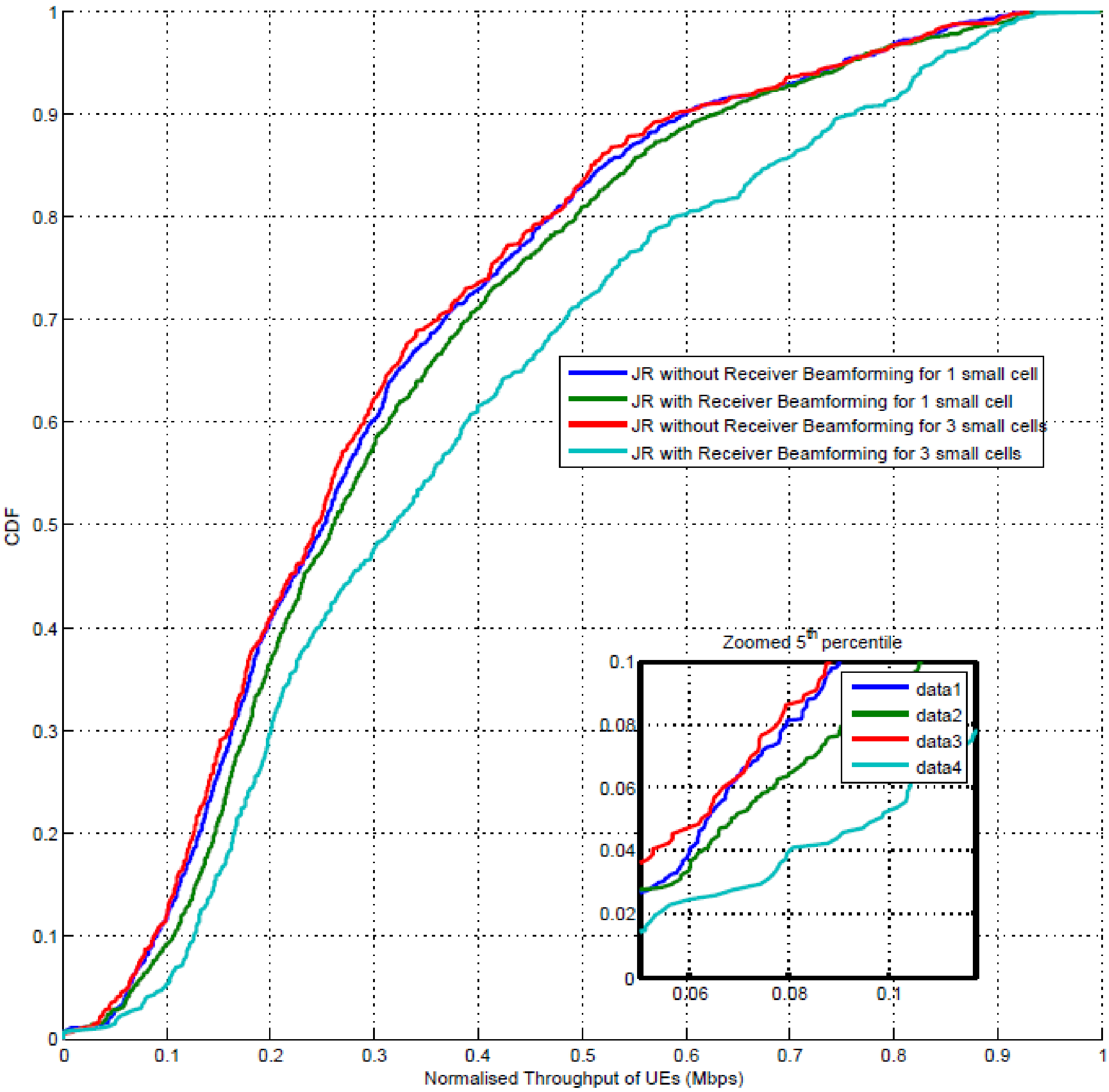

Figure 5-15: JR in Heterogeneous Network Comparison

It can be observed that by increasing the number of small-cells the overall throughput of the macro cell will significantly increase, even though it is expected to also observe increased interference in the absence of a suitable interference mitigation algorithm. When the number of small-cells is increased up to 3 inside the macro-grid (target sector) the interference towards the RRUs and eNodeBs increases, degrading the overall throughput by averagely 10-15%. By using receiver beamforming interference is shown in Figure 5-14 to be minimised allowing the overall throughput to be further enhanced. However for a network with only one small-cell (Figure 5-13) in the target sector, with receiver beamforming used in the eNodeB, the cell-edge throughput shown only a moderate increase limited to 0.06 (7%). However by using the receiver beamforming technique to reduce the interference in this scenario achieves significant 0.452 (57%) throughput improvement as shown in Figure 5-14. By observing Figure 5-15 it is easier to compare how the interference increases when the number of small-cells increased in the target sector and how the interference can be significantly mitigated by using the receiver beamforming technique. Thus, it is clear that for a heterogeneous network with a higher number of small-cells, use of adaptive antennas with receiver beamforming can provide better interference mitigation.

5.6 Summary

This chapter presented a novel cooperative uplink Inter-Cell Interference (ICI) mitigation algorithm based on joint reception performed at the base station by using receiver adaptive beamforming. The concept of smart adaptive receiver antennas, using antenna reciprocity, is adopted to enhance the CS/BF and joint reception algorithms. It is assumed that eNodeBs have the knowledge of UE distribution throughout the network, where it allows for joint scheduling decisions for individual mobile users to be made based on the information received from different cells. As a result, uplink transmission for a user is scheduled according to the known positions of other users in order to minimise ICI. This is enhanced in operation by an advanced receiver beamforming technique that in corporation has the potential to improve the overall uplink capacity. Therefore the benefits of receiving uplink signals from a larger number of antennas, in different geographical locations, are investigated using the proposed uplink joint reception and coordinated scheduling techniques. The eNodeB global view at the central office is exploited to effectively allocate transmission across the whole network.

Compared to CS/BF presented in the previous chapter, joint reception with receiver adaptive beamforming shows a 76% and 52% improvement in cell edge throughput for 1 x 2 and 2 x 4 antenna configurations respectively. In addition, the proposed joint reception scheme demonstrated an increase in the cell-edge spectral efficiency in average by 60% compared to cooperative scheduling. Investigation progressed further by simulating a high-speed UE mobility scenario, where it was observed that CS/BF increases the overall spectral efficiency by 68% and joint reception with beamforming by two times compared to non-CS/BF scheme for a 2x4 antenna configuration. Finally a heterogeneous network environment was considered, initially with only one small-cell in the target sector, demonstrating a modest impact on the cell-edge performance of 7% increment in the cell-edge throughput and receiver beamforming interference compensation. Increasing the number of small-cells to 3, a significant improvement of 57% can be observed in throughout with a parallel decrease in interference. For a heterogeneous network with a higher number of small-cells, use of adaptive antennas for joint reception can provide even better interference mitigation.

Therefore, the proposed joint reception with receiver beamforming scheme for interference mitigation can significantly improve the overall performance of future next generation networks exploiting high-speed fibre backhauls.

Chapter 6

6. D2D Underlying Cellular Networks in a HetNet Environment

6.1 Introduction

This chapter will explore the benefits of Device-to-Device (D2D) communications in a heterogeneous small-cell environment as an essential add-on technology to the currently developed 4G and succeeding 5G cellular networks. Continuing from the last two chapters the contribution to knowledge of this part of the work is on the introduction of adaptive antenna techniques (receiver beamforming) to increase the interference reduction capability of antenna arrays in a heterogeneous D2D environment. D2D communications underlying cellular networks have been recently proposed as a promising technology to satisfy the increasing demand for local data traffic, and therefore provide better user experience by enabling UEs in close proximity to communicate directly. This helps eNodeBs reduce UE traffic (by taking some load off the eNodeB) and maximise cellular resource block utilisation amongst other advantages. One of the main enhancements for future 5G wireless systems is integrating the standard coverage of traditional macro-cells with small-cells of reduced dimensions. In that respect D2D technology promises significant gains by allowing close distance transmission between UEs where lower transmission power levels are required, and secondly by reusing either the uplink or downlink cellular resource block without traditionally going through a base station which will reduce the network load and increase its effective capacity.

Most of the literature available in D2D communication is limited to studying D2D applications to UEs in the same cell (inside the Macro-cell). From the point of view of this research, D2D is considered to offer substantial benefits to cell-edge UEs in a consolidated cells environment (Macro-Macro or Macro and small-cells) where UEs can communicate directly when there is a better channel gain compared to their respective base stations links, contributing therefore to interference cancellation and throughout enhancement. It is envisaged that for interfering UEs or UEs with limited cellular coverage, neighbouring eNodeBs can relay channel gain information to potential D2D UEs with minimum overhead and reduced latency.

A complete cellular network system-level simulator was therefore developed by enhancing further the functionalities of the state-of-the-art SLS model presented in chapters 3-5 to design, simulate and evaluate the performance of small-cell heterogeneous networks exhibiting D2D communications. UEs have therefore been modelled to operate under both D2D and cellular modes (dual mode operation), where UE pairs in D2D mode can both transmit and receive, in compliance with D2D specifications defined in the 3GPP standard.

The performance gains of a hybrid network which consists of UEs in both D2D and cellular modes are analysed in this chapter based on simulation results demonstrating significant performance enhancement in terms of throughput and SINR for inter-cell D2D UEs. Further gains have been observed when CoMP techniques are employed due to their contribution in mitigating interference.

6.2 Modelling of D2D UEs in SLS

Figure 6-1 illustrates the basic single tier cell layout used for D2D performance evaluation, consisting of 7 sites (with 3 sectors each) with an ISD of 500m, portraying eNodeBs and UEs within a RoI, which are created as a map and includes the path-loss, antenna gain etc. As explained in previous sections, by using wrap-around interference modelling and by employing sector 13 as the target sector to generate the performance metric, a single-tier is sufficient to conduct the necessary performance investigations, therefore reducing overheads in the process while still modelling adequate levels of interference.

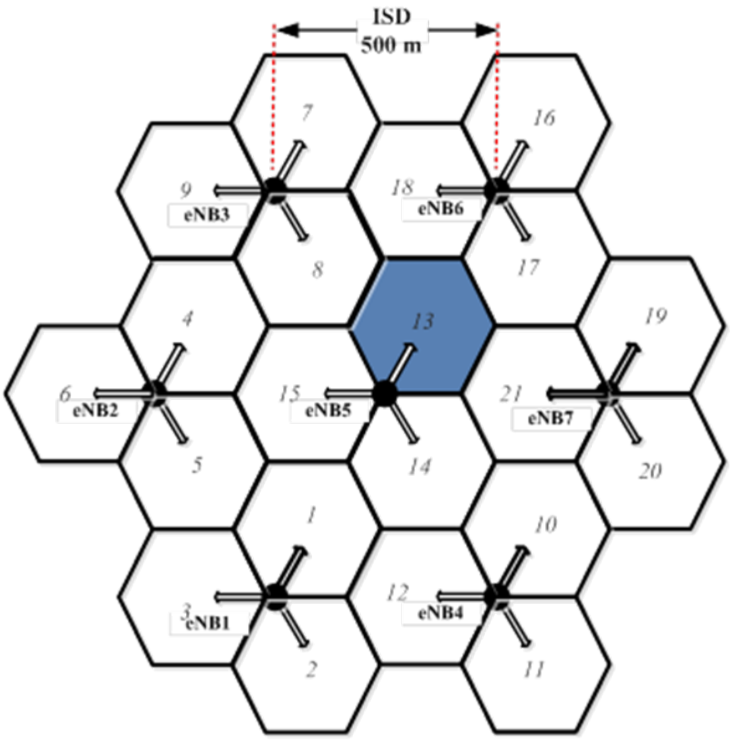

Figure 6-1: Cell layout consisting of 7 sites (with 3 sectors each)

In the target sector there are 10 UEs, where 8 UEs are in cellular mode and 2 are in D2D mode. All surrounding sectors in the model consist of 10 UEs operating in cellular mode. It becomes apparent that in all sectors of the model, including the target sector, cellular UEs continue to be the predominant users of the network and the respective eNodeBs of neighbouring cells are continuously transmitting to those UEs in cellular mode. This ensures that UEs at the cell-edge in the target sector experience interference from neighbouring eNodeBs to achieve realistic results. Figure 6-2 illustrates the D2D UEs in a cellular environment.

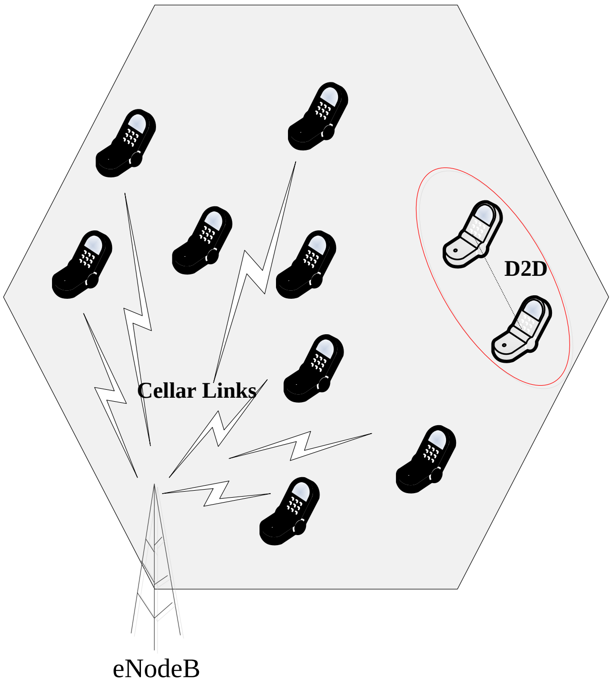

Figure 6-2: D2D UEs in a cellular environment

As mentioned in earlier chapters the sector eNodeBs are equipped with directional antennas where the azimuth varies depending on the sector. Sector antennas with a height of 20m is considered and measured from the average roof top of a typical urban environment [137]. The D2D transmitter and receiver have a height of 1.5m and equipped with an omnidirectional antenna.

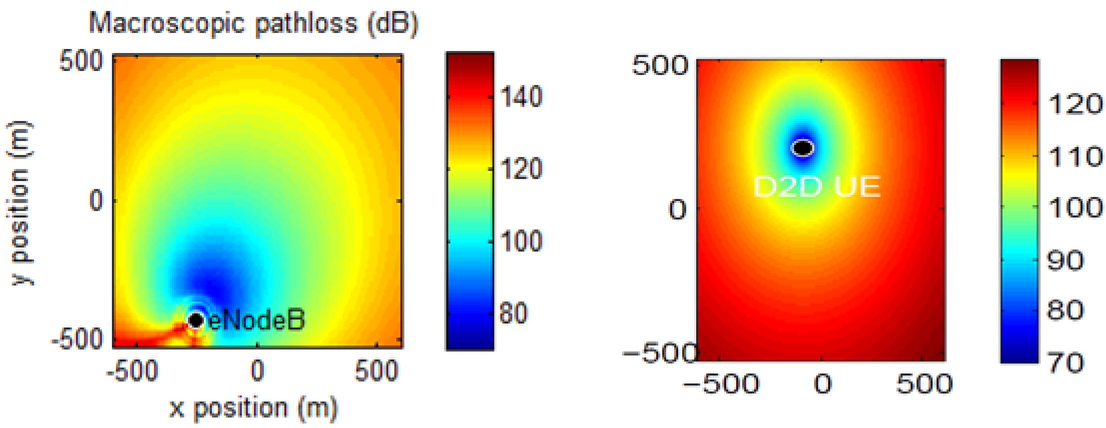

Figure 6-3: Path-loss of the target sector eNodeB with azimuth of 30 degrees and the D2D UE in the ROI

According to the 3GPP standard, LTE UEs can transmit at a maximum power of 23dBm (approximately 0.25W) [190]. Figure 6-3 draws the path-loss of the target sector eNodeB with azimuth of 30 degrees and the D2D UE in the ROI. The colour chart in the figure indicates the path-loss level (in dB) of the regions surrounding the transmitting antennas. It can be observed that the path-loss is considerably lower (dark blue to light blue region) closest to the eNodeB and D2D UEs.

The eNodeB antenna in the target sector has a maximum antenna gain of 15dBi and the D2D transmitter has a maximum antenna gain of 0dBi. The key simulation parameters are summarised in Table 6-1.

Table 6-1: Key simulation parameters

Parameter	Assumption
Cellular layout	Hexagonal grid, 7 RRHs, 3 sectors per RRH
Inter-site distance/Cell sectors	500 m/120 deg.
Antenna pattern (horizontal)	$A(\theta) = -\min[12(\theta/ \theta_{3dB})^2, A_m]$ θ = 65 degrees, Am = 20 dB
Antenna spacing	$\Delta = 0.5\lambda$
BS height /antenna gain	20m /15 dBi
UE antenna height /antenna gain	1.5m /0 dBi
Number of UEs per sector	10
UEs distribution	Homogeneous; pre-set positions
Transmission modes	CLSM (2 x2 maximum of 2 streams)
Frequency / Bandwidth	2GHz (reuse factor 1) / 20MHz

Number of iterations	100
D2D Tx parameters	1.5m height, 0dBi gain, Max Tx power: 0.2W
Schedulers	RR

The UEs are uniformly distributed within the sectors, and are attached to their serving eNodeBs based on the channel SINR (which is determined by the signalling from the eNodeBs). The D2D candidates are selected based on their distance to each other. If two UEs in the target sector are less than or equal to 10m apart, they are selected to represent a D2D UE pair. Subsequently for each TTI the simulator selects the transmitter (Tx) and receiver (Rx) of the D2D pair. It was assumed that the selected D2D pair UEs are scanned by its respective eNodeBs to see whether the UEs are in the same cell or in different cells. This is highly likely in a heterogeneous environment where the eNodeB or RRU (small-cell) has a small ISD. By determining whether the prospected D2D pair belongs to the same eNodeB or different eNodeBs the algorithm will decide the type of D2D communications taking place, inter-cell or intra-cell.

The system level simulator also accounts for any interference experienced by cellular UEs in the target sector originating from both the D2D transmitter and the neighbouring eNodeBs. Likewise the D2D receiver experiences interference potentially from both the target sector (home sector to the D2D UE pair) and its neighbouring sectors. Based on the simulated model shown in Figure 6-1 this would indicate target sector will experience interference from 7 eNodeBs.

6.3 Interference Mitigation in Hybrid Networks and Current Research Initiatives

To trigger interference between the two transmission modes, D2D and cellular UEs utilise the same frequency and time resources simultaneously. There are two main interference scenarios which affects cellular UEs' performance in the presence of D2D communications. Intra-cell and inter-cell interference are shown in Figure 6-4 [191]. Intra-cell interference concerns the D2D UEs, originated by the D2D UE (cell-edge UE) to cell centre UE when they are assigned by same resource from the eNodeB. Inter-cell interference's source is eNodeBs of other cells (neighbouring sectors), affecting both cellular and D2D UEs in the target sector. By default, in LTE-A there is negligible intra-cell interference due to the orthogonality of the subcarriers. However as already mentioned, severe interference will be present due to the operation of D2D communications sharing the same resource blocks on the same frequency at the same time with cellular users. Therefore, there is solid ground for developing techniques to mitigate those effects interfere allowing small-cell LTE-A networks benefit from the offered D2D advantages [104].

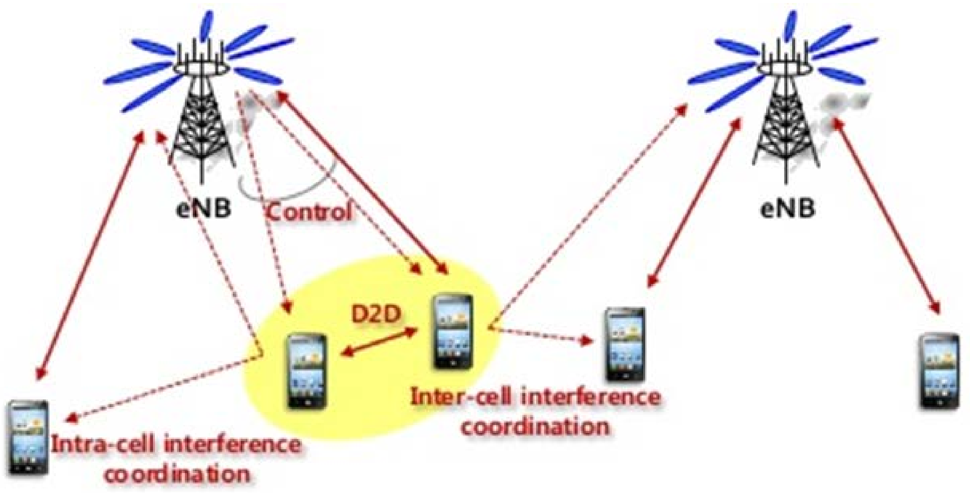

Figure 6-4: Two main interference scenarios in the D2D communication [104]

There are several solutions proposed in literature to overcome such interference. In [190, 192] the allocation of reserved resource blocks, which are orthogonal or separate from those of the cellular UEs, is proposed to more effectively utilise D2D by mitigating intra-cell interference but leading to low resource utilisation. Therefore the observed network throughput is expected to be relatively small, since both the cellular and D2D UEs will have limited available resources for transmission. In [193, 194], centralised coordination between sets of cells was considered in a multi-cell D2D network. Particularly in [194], a method where all UEs, both in cellular and D2D operating mode return instantaneous CSIs to the eNodeB was introduced, where both the D2D transmitter and eNodeB are continuously transmitting at full power. However this introduces massive overhead in the network in addition to requiring knowledge of UEs' location (geographical positions) to be able to implement the proposed interference mitigation algorithm. In [157], UEs interference was considered between the cellular and D2D channels within a single cell, abstracting the interference signals from the neighbouring cells. A power control algorithm was also proposed to minimise SINR degradation of cellular UEs. Finally a scenario was presented in [104] to remove inter and intra-cell interference, based on the coexistence of (CoMP) and D2D, introducing coordination and zero forcing algorithms.

Similar, in concept, to the last scenario, this chapter proposes to enhance small-cell performance by optimising the benefits of D2D while at the same time mitigating the induced inter and intra-cell interference between D2D and cellular users with the help of coordinated multipoint technology complemented in functionality by the novel receiver beamforming algorithms proposed in previous chapters. We target to minimise complexity/overhead and maximise resource utilisation for all UEs, both cellular and D2D.

6.4 Performance Gains of D2D Communication Underlaying Cellular Network Enhanced by Receiver Beamforming

The coexistence of D2D communications in the same topology with typical macro and small cell deployments, supported in their operation by receiver beamforming promise to reduce potential interference for both cellular and D2D UEs, while allowing the network benefit from high peak rates achieved due to the close proximity of D2D UEs and potentially favourable channel propagation conditions. It is also important to note that when devices communicate over a direct link, the end-to-end latency can also be reduced [195]. The reuse gain due to the simultaneous use of radio resources by both cellular and D2D links is fully investigated in subsequent sections, however the hop gain allowed by the use of either UL or DL to be fully committed to the transmission between D2D transceivers, also providing an advantage of the implementation of D2D communications is not covered in this study [99].

It is proposed that, the cellular infrastructure provides the necessary control to efficiently manage the operation of the D2D links with the purpose of exhibiting inter and intra-cell D2D communications enhanced by receiver beamforming. One of the primary limitations of D2D technologies is the lack of efficient device discovery and connection management [196]. Given limited battery lifetime on mobile devices, the power needed for device discovery and D2D connection establishment is unacceptable to most users in addition to the lack of efficient, robust service continuity limits the kinds of services a user will engage in over D2D. However by using network assisted D2D topologies the involvement of eNodeB can significantly reduce the overheads and requirement on UEs which have limited abilities. Network assisted D2D communications in cellular spectrum can take advantage of the proximity of communicating devices, allow for reusing resources between D2D pairs which can lead to power savings, increased throughput, and higher spectrum efficiency [197].

[198] provides an example of how the cellular network or eNodeBs can assist with the D2D session setup. [52] describes a peer discovery method where 2 UEs in close proximity are assigned by cellular UEs to a D2D pair (D2D transmitter and receiver). If the serving gateway detects potentially the propagation of D2D traffic for UEs at close proximity a network assisted D2D session could be set up by the eNodeB [52]. Figure 6-5 presents intra and inter-cell D2D deployments as the two scenarios used to evaluate the performance of the coexistence of D2D and cellular mode UEs in a small and macro cell environment.

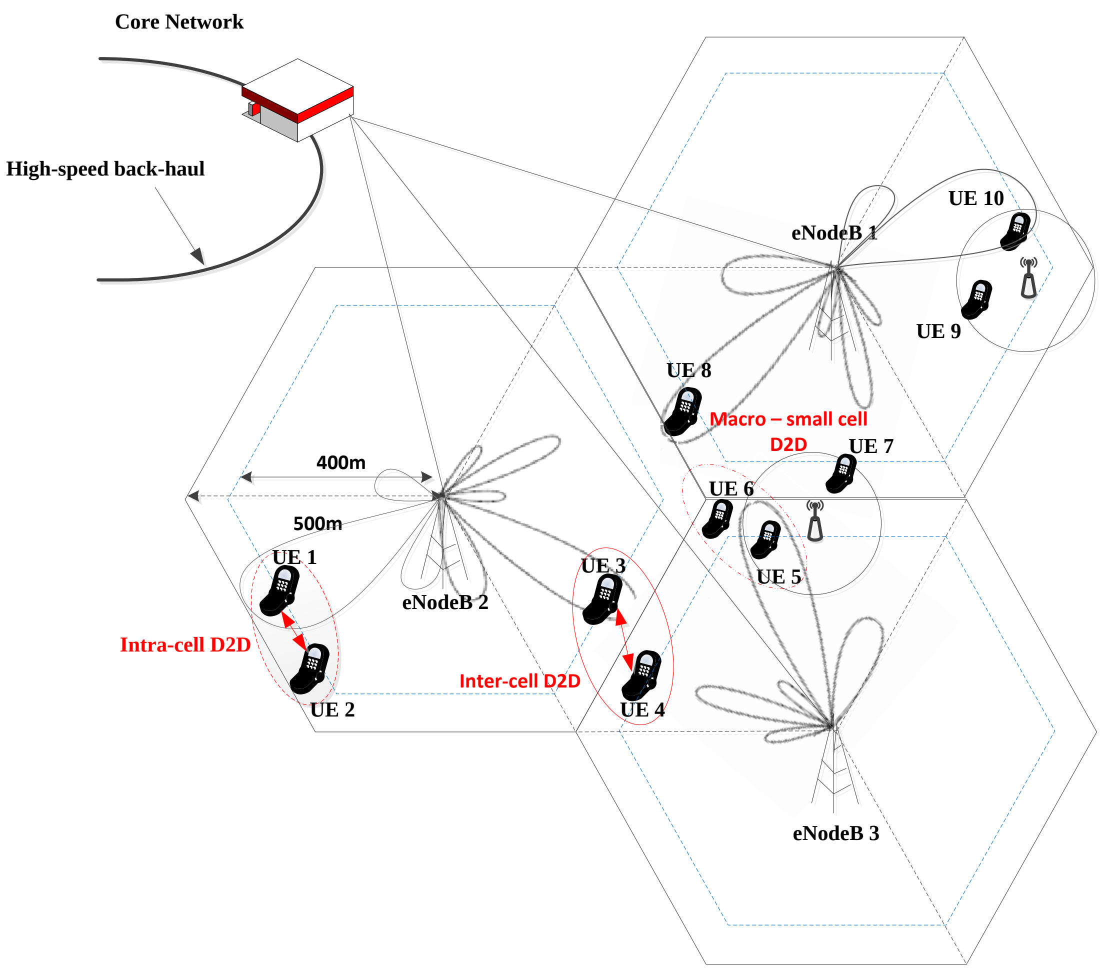

Figure 6-5: Intra and Inter-cell D2D communication in a heterogeneous network

As shown in the Figure 6-5, if a pair of cell-edge UEs are in close proximity; this pair is selected to establish D2D communications. If both users are inside the same sector (e.g: UE1 and UE2) intra-cell D2D is implemented. If UEs are in different sectors (e.g: UE3 and UE4) inter-cell D2D can be explored. Figure 6-6 demonstrates the flow chart summarising the mode selection process, newly added in the system level simulator to further enhance its operation supremacy, and determine whether an UE operates in cellular or D2D mode.

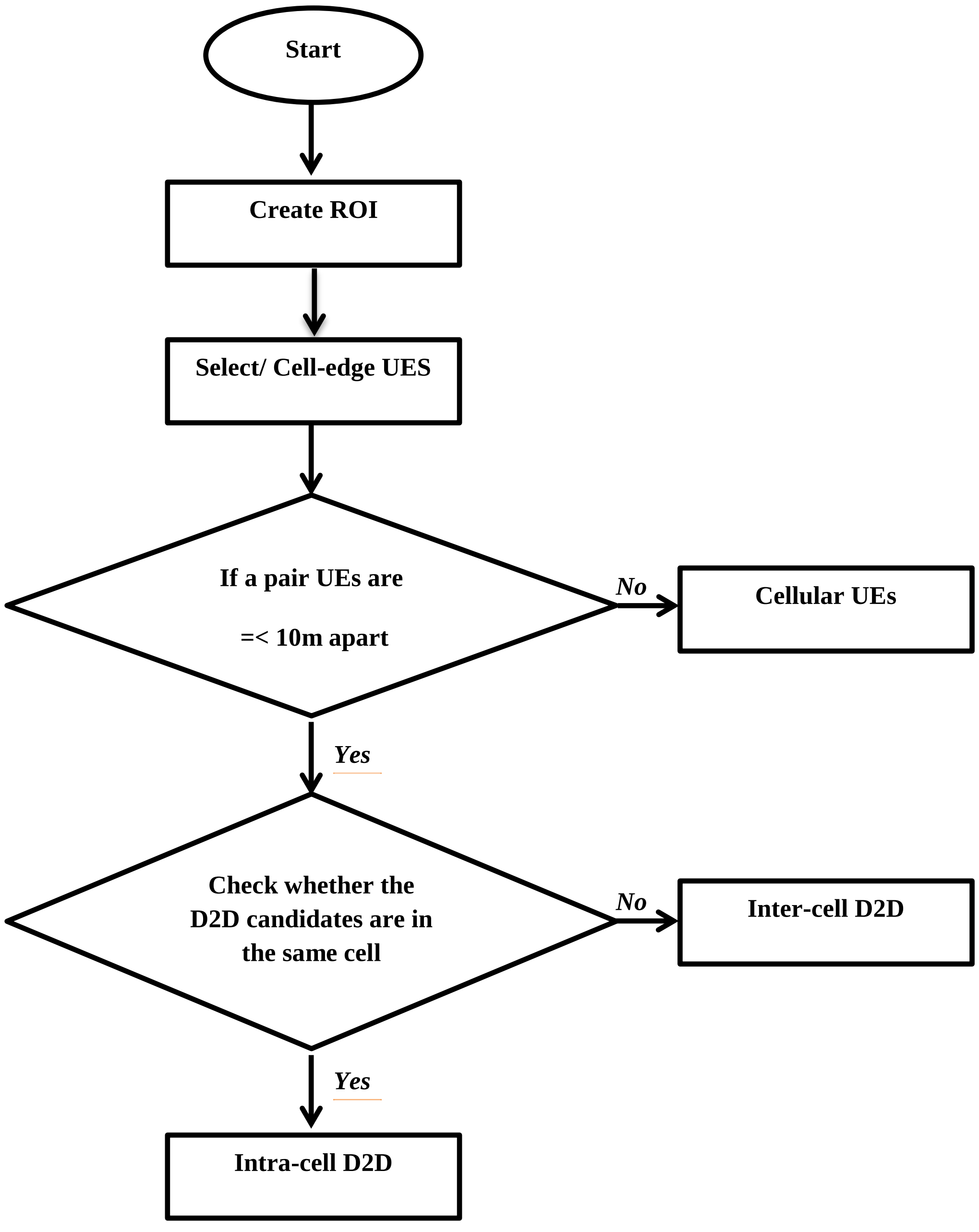

Figure 6-6: Pseudo code for the mode selection for UEs

Interference from neighbouring eNodeBs surrounding the target sector was taken into consideration especially for the scenario with inter-cell D2D. This is due to the fact that performance of UEs in the target sector will be affected by the presence of interference from neighbouring eNodeBs due to signalling and transmissions (especially at the cell-edge) in addition to the interference imposed by the D2D transmitter. It was assumed, similar to previous chapters that eNodeBs have the knowledge of the positions of the D2D UEs in the network. By knowing the exact positon of the D2D transmitter (primary user) and the receiver, receiver beamforming technique is then applied at the eNodeB by creating a null towards the D2D transmitter, minimising therefore the interference presenting itself between the D2D UEs and eNodeBs. Scheduling is performed accordingly (eNodeB as discussed above). It should be taken into consideration that for inter-cell D2D coordination the UE location information in addition to network related information such as Channel State Information (CSI) which includes CQI, Pre-coding Matrix Index (PMI) and Rank Indicator (RI) informed by the UE (D2D or cellular UE), should be exchanged between cooperating eNodeBs to be able to perform receiver beamforming. However to ensure a D2D communication is sufficiently simulated in the model and adequate results are gathered for analysis, D2D UE positions have been fixed.

To start with the performance evaluation, the throughput distribution in the target sector (sector 13) between D2D UEs and all the UEs (cellular and D2D) is initially presented. A total of 1000 samples were considered for each UE (both cellular and D2D receivers), the measured SINR of each UE has been averaged over 100 TTIs and multiple iterations run in the simulation to record the most accurate results possible.

Figure 6-7 demonstrates the impact of D2D TX power to cellular UEs in an intra-cell D2D environment with 10m proximity.

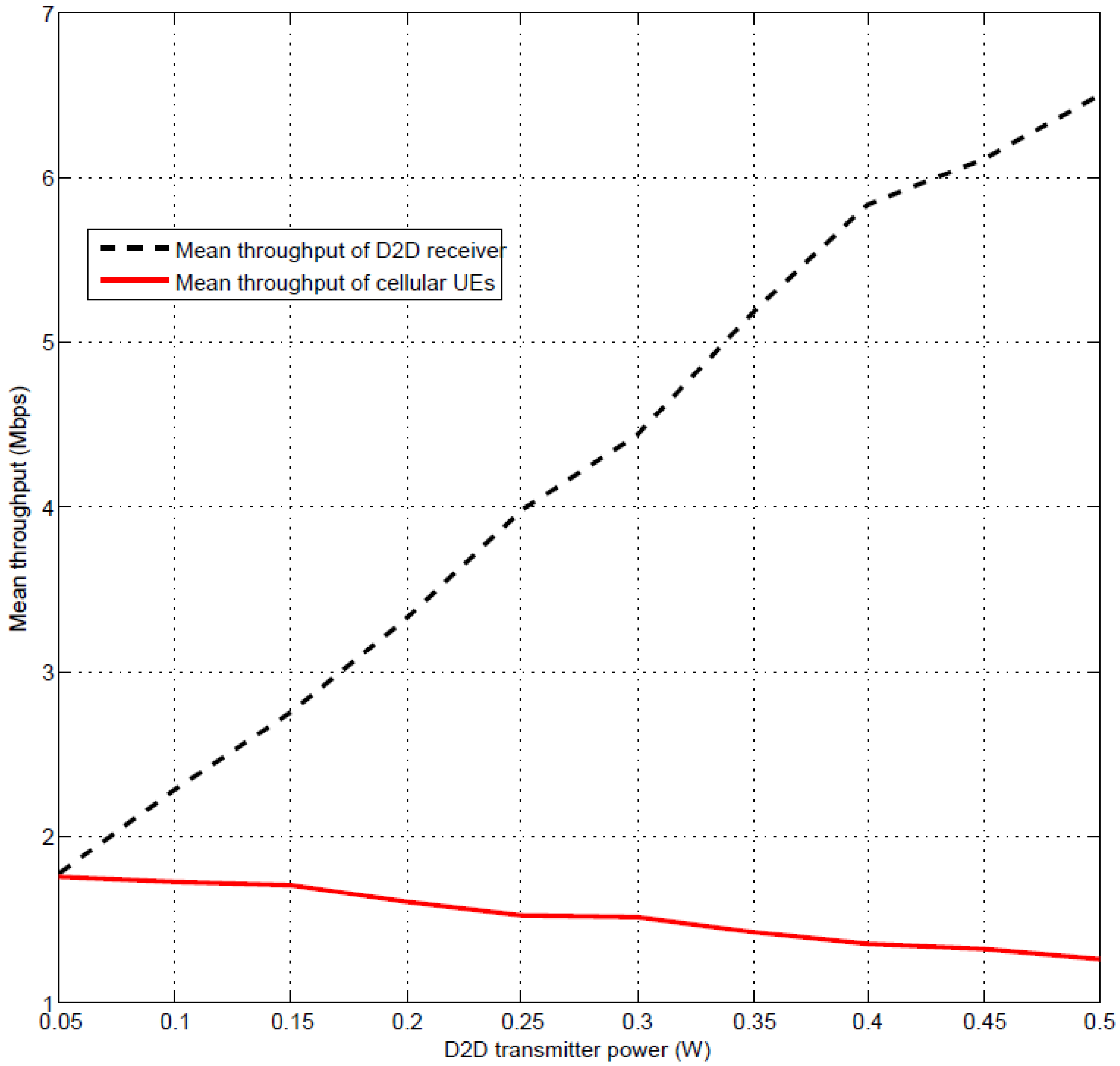

Figure 6-7: Impact of D2D TX power to the cellular UEs in an intra-cell D2D

As a first observation, Figure 6-7 confirms that even at very low D2D transmitter power the mean throughput of the D2D receiver was similar to that of cellular users' (1.8Mbps at 50mW). By increasing the D2D transmission power, it is observed that the cellular UEs' performance remains initially unchanged and thereafter decreasing, due to the impact from the interference generated by D2D transmission. At the same time the increased transmission power resulted in a better and significantly increasing overall mean D2D receiver throughput compared to cellular UEs. At 500mW D2D enjoy data rates at approximately 6.5Mbps in contrast to cellular UEs that due to interference operate slightly above 1Mbps. The results presented in following sections aim to demonstrate how the applied interference mitigation techniques help increase the target sector overall performance. In that sense, the network throughput was evaluated in the absence of any CoMP (as shown above), the application of CoMP with receiver beamforming and finally in the presence of both D2D and receiver beamforming. In all cases the D2D receiver is assumed to maintain a fixed position to ensure a common reference is established for comparison purpose.

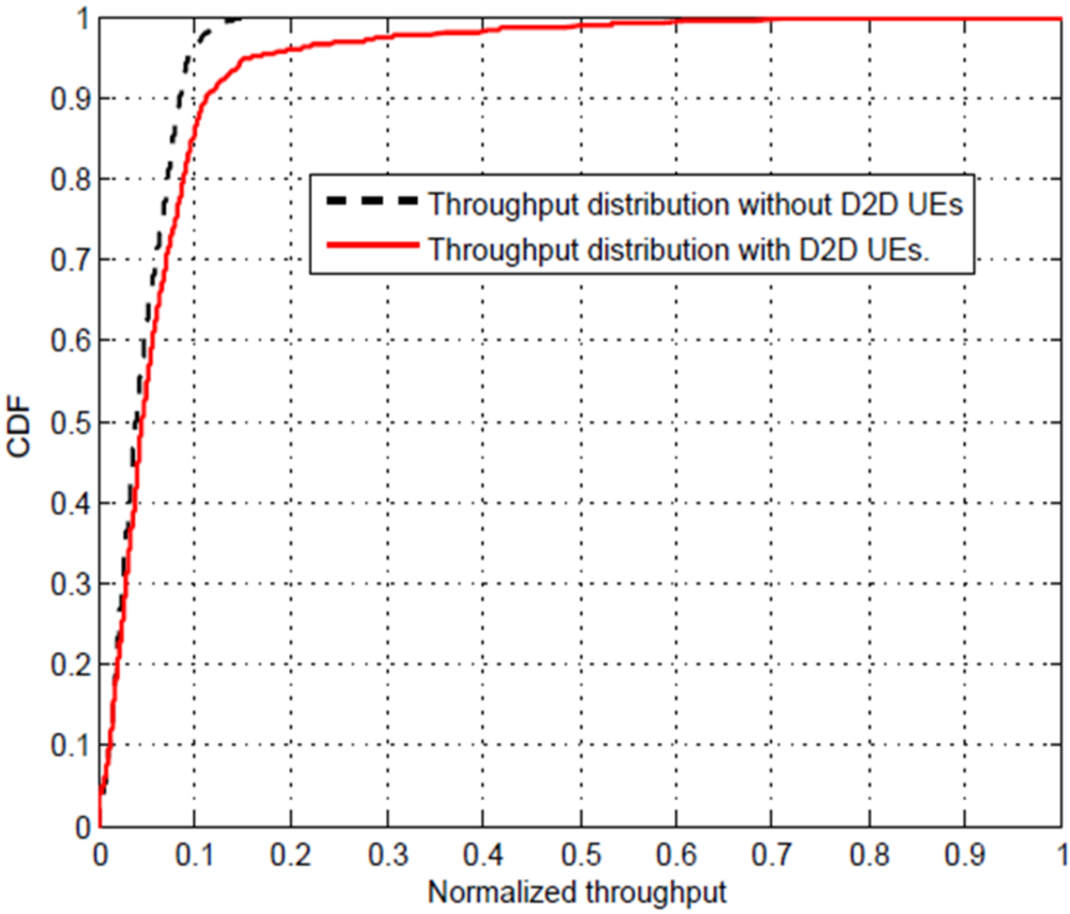

Figure 6-8: Normalized CDF of UEs goodput distribution with and without D2D transmission

Figure 6-8 therefore presents the normalised network CDF with and without D2D UEs.

The latter emulates a network with only cellular UEs with both eNodeB and D2D transmitters operating at maximum power. The minimum distance between a D2D pair is 10m during the simulation. The throughput distribution of the target sector (sector 13) for both D2D UEs and for all the UEs (cellular and D2D) are presented in Figure 6-8. Throughout the simulation it was also assumed that both the D2D transmitter and target sector eNodeB are transmitting at maximum power (max. power) throughout the simulation following from the performance figures, observed in Figure 6-7. The throughput of UEs in the target sector is represented using a normalised CDF. Here the 5th percentile represents the cell-edge performance, UEs which are furthest from the eNodeB or having poor channel conditions, while the 95th percentile shows the best UE performance in the target sector.

Even for the study case where a single D2D UE pair only cooperates with cellular UEs, the throughput gain achieved by all UEs in the target sector has still been shown to increase. This trend is more significant in the 70th percentile and above (the higher end of the distribution) illustrating notable throughput improvement when D2D UEs are there compared to their cellular counterparts. The graphs show that the D2D end UEs performs better on an average of 94.8%.

However, the throughput degradation caused from the interference impact of the D2D transmitter in the hybrid network at the cell-edge UEs is less than 25% when a pair of D2D UEs is included in the sector. D2D communication was modelled to be network assisted where the sector eNodeB has some control over the D2D transmission, where the D2D transmitter reuses the resource blocks of its occupying sector simultaneously with the cellular UEs.

A receiver beamforming technique has been therefore implemented to minimise interference and increase the cell–edge throughput when there is a D2D pair inside the sector. Figure 6-9 following shows the throughput distribution for the intra-cell D2D scenario.

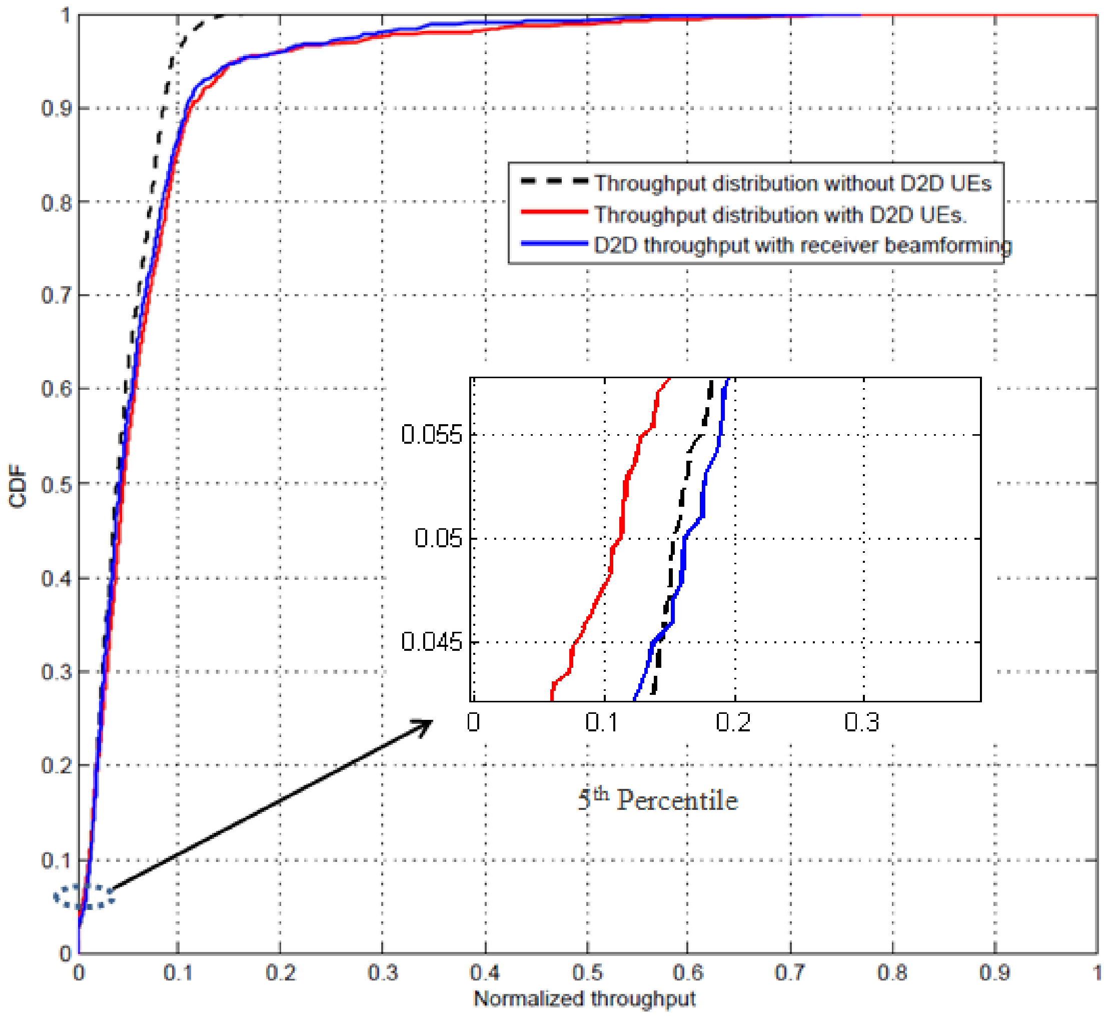

Figure 6-9: Inter-cell D2D communication with compared to no D2D and D2D with receiver beamforming

Following the application of receiver beamforming, the drawn characteristic clearly confirms that the cell-edge throughput has increased in the presence of D2D. Without a proper interference mitigation technique the cell-edge throughput had decreased by 25%, however with receiver beamforming it has improved by 6% and 42% compared to without D2D and with D2D respectively. The best UE performance in the target sector (95th percentile) corresponds to a 72% improvement compared to the non D2D scenario.

6.5 Summary

D2D communications is one of the promising add-on technologies able to provide the projected data rate increase of 10Gbps in future wireless networks. One of the advantages of D2D is that it can reuse the cellular network resources while requiring only small amounts of transmission power. It does not need additional infrastructure for implementation, as opposed to implementing small-cells in a HetNet environment. In this chapter, inter-cell D2D communication has been studied where potential UEs of neighbouring cells at close proximity to the target cell-edge for both Macro-Macro or Macro combined with small-cells scenarios, communicate directly when there is a better channel gain compared to their respective base station links.

The performance gain of the proposed technology was evaluated using the state-of-the-art SLS implemented in preceding chapters with yet additional functionalities. Simulations results confirm that a D2D receiver can attain over 3Mbps mean throughput at close proximity (10m) and maximum transmission power from the D2D TX, which is better than 2Mbps achieved by cellular mode UE at close proximity and/or similar channel conditions from its serving eNodeB.

The impact of interference from the D2D transmission in the hybrid network consisting of UEs in both cellular and D2D mode is higher compared to a traditional cellular network. The cell-edge performance of the target sector has been shown to reduce its throughput with over 100Kbps with just a single D2D pair transmission inside the sector. Therefore interference mitigation using a CoMP algorithm was implemented with the aim of achieving the performance gain of including the technology, while restoring the performance degradation to a minimum at the cell-edge of the investigated sector.

With just a single pair of D2D UEs the achievable throughput gain of UEs in the sector has been shown to improve. Compared to the cellular users in the same sector (target sector) the D2D receiver performs better on an average of 94.8%. Really low throughput degradation is achieved due to the network assisted D2D. However, the throughput degradation caused from the interference impact of the D2D transmitter in the hybrid network at the cell-edge UEs is less than 25%. By using receiver beamforming to reduce the interference in the inter-cell D2D scenario, the cell-edge throughput has improved by 6% and 42% compared to without D2D and with D2D scenarios respectively. The best UE performance in the target sector (95th percentile) has a significant improvement of 72%.

Chapter 7

7. Research Summary and Future Work

7.1 Introduction

Over the last few years the demand for accessing the internet using mobile devices has increased rapidly. At the same time, continuous reduction in terminal costs and mobility has played a major role in gaining the popularity of mobile communication. To provide the solution for this growing demand the candidate solution should be able to provide a framework for high mobility broadband services and cell edge performance. Following the successful standardization of High Speed Packet Access (HSPA), the 3rd Generation Partnership Project (3GPP) specified the universal mobile telecommunications system (UMTS) terrestrial radio-access network or UTRAN LTE to meet the above mentioned increasing performance requirements of mobile broadband. The network evolution has led to the currently deployed 4G network standards such as the LTE and LTE-Advanced. The LTE rel.8 network is specified to provide up to 100Mbps and 60Mbps DL and UL respectively and up to 1Gbps DL and 500Mbps UL for the LTE-A release 10 and beyond [17]. When compared to LTE Rel.8, LTE-Advanced provides lower latency and round-trip delays (5ms), better peak spectrum efficiency (downlink: 30b/s/Hz; uplink: 15b/s/Hz), reduce inter cell interference, and support coexistence between the various flavours of cells macro-cells, micro-cells, femto-cells, and so on [17, 76]. However with the advantage of fast backhauling using optical networks, can provide the bandwidth advantages of the optical networks and mobility features of the wireless networks for subscriber stations even though interference becomes a critical issue when providing higher bandwidth and spectral efficiency in the wireless domain. With the emergence of ultra-dense networks with small-cell deployments require a high degree of coordination to mitigate the strong inter-cell interference. It can also be seen that with the emergence of Internet of Things (IoT), smart grids, Machine-to-Machine (M2M) communication to mention a few, more bandwidth is required in the uplink since users are demanding bandwidth for internet services in uplink.

In this direction it can be seen that in the present day, the demand for uplink communication has become a critical factor, same as downlink data transmission which was the main concern few years back. A major limiting factor in the current 4G networks and future 5G networks is the issue of cell-edge user performance degradation (in both DL and UL) due to the inter-cell interference, with some of the other limiting factors such as fading, path-loss, and transceiver equipment constraints amongst others.

LTE-A an Orthogonal Frequency Division Multiplexing (OFDM) based network utilize a frequency re-use of one (denoted by N = 1). A frequency reuse of N = 1 implies that the base stations in cells transmit on all available time frequency resource blocks (RBs) simultaneously [148]. As its advantages, it increases the inter-cell interference resulting the interference limited system for N = 1 deployment to not to achieve the full potential capacity that the LTE/ LTE-A standard can support. This has to be overcome by the implementation of one or more viable interference mitigation and/or cancellation techniques at the base station and mobile terminals. Due to transmit power limitations in mobile terminals, the constraint on the uplink link budget will necessitate the need for smaller cell sizes or better interference mitigation techniques at the base stations. This requirement is driven by the need to meet targeted higher data rate throughputs for users not only near the base station, but also for cell edge users. The trend of increasing demand for high quality of service at the user terminal or user equipment in 5G networks, coupled with the shortage of wireless spectrum, requires more advanced wireless communication techniques to mitigate inter cell interference and increase the cell edge throughput.

In this direction CoMP has been identified and proposed as a solution to overcome the aforementioned bandwidth bottleneck in the wireless networks due to interference. Coordinated multi-point transmission and reception is a network multiple-input multiple output (MIMO) transmission technology being considered for the 3GPP LTE-Advanced standard [32], and a promising candidate for future 5G cellular standard being developed by 3GPP standardization group [39].

Cell edge users mostly suffer from throughput reduction due to bad coverage and consequently unexpected uplink transmission delays. Hence, in order to increase the reliability and capacity of the services for the UEs at the cell edges, CoMP utilizes cooperation among neighbouring eNodeBs [32, 53]. In this technique, antennas of multiple cell sites are used in such a way that they can contribute to increase the quality of the received signal at the eNodeB and drastically reduce the inter cell interference. CoMP transmission and reception techniques are based on cooperation between different base stations using a fast backhaul network. To achieve this, very fast inter-eNodeB connections are needed. There are mainly two types of CoMP that differ in the degree of coordination which are known as co-ordinated scheduling/beamforming (CS/CB) and joint processing/ reception (JP/JR) [32].

Moreover, numerous candidate technologies such as D2D communication, and Heterogeneous networks (HetNets) are projected as key influences in achieving the dramatic data rates anticipated for the future 5G networks [7, 55]. Device-to-Device communications underlying cellular networks have been recently proposed as a promising technology to satisfy the increasing demand for local data traffic, and also to provide better user experience in the next generation 5G cellular networks. D2D technology enables UEs in close proximity to communicate directly. This helps the eNodeBs to reduce UE traffic (by taking some load off the eNodeB) and maximise cellular resource block utilisation amongst other advantages.

One of the main enhancements for future 5G wireless systems is integrating the standard coverage of traditional macro-cells with small cells of reduced dimensions. Therefore from the current use of the scheme to increase cell capacity and improve cellular user experience in a macro-cell environment by minimizing the interference for inter-D2D communication was considered.

In this direction the scope of this research is mainly focused on the UL performance of the future generation 5G networks (i.e. the link from the UE to the eNodeB) in interference mitigation and allocation of resources. Hence this thesis address these issues by first of all implementing and optimising an efficient state of the art uplink LTE system level simulator platform in order to accurately and timely obtain performance metric for the UEs in the network.

7.2 Thesis Summary and Outcomes

This thesis has provided a high level overview of the evolution of LTE and LTE-A technologies, considering the emerging need for achieving multi-Gbps data rate for future 5G networks by providing solutions to overcome the above challenges. New technologies and architectures providing such services at low cost and high efficiency to the operators and end users are taken in to consideration. Comprehensive literature review was followed as the initial stage. When considering about the wireless technologies, LTE and WiMAX were recognised as the major candidates for 4G. The carried out literature survey revealed that even though LTE and WiMAX are very alike, LTE has gained more popularity mainly due to its backward compatibility for legacy systems such as GSM and HSPA, in addition to higher bandwidth with increased overall system capacity, higher mobility, reduced latency, improved spectral efficiency and cell-edge performance compared to WiMAX. According to a survey by Global mobile Suppliers Association (GSA) (an association with members such as Qualcomm, Ericson, Huawei, etc.) and the GSMA intelligence data, there were 352 operators with live commercial 4G-LTE networks globally as of the end of January 2015, with more than half of the world's mobile markets covered by at least one LTE operator. LTE-A in other hand fulfils and even suppress the IMT-Advanced requirements, is a very attractive option for an operator to meet the current demands on mobile broadband.

From the carried out study it is anticipated that trillions of wireless nodes in IoT with diversified applications and services which will be available in future 5G networks may not be handled efficiently by the current wireless communication networks. Hence 5G studies are gaining more momentum worldwide and there are several individual and independent projects and research initiatives working on 5G which includes METIS and METIS II, 5GNOW, Combo, MOTO, MCN and iJOIN, etc. Adopting new protocols, acquiring additional spectrum, and/or implementing additional supporting technologies are some measures identified in this study to achieve the dramatic data rates increase in order to enhance the network capacity. Some of these technologies include CoMP techniques such as coordinated scheduling beamforming, joint reception, smart or adaptive systems, HetNets and D2D communication underlaying cellular networks which were considered in this research.

One of the major limitations of current wireless communication in general is the limited radio spectrum availability, which is not only finite and very congested. Another key limiting factor for the current 4G network is inter-cell interference which will significantly lower the spectral efficiency of the cell edge users. Hence, this thesis focuses on efficient spectrum utilisation and interference mitigation uplink in the currently deployed 4G networks as an initial step towards achieving the implementation of the future 5G network. In order to overcome the above mentioned challenges key functionalities such as inter-cell coordination (CoMP and smart antennas) and technologies such as D2D communication were taken into consideration. In order to test these algorithms and techniques however, an efficient simulation platform is required to accurately represent the network. This greatly reduces CAPEX as the algorithms are critically tested and analysed prior to field deployment or enhancements. Hence as a part of this study a state of the art simulator is modelled to enable research in wireless communications and implement and investigate novel techniques/ algorithms for/in Co-ordinated MultiPoint (CoMP), small-cells (heterogeneous networks) and Device-to-Device (D2D) underlaying cellular communication as a step towards achieving next generation networks. This model covers the links between multiple eNodeBs and UEs (Multi-cell multi-user) which enables realistic investigation on network related issues such as interference management and network planning optimization for both rural and urban environments.

To that extent, to investigate the aforementioned techniques a comprehensive system level simulator was developed using MATLAB. It follows the 3GPP specification for the LTE-A network features and characteristics. This includes path-loss models, eNodeB/UE specifications, MIMO/ smart antenna configurations, appropriate channel models such as WINNER II model and the defined channel bandwidths amongst other features of the 4G network standard. The system level simulator was implemented by abstracting the link-level functionalities (i.e. the physical layer) with sufficient detail and high accuracy, and then performing link-level to system-level mapping (L2SM). By abstracting the link-level functionalities using a link quality model (LQM), where it outputs an SINR metric that is mapped to a link performance model (LPM) to determine the block error rate (BLER). This will be then used to determine the throughput of the UEs in a multi-cell network environment. To attain accurate results for different environments the simulator was run for several numbers of iterations, where the UE performance is averaged over multiple TTIs.

The simulator was then used to study the effects of CoMP techniques in uplink. By using the CoMP techniques to achieve interference avoidance/cancellation in the uplink, the system throughput and spectral efficiency can achieve significant improvements at the cell edge. By coordinating and combining signals from multiple antennas, CoMP helps to deliver a more consistent user experience for users on the cell edge or moving into new cells and instigating a handover. It can essentially turn the signal interference at the cell edge into a useful signal and help operators optimise their network. Hence a novel uplink CoMP beamforming technique ''receiver beamforming'' was introduced. This technique is based on the concept of antenna reciprocity at the eNodeB to focus its receiver beam at a specific area using smart adaptive antennas to improve the uplink signal-to-interference-noise-ratio (SINR) and also to achieve interference avoidance of cell-edge users. Smart antenna or adaptive antenna array technology allows the performance of the antenna to be altered to provide the performance that may be required to undertake performance under specific or changing conditions in the cellular network. Antenna adaptivity in the proposed technique is complemented by the presence of switched antenna beamforming applicable to selective cluster UEs saving on processing power at the eNodeB. By using this algorithm the eNodeB can steer its receiver beam at specific set of UEs or an area by taking the location of UEs into consideration. It can be observed from the gathered simulation results, that by using the receiver beamforming technique in an appropriate configuration at the base station, it will offer significant benefits in system performance. System level simulations of a complete cellular network have demonstrated in average 50% increase in spectral efficiency at the cell edges compared to a scenario where receiver beamforming is not applied.

Furthermore, a novel cooperative uplink Inter-Cell Interference (ICI) mitigation algorithm based on joint reception at the base station using receiver adaptive beamforming was investigated. The concept of smart adaptive receiver antennas, using antenna reciprocity, is adopted to enhance the CS/BF and joint reception algorithms. The eNodeBs process the joint scheduling decisions for individual mobile users to be made based on the information received from different cells. As a result, uplink user transmission is scheduled according to the known positions of other users in order to minimise ICI. This is enhanced in operation by the proposed novel advanced receiver beamforming technique that in corporation has the potential to improve the overall uplink capacity. The eNodeB global view at the central office is exploited to effectively allocate transmission across the whole network. Compared to CS/BF, joint reception with receiver adaptive beamforming shows a 76% and 52% improvement in cell edge throughput for 1x2 and 2x4 antenna configurations respectively. In addition, the proposed joint reception scheme demonstrated an increase in the cell edge spectral efficiency in average by 60% compared to the cooperative scheduling. For a high-speed scenario, it can be observed that CS/BF increases the overall spectral efficiency by 68% and joint reception with beamforming by two times compared to non-CS/BF scheme for a 2x4 antenna configuration. In a heterogeneous network environment with only one small-cell in the target sector will have small impact of 7% increment in the cell-edge throughput with receiver beamforming. But when the number of small-cells is increased up to 3 inside the macro-grid, a significant improvement of 57% can be achieved by using the receiver beamforming technique since it minimises the interference substantially. For a heterogeneous network with a higher number of small-cells, use of adaptive antennas for joint reception can provide better interference mitigation.

Particularly, inter-site/cell coordination and critical evaluation of D2D communication underlaying the cellular networks have been carried out in this research. The solution for the inter-site/cell coordination in this thesis was provided by implementing a CoMP algorithm, employing the CoBF/CoSH techniques to improve cell edge UE performance. The D2D evaluation features solution to key issues anticipated for the technology's implementation in the forthcoming networks, in terms of interference management and performance enhancement of the technology itself. Therefore as the final stage D2D underlaying cellular communication has been modelled and studied as one of the promising add-on technologies to realise the projected data rate increase in the future wireless networks. One of the advantages of the D2D technology is that it reuses cellular network resources while using small power transmission. D2D communication (inter-cell D2D communication) where potential nearby UEs (especially at the cell edge) in different cells (Macro-Macro or Macro and small-cells) communicating directly when there is a better channel gain compared to their respective base stations was studied. . The result shows that a D2D receiver can attain over 3Mbps mean throughput at close proximity (10m) and maximum transmission power from the D2D TX, which is better than 2Mbps achieved by cellular mode UE at close proximity and/or similar channel conditions from its serving eNodeB. With just a single pair of D2D UE the achievable throughput gain of UEs in the sector can be improved. Compared to the cellular users in the same sector (target sector) the D2D receiver performs better on an average of 94.8%. A really low throughput degradation is achieved due to the network assisted D2D communion is considered in this study. However, the throughput degradation caused from the interference impact of the D2D transmitter in the hybrid network at the cell edge UEs is less than 40kbps when a pair of D2D UEs is included in the sector. By using receiver beamforming to reduce the interference in the inter-cell D2D scenario, the cell-edge throughput has improved by 6% and 42% compared to without D2D and with D2D (non-CoMP) scenarios respectively. The best UE performance in the target sector (95th percentile) has a significant improvement of 72% compared to the no D2D scenario.

7.3 Future Work

This section summarises the key features and areas that could be further investigated, in addition to the achievements in this thesis. In this thesis critical evaluation of the uplink inter-cell interference and the solutions to overcome was studied. A novel solution based on smart antenna systems was proposed to overcome the interference issue in current 4G and future generation networks in chapter 4 and 5. The technologies investigated in this research study and solutions proposed can be further enhanced by exploring additional technologies to support them.

The proposed CoMP receiver beamforming techniques in this research yielded substantial improvement in the cell edge performance by mitigating the interference, however it requires coordinated resource allocation/ beam forming between cooperating sites, where all the resources to a single UE is allocated by its serving eNodeB. Uplink joint reception using receiver beamforming technique developed in study requires the signals from several antennas in the network to be routed to a central baseband receiver, where they can be combined and used in the detection process for every user. Both CoMP schemes proposed employ the X2 interface to exchange information between the cooperating cells/ eNodeBs. The X2 is a logical interface that is established in the EPC to make possible a communication path between eNodeBs in the LTE network [199]. The interface is used to carry out handover processing and/or achieve coordination by exchanging signalling information between eNodeBs. One of the disadvantages with these techniques is that large amounts of data need to be transferred between the eNodeBs (using the X2 interface) for it to operate. Uplink CoMP techniques like joint reception, needs real time and great amount of data exchange among eNodeBs and centralized data processing. One efficient approach to reduce the signalling overhead and backhaul requirement of joint reception is clustered cooperation [200], where TPs within the same cluster coordinate to serve users in this cluster; some form of inter-cluster interference management may also be performed. For the further evolution along this path, as an upgrade to the backhaul links, a more radical approach for coordination has been proposed recently, which is the cloud radio access network (C-RAN) [201].

Centralised baseband can be achieved by the use of CRAN deployment. By using the centralised approach scheduling decisions can be coordinated among cells to control interference with minimum latency. In a heterogeneous environment the cooperating units can be separate eNodeBs' or RRUs in different instances. CRAN is an evolutionary step in base station implementation where Radio Remote Heads (RRHs) are connected using an optical transport unit to a central office, responsible for all Baseband Unit (BBU) processing [170]. The CRAN architectures which 3GPP standard complied enjoys significant benefits including energy efficiency due to less power consumption and site support equipment due to the consolidation of BaseBand Unit (BBU) processing. It will significantly lower the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) which leads to significant cost savings on site rentals and maintenance. Advanced transmit and receive techniques such as CoMP can be implemented using the CRAN infrastructure, due to very low latency in the core, leading to remarkable network capacity improvements. BBU pooling can serve as a local breakout point to offload core network traffic to different network nodes as well as different radio access technologies if available [40, 112].

As described in Figure 7-1, the CRAN network includes a central office connecting several remote radio heads (RRHs) via a high speed optical fibre [202]. A point to point connectivity has been described however other topologies, such as tree based passive optical networks [43], are also possible. Complete eNodeB baseband processing and resource allocation is performed centrally resulting in a very simplified RRHs designs. Inter-antenna communication for the cooperative transmission is established within the central location thus reducing significantly the latency [43]. DOA estimation algorithm used in the proposed algorithm causes time delay and extra computational load, however by using centralized processing, each BBU at the central office is aware of the overall distribution of all UEs across the network which will avoid the exhaustive search through all possible angles to estimate the DOAs. Therefore the CRAN approach can be investigated to enhance the proposed techniques to achieve the latency requirements in the future 5G networks.

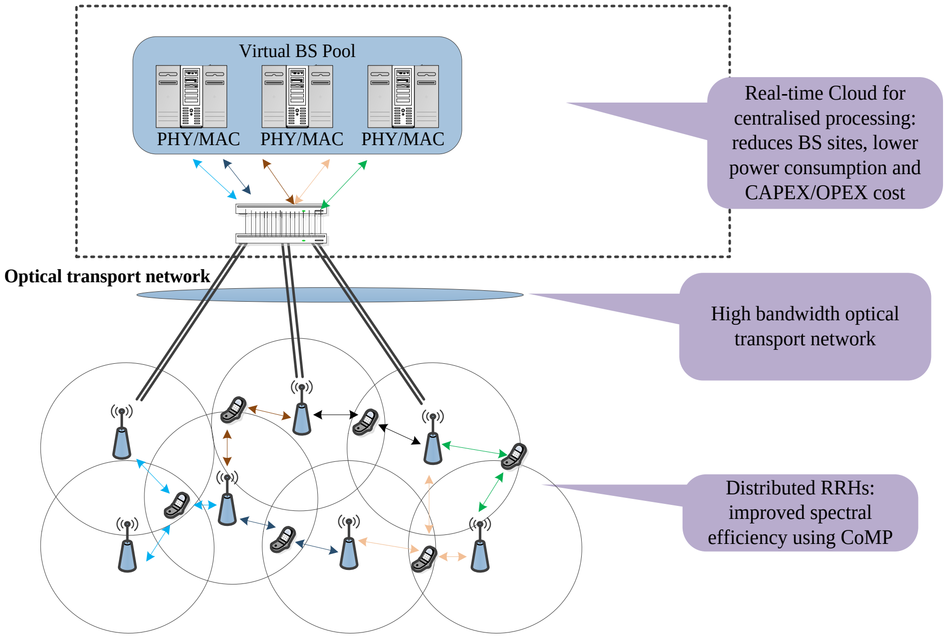

Figure 7-1: High level representation of CRAN network [199]

Figure 7-2 illustrates coordinated scheduling and joint reception in CRAN environment.

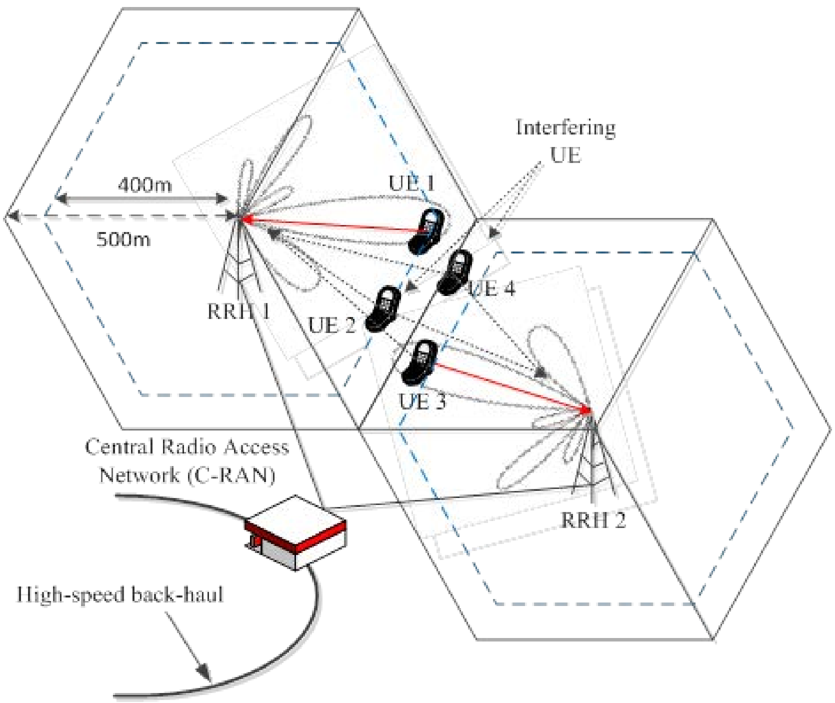

Figure 7-2: Joint reception in CRAN environment

In this approach the actual implementation of uplink CoMP requires changes on the network side (RRH side). RRHs can share the received data via backhaul and with reduced latency at the central office due to the centralized processing capability.

Another possible direction is using the CRAN to enhance the D2D communication technology by combining it with other equally promising technologies such as CoMP receiver beamforming and joint reception. As the UE capabilities are limited, a CRAN based architecture can be employed/ considered, so that neighbouring RRHs can relay channel gain information to potential D2D UEs with minimum overhead and reduced latency. Adaptive antenna techniques can be used to increase the interference reduction capability of antenna arrays in CRAN based architecture where centralized and coordinated baseband processing among base stations become feasible.

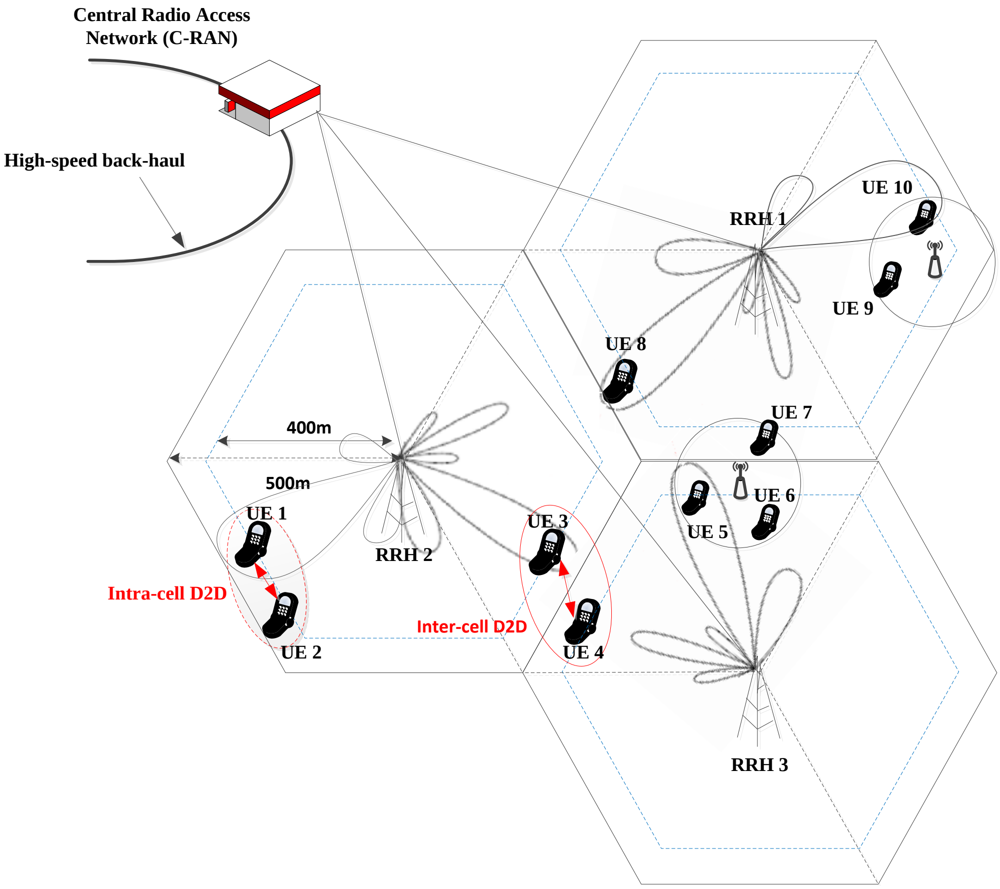

Figure 7-3: D2D communication in a CRAN environment

Figure 7-3 depicts the D2D communication in a CRAN environment. In network assisted D2D the involvement of RRH can significantly reduce the overheads and requirement on the UEs which have limited abilities. Centralised processing could be a key solution to minimise the delay and overhead limitations in implementing key algorithms in the future cellular networks. Compared to the algorithm implemented in this research study, the SINR evaluation feedback from a cluster of eNodeBs will further consider interference from D2D transmission in neighbouring sectors. Therefore by using the CRAN implementation the proximity of the eNodeBs in the pool and fibre links interconnecting the RRUs would effectively reduce latencies/overhead and ensure fast exchange of control information in the hybrid network.

In addition to architectural improvements mentioned above multi-antenna technologies such as Massive MIMO has attracted great attention from both academia and industry. Therefore it is worthy investigating the possibility of combining receiver beamforming technique with Massive MIMO systems. Massive MIMO consist of equipping base stations with antenna arrays composed of a large number (100 or more) of small antennas plugged together. Ideally, with a widely separated antenna array, each additional element adds a degree of freedom that can be exploited, which introduces very attractive advantages. By relying on signal processing combined with receiver beamforming, Massive MIMO can increase the link capacity and at the same time improve the radiated energy efficiency. This is achieved by focusing signal strength in a specific direction and creating very narrow radiated beams which made possible by the large number of antenna elements available. Hence, it is possible to efficiently transmit or receive independent data flows to different user terminals during the same time-frequency block, thus exploiting spatial separation of the users (multi-user beamforming) in downlink and by using the high beam resolution to split, in the angular domain, different signals arriving in the same time/frequency slot in uplink [201].

In 5G research, more interest will be given to high carrier frequencies which provide offer significant opportunities such as higher bandwidth and smaller antenna elements. With more antenna elements and small size it becomes possible to for vendors to perform receiver beamforming in the heterogeneous networks where it can be implemented inside the small cells. This will give significant improvement in interference mitigation compared to the omni-directional small cell antennas [201]. Figure 7-4 illustrates receiver beamforming at the secondary transmitter.

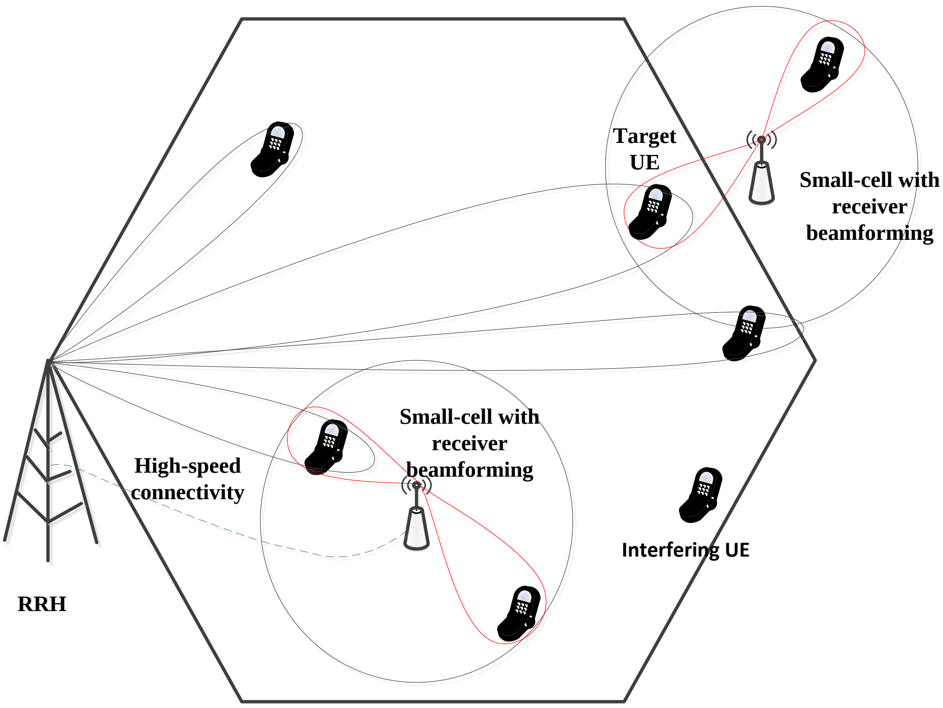

Figure 7-4: Receiver beamforming at the secondary transmitter

The use of receiver beamforming at the small-cell (the secondary transmitter) would allow its performance to be maximized, while the interference to the primary receiver would be minimized. Or by using a technique such as joint reception or coordinated beamforming both the macro and small cell can be further improve the interference reduction if integrated with an appropriate resource allocation algorithm [203]. This CoMP scheme can be considered to be an evolution of ICIC, which can be included in the future generation network to reduce the interference through coordination between neighbouring cells in a heterogeneous environment.

The above mentioned can be further enhanced by an appropriate power control algorithm which should be investigated. The power control algorithm requires control signal sharing between the eNodeB and the target users. As it is the case for a typical LTE network signalling, the eNodeBs transmits CSI reference signals (CSI-RS) in order for the users to measure and estimate the channel. Users in the target sector then feedback their CSI to the sector's eNodeB, which includes the link quality as experienced by the CSI-RS. By defining a minimum SINR threshold, which is compared to the instantaneous cell-edge SINR of the users, the eNodeB can then send necessary control information to the UEs to reduce the power in a scenario where it can receive the required threshold power due to better SINR achieved at the eNodeB by using receiver beamforming. At the same time by using this power control with conjunction to receiver beamforming, if the UE is close to the eNodeB, the radiation power of the receiver beam from the eNodeB can be minimized to a certain level (assuming a threshold level that the receiver antennas of the eNodeB can achieve a certain SINR) which will reduce the interference to other UEs on the same path. This will increase the power consumption of the eNodeB which will provide operational cost benefits to the operator.

However, the comprehensive analysis of present day interference cancellation techniques also gave an insight into the potential value of interference cancellation using Vandermonde-subspace frequency division multiplexing (VFDM) technique. VFDM is a technique for interference cancellation in overlay networks that allows a secondary network to operate simultaneously with a primary network, on the same frequency band. In this technique it projects the signal to the secondary receiver on the null-space of the channel from the secondary transmitter to the primary receiver [204]. VFDM also benefits from the frequency selectivity of the channel to create a frequency beamformer (similar to the classical spatial beamformer) [204-206204-206]. Therefore the use of VFDM in conjunction with receiver beamforming in a heterogeneous network to support the interference mitigation will provide significant throughput gains compared to joint processing on spatial multiplexing based approaches proposed in the literature.

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