LTE-A enhanced Inter-Cell Interference Coordination (eICIC) with Pico Cell Adaptive Antenna

by

Ashwini Madhav Sadekar

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Abstract

In LTE-Advanced heterogeneous networks, pico-eNBs are deployed to adequately offload traffic from macro layer and bring users closer to the base station to enhance the cell edge user experience. However, macro-eNB causes strong interference to pico cell edge users due to its higher transmission power. Hence, inter-cell interference is the biggest challenge in LTE-A HetNets. Research is performed for years to solve this critical problem in an efficient way and many contributions have been made.

This thesis is an in-depth analysis of inter-cell interference in LTE-Advanced HetNets (Heterogeneous Networks) and explores various solutions proposed in the literature to reduce interference. It presents a pioneering tactic based on the blend of eICIC (enhanced Inter-Cell Interference Coordination) and smart antennas to further reduce the macro interference.

The simulations for downlink co-channel deployment of macro-eNB (evolved Node B) and pico-eNB, demonstrates overall network performance gain and improved QoS (Quality of Service) for the pico cell edge users' achieved using the proposed scheme.

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Acronyms	Definition
1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ABS	Almost Blank Sub-frame
AMC	Adaptive Modulation and Coding
AWGN	Additive White Gaussian Noise
BLER	Block Error Rate
BS	Base Station
CA	Carrier Aggregation
CDMA	Code Division Multiple Access
CoMP	Coordinated Multi-Point Transmission and Reception
CP	Cyclic Prefix
CRS	Cell Specific Reference Signal
CSG	Closed Subscriber Group
CS	Circuit-Switched
CQI	Channel Quality Indicator
DL	Down Link
ECR	Effective Code Rate
E-DCH	Enhanced Dedicated Channel
EDGE	Enhanced Data Rates for GSM Evolution
EVDO	Evolution-Date Optimized
eICIC	enhanced Inter-Cell Interference Coordination
eNB	E-UTRAN NodeB
EPS	Evolved Packet System
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplexing
FEICIC	Further Enhanced Inter-Cell Interference Coordination
FFT	Fast Fourier Transform
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GW	Gateway
HARQ	Hybrid Automatic Repeat Request
HeNB	Home evolved Node B
HetNet	Heterogeneous Network
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
HSS	Home Subscriber Server
ICI	Inter-Cell Interference
ICIC	Inter-Cell Interference Coordination

Acronyms	Definition
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IMT-2000	International Mobile Telecommunications-2000
IMS	IP Multimedia Subsystem
IP	Internet Protocol
IMT- Advanced	International Mobile Telecommunications-Advanced
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
ITU-R	ITU-Radio Telecommunication Sector
LPN	Low Power Node
LTE	Long Term Evolution (of 3GPP mobile networks)
LTE-A	LTE-Advanced
MAC	Media Access Control
MBMS	Multimedia Broadcast Multicast Services
MBSFN	Multi-Broadcast Single-Frequency Network
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MSR	Multi-Standard Radio
MTC	Machine Type Communications
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
O&M	Operation and Maintenance
OTA	Over-The-Air
PBCH	Physical Broadcast Channel
PCRF	Policy and Charging Rules Function
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PDN	Packet Data Network
PDN-GW	Packet Data Network Gateway
PHY	Physical Layer
PRACH	Physical Random Access Channel
P-SCH	Primary Synchronization signals
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RACH	Random Access Channel
RAN	Radio Access Network
RB	Resource Blocks
PRE	Pico-cell Range Extension
RE	Resource Element
Rel-9	Release-9

Acronyms	Definition
Rel-10	Release-10
Rel-12	Release-12
Rel-99	Release 1999
RF	Radio Frequency
RRC	Radio Resource Control
RRM	Radio Resource Management
RS-CS	Resource-Specific Cell-Selection
RSRP	Reference Signal Received Power
RS	Reference Signal
SC-FDMA	Single Carrier – Frequency Division Multiple Access
S-GW	Serving Gateway
SIC	Successive Interference Cancellation
SINR	Signal to Interference and Noise Ratio
SMS	Short Message Service
SON	Self Organizing Network
SRVCC	Single Radio Voice Call Continuity
S-SCH	Secondary Synchronization signals
TA	Tracking Area
TB	Transport Block
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TDM	Time Division Multiplexing
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS Terrestrial Radio Access Network
VoIP	Voice over Internet Protocol
W-CDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access

1 Chapter: Introduction

The last decade has witnessed an extraordinary growth in the number of wireless mobile users as well as the amount of cellular data traffic generated by them. The mobile data demands have been increasing at high rates due to the availability of gadgets such as smartphones, tablets and laptop computers [46]. The market analysis confirms that this trend will continue since the mobile data is becoming a greater part of peoples' day-to-day lives. Services and applications demanding mobile data include web browsing, online social media, music and video streaming to name a few [21].

Thus, new standards are coming into picture to meet the requirements of uprising mobile data revolution and to improve network capacity to carry these applications [20] [23]. As a result, wireless systems are continuously developing to accommodate the traffic demands. Indeed the wireless communications systems have revolutionized the whole idea of communication providing seamless connectivity and mobility [20].

The evolution of wireless standards is primarily aimed at improving performance and network efficiency to support and accommodate huge growth of mobile traffic [23]. Personal mobile communications are often grouped into generations and referred to as 1G for First Generation, 2G for Second Generation and so on. The First Generation (1G) brought into reality the basic mobile analog voice telephony, whereas the Second Generation (2G) brought about the digital voice communications and considerably increased capacity and coverage.

Further, the Third Generation (3G) integrated voice and data in a comprehensive way and extended the high speed mobile data, followed by the Fourth Generation (4G) that accounted for a wide variety of packet based services and applications to support the increasing traffic demands [23] [24]. The third generation of mobile telecommunication systems is data centric, aimed at mobile services system capacity, spectrum flexibility etc. based on ITU (International Telecommunication Union) IMT-2000 (International Mobile Telecommunications-2000) project [1].

The IMT-2000 meant to transform various voice-centric 2G mobile standards, the evolution from a 2G TDMA-based GSM technology to a 3G wide-band CDMA-based technology called the Universal Mobile Telecommunications System (UMTS) [32]. 3GPP (Third-Generation Partnership Project) is the executive standardization group that prepares technical specifications for the 3G mobile systems and beyond within the scope of ITU IMT-2000 project's objectives [32]. Figure 1.1 shows the basic stages of 3GPP wireless standard evolution.

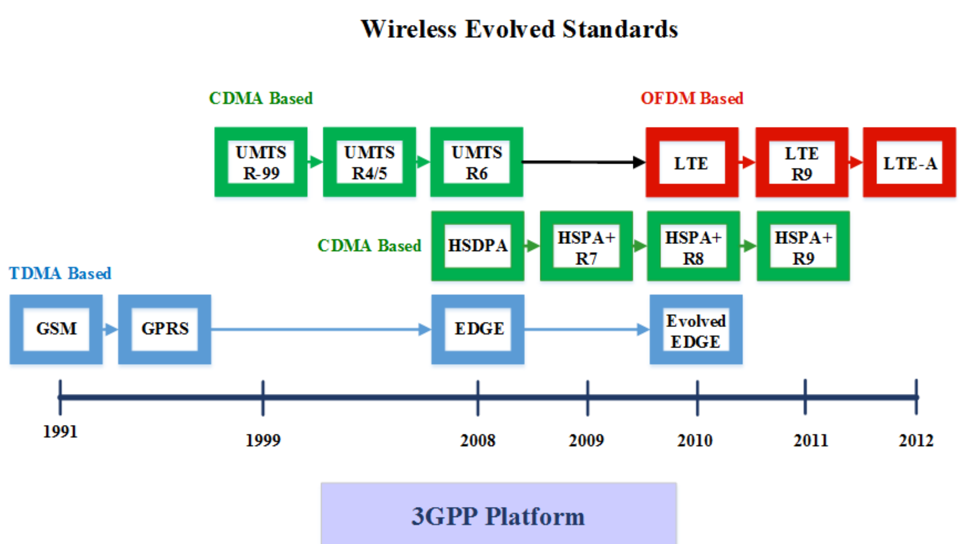

Figure 1.1 Wireless 3GPP evolved standards

In parallel with the ITU 3G standardization activities, a pioneering packet based wireless technology known as mobile WiMAX was introduced as IEEE 802.16e standard for mobile broadband access [23]. The 802.16e standard adopted a novel access technology known as OFDMA (Orthogonal Frequency Division Multiple Access). OFDMA proved to be an excellent air interface technology that offers scalable bandwidth, higher data rates, better spectral efficiencies than that of 3G based HSPA (High Speed Packet Access). Most importantly, the main motivation for OFDMA is to combat the multi path propagation, distortion at high speed.

WiMAX development influenced 3GPP and refocused its development to introduce the Evolved UMTS Terrestrial Radio Access (E-UTRA) based on the OFDM (Orthogonal Frequency Division Multiplexing) air interface and is referred to as LTE (Long-Term Evolution) [23]. Figure 1.2 shows 3GPP wireless standard evolution.

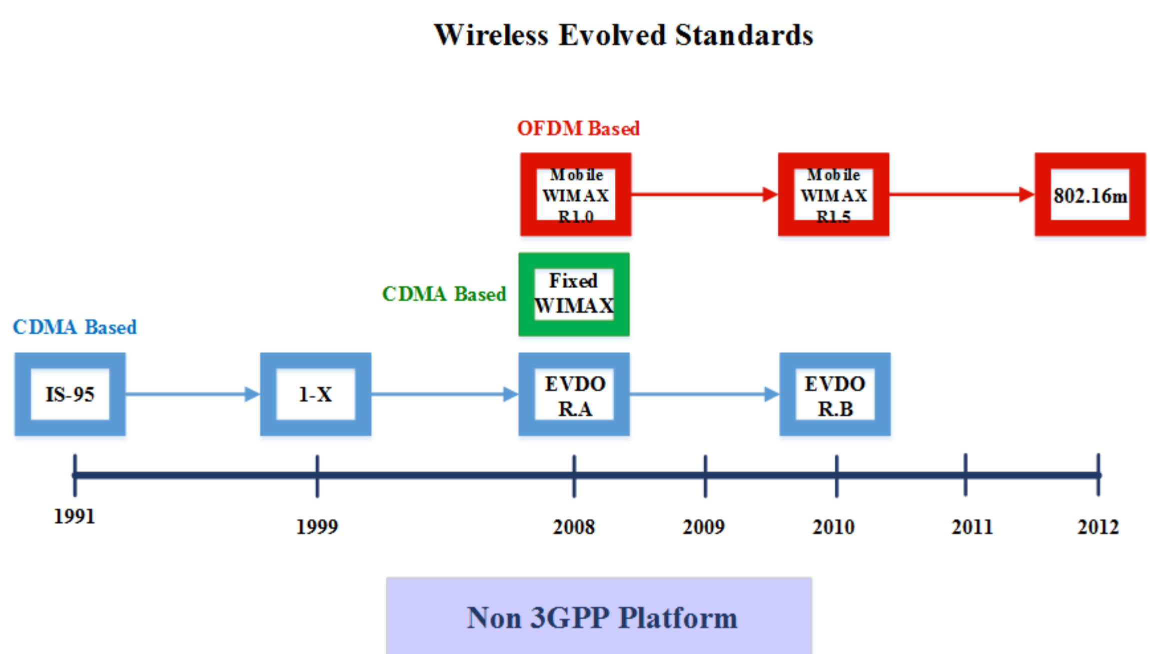

Figure 1.2 Wireless Non-3GPP evolved standards

Since LTE fulfilled IMT-2000 requirements, it is a part of IMT-2000 family of standards. LTE Release-8 was the first LTE release [23] [24]. It is based on all IP networks, and is a cost effective technology. LTE Release-8 supports total integration with existing systems and legacy standards, offers high peak data rates, provides flexible bandwidth of up to 20MHz, encourages low latency less than 5 msec., improves system capacity and network coverage, offers MIMO (Multiple Input Multiple Output) antenna support and effective packet data transmission. Eventually, Release-8 was further enhanced with various features such as Closed Subscriber Group (CSG) and Self Organizing Network (SON) [23] [24].

Later in December 2009, LTE Release-9 was introduced with new features such as, LTE HeNB (Home evolved Node B) location services and Multimedia Broadcast Multicast Services (MBMS) [23] [24].

Furthermore, LTE Release-10 was introduced in March 2011 also known as LTE-Advanced. Release-10 offers new features such as carrier aggregation, relay and Heterogeneous Networks (HetNet), enhanced ICIC (eICIC), downlink MIMO and uplink MIMO. Moreover, 3GPP Release-11 and Release-12 are under development to further enhance and progress radio access technologies beyond LTE Release-10 and HSPA Release-10 and to promote small cells and heterogeneous mobility enhancements [23] [24].

1.1 Motivation of the Work

In order to meet an expected significant increase in mobile data and to improve the network capacity and performance, the migration from traditional homogeneous macro only networks to more diverse heterogeneous network architecture is undoubtedly necessary.

A heterogeneous network is composed of several layers of networks of different cell sizes. Essentially, heterogeneous networks are a blend of a variety of base stations such as high power macro-eNBs and low power pico-eNBs [48] [50]. The macro-eNBs cover a wide area. Whereas, the pico-eNBs are customarily used in hotspots to reduce the transmitter-to-receiver separation distance and enable better spatial reuse of the spectrum as well as to offload traffic from the macro layer [57].

There is a diverse range of low power base stations such as, micro cells, pico cells, femto cells and relays. These low power base station nodes can be deployed in different settings such as hotspots, office environments, homes etc. [20]. However, such mixed deployments might trigger high interference conditions.

Introducing LTE and LTE-Advanced systems helped in boosting data bit rate and maintaining the cell edge spectral efficiency [26]. When in fact, severe Inter-Cell Interference (ICI) challenges this evolution [48]. Technically, this is attributed to two reasons; the first being the unity frequency reuse factor in LTE networks. This means that all neighbor base station nodes (eNB) use the same frequency channels, which will lead to more interference. The second is the mixed heterogeneous network deployment in LTE. The random placement of these miniature access points can cause severe interference problems particularly for cell edge users [47].

In OFDMA systems, ICI is caused by the collision between resource blocks. With the conflicting conditions, the overall system performance is determined by the collision probabilities and the impact of a given collision on the Signal to Interference and Noise Ratio (SINR) associated with the colliding resource blocks.

The ICI problem was handled by coordinating base-station transmissions to minimize interference. To achieve this goal, 3GPP LTE standard specified the Inter-Cell Interference Coordination (ICIC) solutions since Release-8. The technology deals with interference issues at cell-edge and mitigates interference on traffic channels only [27]. Briefly, ICIC mechanisms aim at reducing the collision probabilities and at mitigating the SINR degradation that such collisions may cause in order to improve the system performance and increase the overall bit rates of the cell and its cell edge users [54].

LTE Release-10 bypassed these limitations and introduced enhanced Inter-Cell Interference Coordination (eICIC). Enhancements were introduced to deal with interference issues in heterogeneous networks and mitigate interference on traffic as well as control channels [27].

Coordination techniques developed in LTE Release-8, 9 and 10 are classified to be semi-static. This issue affects the achievable benefit since it is unable to follow the dynamic interference condition caused by dynamic scheduling. Dynamically coordinating the transmission and reception of signals at multiple cells in a distributed way could lead to further performance improvement.

This thesis presents a pioneering tactic based on the blend of eICIC and adaptive array antennas technology to reduce the interference from macro-eNB and enhance the overall network performance. Figure 1.3 schematically demonstrates the basic concept, where the antenna pattern of the pico cell is adapted to equalize the interference among its edge users.

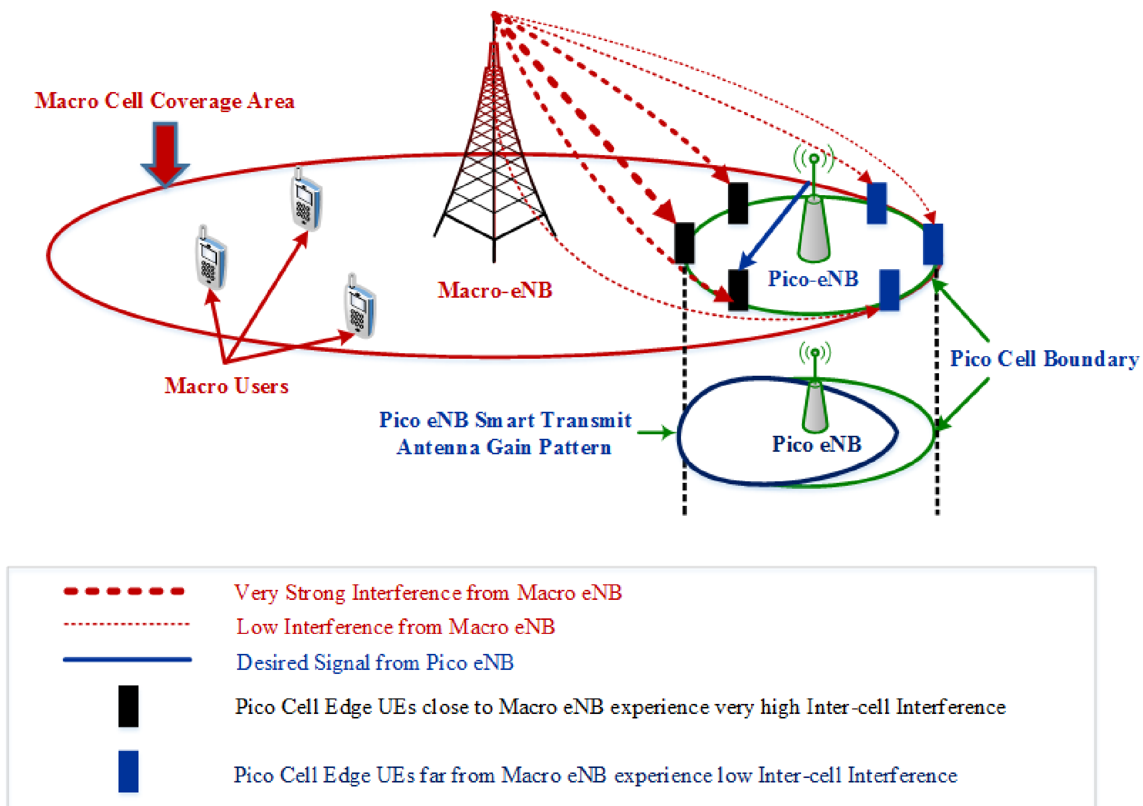

Figure 1.3 Macro-pico cellular network with pico adaptive antenna

1.2 Problem Statement

In this thesis, heterogeneous networks and enhanced Inter-Cell Interference Coordination (eICIC) for downlink co-channel deployment combined with the use of smart adaptive antennas at pico cells to mitigate the interference between high power and low power base stations, is being studied.

An elementary scenario of macro-eNB and pico-eNB deployment with a single carrier with different network configuration parameters is considered. The eICIC concept and variable gain smart antenna for pico-eNB are united. The network performance is analyzed for different numbers of macro-eNB users and pico-eNB users, and their distribution.

1.2.1 enhanced Inter-Cell Interference Coordination (eICIC)

eICIC in time domain introduces a Resource-Specific Cell-Selection (RS-CS) method based on sub-frame blanking, known as Almost Blank Sub-frame (ABS), that does not send any traffic channels and are mostly control channel frames with very low power [43]. The basic idea is to have certain sub-frames during which the macro-eNB is not allowed to transmit data allowing the pico cell edge users, who suffered high interference from the macro-eNB, to be served with better conditions [42] [57].

Transmissions from aggressor macro-eNBs are periodically muted during entire sub-frames. Figure 1.4 demonstrates the concept of ABS. The UEs (User Equipment) associated with pico cells can send their data during such ABS and avoid interference from macro cell. In fact the muting is not complete since certain control signals still need to be transmitted even in the muted sub-frames to avoid radio link failure [43] [54].

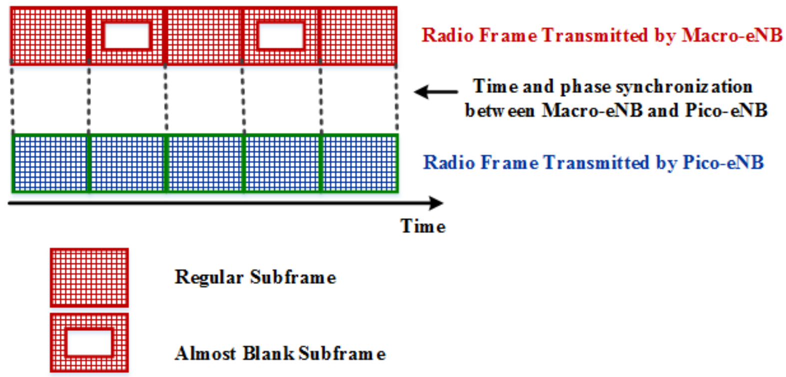

Figure 1.4 Almost Blank Sub-frames (ABS)

Initially macro-eNB constructs a default Almost Blank Sub-frames (ABS) pattern. On the other hand, pico-eNB reports the unserved edge users' information to macro-eNB using X2 interface. Based on the information exchange of loading conditions, macro-eNB alters the ABS pattern to accommodate the pico cell edge users scheduling, considering its own users at the same time [46]. As soon as the ABS pattern gets remodeled at the macro-eNB, then pico-eNB schedules its edge users who otherwise suffer strong interference from macro-eNB. Also pico-eNB is authorized to adjust its transmitting antenna gain for its edge users, raising their SINR value further to provide a higher throughput.

1.3 Thesis Contribution

In this work a comprehensive study of the time-sharing eICIC concept as a function of macro cell and pico cell loading is carried out. Network performance is analyzed for different combinations of ABS muting ratio vs. different number of macro cell and pico cell users. The analysis provides a coherent means to anticipate the appropriate ABS muting pattern based on the loading conditions of the network that will fairly maximize the network throughput.

Once the suitable ABS muting ratio is configured, the interference from macro-eNB to pico cell edge users could be still minimized using adaptive array smart antenna that will adjust its beam towards the pico cell edge users who experience higher interference from macro-eNB. Smart antennas would further enhance the network throughput in a macro-pico network scenario.

The main objectives of this work are:

To develop a simulation model in MATLAB to,

- Construct mixed macro-pico network architecture and the user distribution, so as to investigate the dynamic performance of different ABS muting patterns and pico transmitting antenna gain patterns.
- Deduce an appropriate ABS allocation under various load conditions that will help obtain a satisfactory overall network performance in terms of throughput.
- Analyze network performance without eICIC, with eICIC and with eICIC combined with pico Adaptive array antenna.
- Study the SINR distribution throughout the network; find out the pico cell users who cannot be scheduled due to their low SINR value as a result of the strong interference from macro layer. Figure a way to raise the SINR of the victim users by providing variable antenna gain and reduce the macro layer interference in order to schedule them.

1.4 Thesis Organization

This thesis is organized in six chapters. The current chapter discusses briefly about history of wireless evolution from 2G to LTE Advanced and the LTE-Advanced heterogeneous networks and interference conditions. It emphasizes the necessity of studying the impact high macro interference on pico cell edge users. The chapter discusses the problem being solved and contribution towards thesis.

Chapter 2 describes the basic architecture of LTE-A heterogeneous networks and its components. The issues that limit a link capacity are described. Propagation issues and the need to employ heterogeneous networks are discussed. LTE is investigated from a technical perspective. LTE downlink transmission techniques as well as the LTE radio frame structure are described. The survey on various interference mitigation techniques and time domain muting is presented.

Chapter 3 describes the development of interference management solution for LTE-A heterogeneous networks. The enhanced inter-cell interference coordination technique is explained in detail. An insight about the Almost Blank Sub-frames (ABS) is given. Also a comprehensive study of the Pico-cell Range Extension (PRE) concept is presented. Chapter 4 focuses on HetNet design elements, deployment challenges, inter-cell interference scenarios, study of SINR distribution within a pico cell. Chapter 5 contains the approach towards achieving the thesis objectives. The design and development of the system model, simulation parameters and the performance evaluation results are presented. Chapter 6 concludes the thesis along with the scope for future research.

2 Chapter: Background and Literature Review

The chapter explains the LTE requirements and the network architecture. A brief idea about downlink transmission techniques and LTE radio frame structure is given. LTE-Advanced is introduced along with LTE-A heterogeneous networks. The literature survey on various interference handling techniques in LTE-A heterogeneous networks and time domain muting of macro-eNB is presented.

2.1 Long Term Evolution (LTE)

LTE (Long Term Evolution) or the E-UTRAN (Evolved Universal Terrestrial Access Network), was introduced in 3GPP Release-8. LTE forms a new access network of the Evolved Packet System (EPS). LTE is the next step in the evolution of mobile cellular networks [23]. It gives extensions and modifications to UMTS system.

This technology, which is known in market as 4G LTE, was intended primarily for high-speed data services to encompass a packet-switched network from end to end with no support for circuit-switched services, the basis of 2G and 3G legacy generations. However, it is determined to deal with circuit-switched connections to tackle the latency of LTE and its sophisticated QoS (Quality of Service) architecture. In other words, LTE is designed to carry all types of IP data traffic. Voice is treated as Voice over IP (VoIP) [26]. The primary LTE requirements are high spectral efficiency, high peak data rates, low latency and spectrum flexibility.

2.1.1 LTE Requirements

LTE consists of two core elements of the evolved UMTS system architecture: Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC) [23] [25]. The overall system makes an endeavor of meeting the following requirements and this thesis is based on these LTE requirements.

- Bandwidth: 3GPP supports a large extent of flexible spectrum usage. LTE can be deployed in 700MHz, 900MHz, 1800MHz and 2.6GHz bands. LTE supports scalable channel bandwidths from 1.4, 3, 5, 10, 15 and 20MHz.

- Peak data rate: Downlink – 100Mbps, Uplink – 50Mbps at 20MHz spectrum allocation. LTE encourages peak data rates higher than HSPA+ and WiMAX.

- Mobility: LTE aims to support an excellent call setup process and high caliber handoffs up to speeds of 15kmph. While slight degradations are passable for connections up to speeds of 120kmph. Nonetheless a lower quality support is anticipated for speeds of up to 350kmph.

- Coverage: The LTE requirements mentioned would work for 5km cells. On the other hand, some degradation in throughput and spectrum efficiency is acceptable for 30km cells. Maximum cell range is 100km. whereas; cells larger than 100km are not incorporated in the specifications.

- Duplexing: LTE supports both FDD (Frequency Division Duplexing) and TDD (Time Division Duplexing), half-duplex FDD as well to accommodate paired and unpaired spectrum allocations. As a matter of fact, most deployments are FDD mode.

- Multiple access: Downlink OFDMA, Uplink SC-FDMA (Single Carrier – Frequency Division Multiple Access).

LTE integrates SC-FDMA as a cost effective and power efficient transmission scheme for uplink.

- MIMO: Downlink 2x2, 2x4, 4x4, Uplink 1x2, 1x4.
- Modulation: QPSK (Quadrature Phase Shift Keying), 16-QAM (Quadrature Amplitude Modulation) and 64-QAM.
- Channel coding: Turbo code.
- User plane latency: LTE has the lowest (5-15 msec.) user plane latency as well as the lowest call set up time of 50 msec.
- Interworking with existing systems: LTE network seamlessly co-exists with the legacy 2G and 3G systems. Likewise interworking of LTE accommodates non-3GPP standards such as the 3GPP2 CDMA and WiMAX networks. Furthermore, LTE interworking applies to all IP network including wired IP networks.
- Other techniques: Additionally LTE requirements have been extended to support features as channel sensitive scheduling, power control, link adaptation, HARQ (Hybrid Automatic Repeat Request), ICIC.

The following subsections cover, an introduction to the LTE radio interface and description of its hierarchical channel structure. Firstly, an overview of the LTE design principles, the network architecture, and radio interface protocols are described. Secondly, the function of each channel type defined in LTE and the mapping between channels at various protocol layers is explained. Next, the downlink OFDMA air interface is stated. This part of the thesis builds an understanding of the physical layer procedures and higher layer protocols of LTE.

2.2 LTE Network Architecture

LTE network has a simplified architecture with a smaller number of network components, thus can be considered as a cost effective infrastructure. The elementary aspects of LTE system architecture are a common anchor Gateway (GW) for all access technologies, packet switching for all services, IP based protocols on all interfaces and support for mobility between various radio access techniques. Accordingly, LTE introduced a new RAN (Radio Access Network) with different elements and interfaces and evolved 'All IP Core Network'. The main elements of LTE evolved packet core network are, Mobility Management Entity (MME), Serving Gateway (S-GW), Packet Data Network Gateway (PDN-GW), eNode-B (eNB), S1 and X2 Interfaces, Home Subscriber Server (HSS) and User Equipment (UE) [23] [36]. Figure 2.1 represents the LTE network architecture.

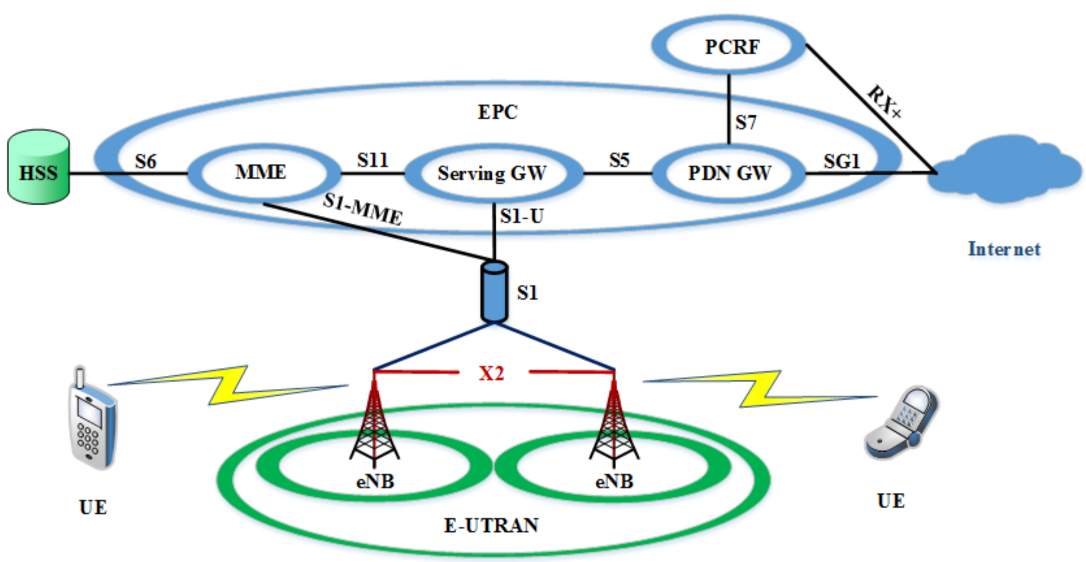

Figure 2.1 LTE network architecture

2.2.1 Mobility Management Entity (MME)

The MME is a standard element within the LTE core network that can be accessed from anywhere and manages all connections between base stations and the core network [23]. MME performs the following functions:

- Authentication of the User Equipment.
- Installation of Data Connection: MME selects the gateway to the internet and establishes the passage to carry only signaling messages while it does not carry data.
- Paging of Dormant UE's: Inactive users are unable to retain their connections. As soon as they become active again, the MME pages them over its Tracking Area (TA).
- Hand-Off Support: When a handoff cannot be set up over the X2 interface directly, alternatively, the MME makes the handoff possible.
- 2G/3G/4G Interworking: MME establishes interworking with 2G/3G elements and facilitates possible handoffs among 2G/3G and 4G networks.
- SMS and Voice Support: MME is also responsible for the accomplishment of the regular tasks from the legacy networks such as SMS and voice telephony.

2.2.2 The Serving Gateway (S-GW)

The function of S-GW is to control the user data plane between the eNBs and the packet data network gateway. Furthermore, it supports mobility and is responsible for routing. Additionally, the S-GW serves as a mobility anchor and makes sure to have a seamless data connection when UEs move across cells served by different eNBs. The S-GW is connected to the eNBs via the S1-U interface [23] [24].

2.2.3 Packet Data Network Gateway (PDN-GW)

PDN-GW is a gateway router to the open Internet. The PDN-GW supports data connectivity to the external packet data networks such as the Internet and IP Multimedia Subsystem (IMS) networks. Moreover, PDN-GW performs packet filtering and routing as well as IP address allocation. There are various PDN-GW in the network and they can be accessed by MME's (Control) and S-GW (user data) [23] [24].

2.2.4 eNode-B (eNB)

The base station in LTE is referred to as Evolved NodeB (eNB). It can perform functions such as providing air interface, scheduling and RRM (Radio Resource Management), apply the QoS, traffic load balancing and interference management [23] [24].

2.2.5 S1 and X2 Interfaces

Two fundamental interfaces in LTE are the S1 and X2 interfaces. The X2 interface is used to exchange messages among eNode-B's and it performs two functions: Hand-Off Operations and Interference Management. Whereas, the S1 interface connects the eNBs to MME and/or S-GW. The interface between eNB and S-GW is called S1-U and it conveys user data. Further, the interface between eNB and MME is known as S1-MME and it transfers control-plane information such as mobility support, paging and location services [23] [24].

2.2.6 Home Subscriber Server (HSS)

The HSS is a database of subscribers' information including user profile and state information, QoS, access-point information, roaming conditions and restrictions, security information, location information, service authorization, information about the available PDN-GWs to which a user can be connected [23] [24].

2.2.7 Policy and Charging Rule Function (PCRF)

Policy and Charging Rules Function (PCRF) is the real-time software component implemented to determine policy rules in a multimedia network. PCRF operates at the network core and accesses subscriber databases and other specialized functions, such as a charging system, in a centralized manner. It is the part of the network architecture that aggregates information to and from the network, operational support systems, and other sources (such as portals) in real time.

PCRF module supports the creation of rules and then automatically makes policy decisions for each subscriber active on the network. Such a network might offer multiple services, quality of service (QoS) levels, and charging rules. PCRF can also be integrated with different platforms like billing, rating, charging, and subscriber database or can also be deployed as a standalone entity.

2.2.8 Physical Layer and Air Interface Radio Aspects

The LTE air interface physical layer offers data transport services to higher layers. The PHY (Physical) layer is responsible for coding/decoding, modulation/demodulation, MIMO processing, and mapping the signal to the appropriate physical time-frequency resources.

Besides, PHY layer performs functions such as, error detection on the transport channel and indication to higher layers, hybrid ARQ soft-combining, rate matching of the coded transport channel to physical channels, power weighting of physical channels, and radio characteristics measurements and indication to higher layers. It also deals with mapping of transport channels to physical channels; transmit diversity, beam-forming, and RF (Radio Frequency) processing [2].

2.3 LTE Downlink Transmission Technique

As has been noted previously, the key reasons why LTE employs OFDM as its downlink transmission scheme are: strong resilience to the multi path fading channel, high spectral efficiency, low complexity receivers, ability to offer flexible transmission channel bandwidths, potential to provision advance attributes such as MIMO, frequency selective scheduling and interference management [23].

In OFDMA, the available frequency spectrum is divided into various narrowband parallel frequency subcarriers, where each subcarrier is capable of conveying one modulation symbol. Different subcarriers are placed in groups to produce a sub-channel that constitutes the basic unit of data transmission in LTE. The channels encounter almost flat-fading and can be equalized individually by single tap equalizers. This strategy allows us to equalize a large bandwidth in a set of simple parallel equalizers [23] [36].

Hence, the biggest advantage of OFDM over serial transmission is the ability to use frequency equalization. In OFDM single complex taps equalize parallel channels individually, whereas, in serial transmission, the multiple-tap time equalizer must simultaneously equalize the entire bandwidth. As the bandwidth increase, the OFDM equalizer scales up easily while the time equalizer becomes very complicated [23] [24]. The name OFDM indicates that the frequency responses of the sub-channels are orthogonal and overlapping. Please refer to **Appendix A** for more details.

To begin with, the information from different users is mapped onto different narrowband subcarriers as per the frequency bands allocated to those users. Next, the frequency domain subcarriers are then converted into time domain signals using an Inverse Fast Fourier Transform (IFFT). Then, a Cyclic Prefix (CP) is appended before the signal is ready to transmit [23].

On the other hand, the reverse action is carried out at the receiver. The cyclic prefix is eliminated in the first place. Next, a Fast Fourier Transform (FFT) operation is performed on the time domain signal to detect the modulation symbols on each subcarrier. The corresponding users then extract frequency resources associated to each user's allocated subcarrier. Finally, equalization takes place and decoding is performed [23]. Figure 2.2 shows the basic blocks of OFDMA.

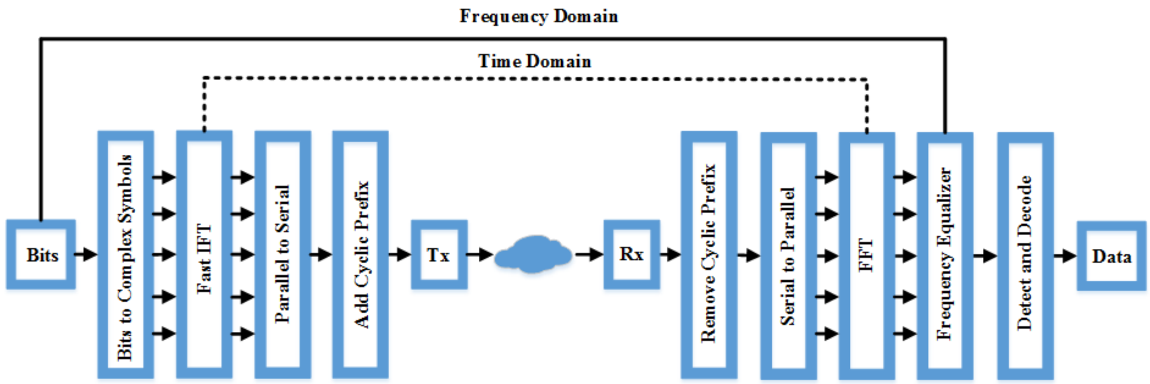

Figure 2.2 Block Diagram of OFDMA

2.4 Cyclic Prefix

The purpose of appending a cyclic prefix is to prohibit interference from previously transmitted OFDM symbols [23]. Hence, cyclic prefix inclusion is an important task in OFDM signal generation. Specifically, cyclic prefix is process of repeating a replica of existing data in the OFDM symbol. While in fact it does not add any new information and hence is discarded at the receiver, this helps to preserve orthogonality between subcarriers at the receiver. Figure 2.3 demonstrates the concept of adding cyclic prefix to an OFDM symbol.

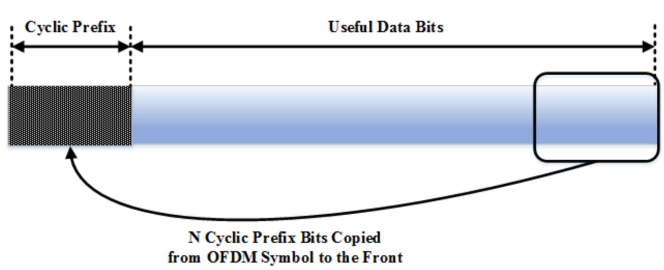

Figure 2.3 Cyclic Prefix (CP)

In addition, cyclic prefix gives a periodic extension to the OFDM signal. This is to ensure that the channel appears to produce a circular convolution to create an ISI (Inter-Symbol Interference) free channel. Having a channel response as circular convolution makes it feasible to perform frequency domain equalization at the receiver [23] [36].

The length of cyclic prefix is a principal design challenge, due to the fact that, cyclic prefix does not carry any useful information and represents redundant data. In that case, it is preferable to keep cyclic prefix as small as possible to reduce the overhead and boost the spectral efficiency. On the other hand, the length of cyclic prefix should be adequate to cover delay spreads experienced in different propagation environments. In order to address this concern, LTE specifies the cyclic prefix length on the basis of the expected delay spread of the propagation channel. Nonetheless, LTE provisions for errors due to imperfect timing alignment [23] [24].

LTE specifies three different cyclic prefix values: normal (length 4.7 μs.) and extended (length 16.6 μs.) for subcarrier spacing of 15kHz and extended (length 33 μs.) for subcarrier spacing of 7.5kHz. The normal cyclic prefix length is able to handle channel delay spread in most urban and suburban environments. Whereas, an extended cyclic prefix can be considered for broadcast services as well as for environments with longer delay spread [23].

2.5 LTE Frame Structure

The smallest unit of LTE radio frame is called as slot and has a length of 0.5 msec. Each time slot comprises of a number of OFDM symbols including the cyclic prefix [23]. Two successive slots make a sub-frame of duration 1 msec. And 10 sub-frames form an LTE radio frame of duration 10 msec.

In particular, link adaptation and channel dependent scheduling for a time varying channel take place at sub-frame level. Hence, the sub-frame length is in accordance with the minimum downlink TTI (Transmission Time Interval) that is 1 msec. compared to one TTI of duration of 2 msec. for HSPA and 10 msec. for the UMTS [23]. Figure 2.4 displays the LTE frame structure.

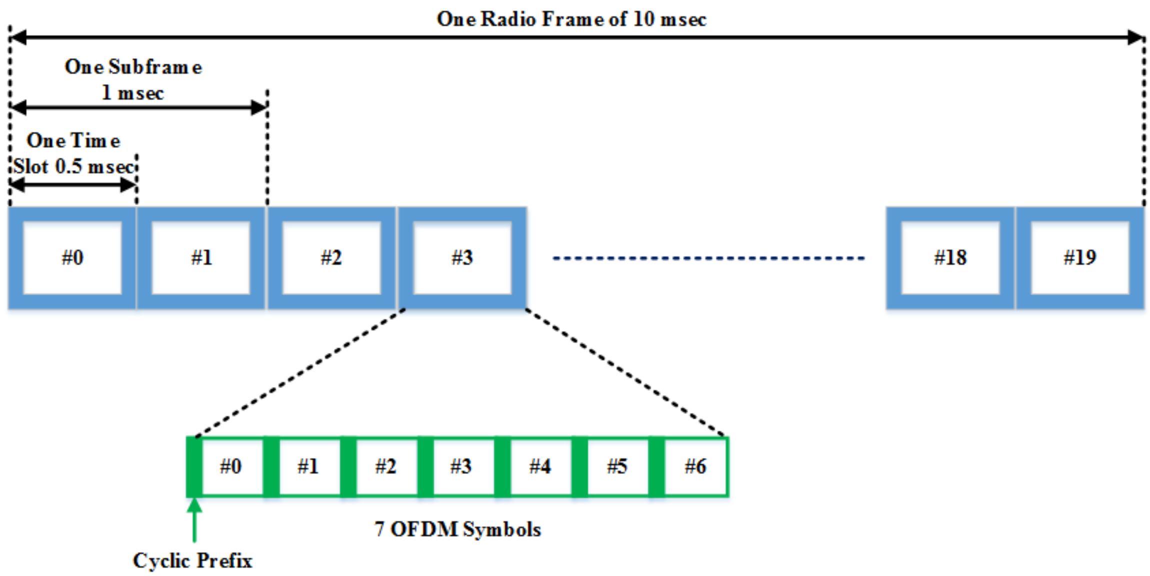

Figure 2.4 LTE frame structure

2.5.1 LTE Physical Resource Block

A time-frequency grid, known as resource grid, can illustrate the physical resource in downlink in each slot of 0.5 msec. Each column and each row of the resource grid correlates to one OFDM symbol and one OFDM subcarrier, respectively [23]. The smallest time-frequency unit in the resource grid outlines a Resource Element (RE) and is composed of one subcarrier during one OFDM symbol. Furthermore, resource elements are clustered into Resource Blocks (RB) [23] [24].

A resource block has duration of 0.5 msec. (one slot) and occupies a bandwidth of 180kHz (12 subcarriers). That implies each resource block consists of 12x7 = 84 resource elements in the case of normal cyclic prefix and 12x6 = 72 in the case of extended cyclic prefix. Each resource grid possesses a number of resource blocks [23]. Figure 2.5 explains the idea of a resource block in LTE.

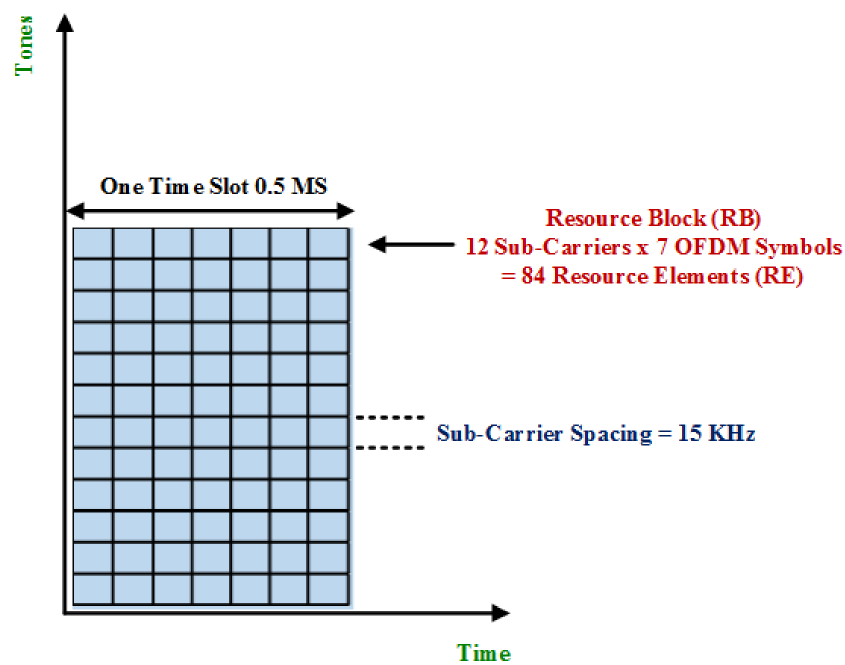

Figure 2.5 LTE physical Resource Block (RB)

Briefly, the LTE physical layer guidelines suggest, a carrier may consist of any number of resource blocks in the frequency domain, from a minimum of 6 resource blocks up to a maximum of 110 resource blocks that can be mapped to a frequency range between 1MHz and 20MHz.

2.5.2 Physical Layer Channel

The LTE DL (Downlink) and UL (Uplink) are composed of physical signals and physical channels. Physical channels carry user data and control information. Physical signals are used for cell search and channel estimation purposes [22].

The main DL physical channels are the Physical Broadcast Channel (PBCH), Physical Downlink Control Channel (PDCCH), and Physical Downlink Shared Channel (PDSCH).

The main DL physical signals are the Reference Signal (RS), and the Primary and Secondary Synchronization signals (P-SCH, S-SCH).

The main UL physical channels are the Physical Uplink Control Channel (PUCCH) and the Physical Uplink Shared Channel (PUSCH).

The demodulation Reference Signal (RS) and the Physical Random Access Channel (PRACH) are the main UL physical signals.

2.6 LTE Advanced

As previously stated, due to the extensive growth of mobile data demands, cellular operators need to analyze the coverage and capacity issues in their existing networks in order to meet subscriber's expectations. LTE-Advance proposes the use of advance technologies such as, heterogeneous networks and MIMO to support the exponential traffic growth as well as to enhance the overall performance of the network [24] [36]. The incentive to enhance LTE Release-10 was to support higher peak rates in a cost effective manner. LTE-Advanced technology can be considered as being capable of satisfying the ITU requirements for IMT advanced. The IMT-Advanced requirements are as follows:

- Higher peak data rates, DL 3Gbps, UL 1.5Gbps
- Increased peak spectral efficiency, 16bps/Hz in Release-8 assuming no more than 4x4 MIMO and 30bps/Hz in Release-10 assuming no more than 8x8 MIMO
- Support for higher number of simultaneously active users
- Improved cell edge performance
- Control plane latency of less than 100 msec.
- User plane latency of less than 10 msec.
- Support for channel bandwidth up to 40MHz

To fulfill the above-mentioned requirements, the pivotal functionalities established in LTE-Advanced include: carrier aggregation, enhanced multi-antenna techniques, support for relay nodes and heterogeneous network deployments. However, these requirements are worked upon and likely to be a part of future releases of LTE-A. Whereas, this thesis focuses on heterogeneous networks in LTE-A Release-10 (based on the requirements as stated in **Section 2.1.1**).

2.7 Heterogeneous Networks (HetNets)

Heterogeneous network formation in LTE-Advanced can assist in achieving capacity and coverage enhancements. Specifically, a heterogeneous network is an accumulation of low power base stations scattered across a traditional macro cell network [37]. However, such mixed deployments might trigger high interference conditions.

As a matter of fact, heterogeneous networks existed in Release-8 and Release-9 as well, although Release-10 offers enhanced Inter-Cell Interference Coordination (eICIC) technique to obtain good performance within mixed heterogeneous network deployments [42] [47].

2.8 Literature Review

The studies so far based on Heterogeneous Networks and eICIC focus on employing PRE (Pico-cell Range Extension) and eICIC to manage the strong interference from macro layer improving the overall system performance. Configuration of ABS patterns to improve the network capacity as well as to achieve a higher user satisfaction and QoS have been studied in the literature so far.

In [57] the performance of eICIC in LTE-A combined with PRE in downlink for a macro-pico scenario is analyzed. The overall system performance is evaluated for a number of different cases such as different number of pico cells, different transmission power levels, different number of UEs and their distribution in the network and packet scheduler. The simulation results show the recommended settings of the PRE offset bias values and ABS muting ratio. The analysis demonstrates an increase in the percentage of UEs offloaded to pico-eNB with the help of both PRE and eICIC. To sum up, the author concludes that the optimal PRE offset and eICIC muting ratio depends on factors such as, number of pico-eNBs in the macro cell network.

The major technical challenges associated with enhanced inter-cell interference coordination in heterogeneous network deployment are presented in [47].

The benefits and characteristics of the network controlled enhanced inter-cell Interference coordination solution is identified in [46]. As well as, how the advanced User Equipment (UE) receiver architectures operation is beneficial in terms of further reducing co-channel interference is discussed in [46]. The performance results give a practical exhibition and explanation of the eICIC concept that adapts with the traffic conditions. Besides, it specifies a methodical interference management scheme for co-channel multi-layered network deployments. The need of a multi-layered network having macro-eNBs for continuous wide coverage to all places, accompanied by miniature cells for capacity and coverage enhancements throughout the network is explained. Additionally, the work shows that the integration of network controlled multi-layered interference management solutions and the use of mobile terminal architectures with interference suppression; serves the heterogeneous network's purpose [46].

An in depth idea about 3GPP heterogeneous networks is given in [20]. The network performance is evaluated for a macro-pico Deployment. It illustrates the performance gain achieved with the introduction of pico-eNB into the macro cell network. Moreover, improved gains could be achieved using the resource partitioning techniques. With the available eICIC solution, an interference cancellation user terminal ensures that cell acquisition channels of weak cells can be identified that further removes CRS interference [20].

An ABS framework is proposed to reduce the interference in HetNet environments of macro and femto cells [35]. A tracking procedure is introduced to mark and unmark the users suffering with strong interference. Also, a new control message to coordinate between macro and femto cells is proposed. The macro cell scheduling process is enhanced. Also, an approach for the estimation of victim users' Signal to Interference and Noise Ratio (SINR) level during ABS is proposed. The performance evaluation results show a significant improvement in the throughput of the macro cell victim users with a slight degradation in the throughput of the femto cells.

In this thesis, heterogeneous networks and enhanced Inter-Cell Interference Coordination (eICIC) to mitigate the interference between high power and low power base stations, is discussed in detail. This work proposes that, extending pico's signal strength towards the macro interference affected users can be achieved using adaptive pico transmit antenna gain along with eICIC. This thesis studies the benefits of employing eICIC technique in a macro-pico network and extends the idea by complimenting with pico transmit smart antennas. Pico transmit antenna adapts its gain to redistribute power in the direction of strong macro interference.

3 Chapter: LTE-Advanced Heterogeneous Network

The chapter discusses the LTE-A development from Release-8 to Release-12. The motivation for heterogeneous networks is explained. Different HetNet components are described and pico cell is explained in detail. Then the chapter discusses various HetNet deployment challenges with an emphasis on interference scenarios. Finally the concept of Pico-cell Range Extension (PRE) is introduced.

3.1 LTE Advanced Heterogeneous Networks

In recent years, there has been a significant growth in mobile data escalation with an increased use of data oriented devices for example smartphones, tablets etc. [46]. Thus, in order to carry those high amounts of data, the cellular networks shall also be evolved with time. Hence, the migration from traditional homogeneous macro only networks to heterogeneous network architecture is absolutely necessary to support an immense connectivity [21].

A heterogeneous network is composed of several layers of networks of different cell sizes. Accordingly, as previously stated heterogeneous networks are a blend of a variety of base stations such as high power macro-eNBs and low power pico-eNBs [42]. The macro-eNBs cover a vast area to serve the high mobility users efficiently. While the pico-eNBs are customarily used in hotspots for two reasons; to offload traffic from the macro layer and to bring the user closer to the base station node to improve the data rate.

In this section, LTE - Advanced overview is described including evolution and main design features.

3.1.1 LTE-Advanced Development from Release-8 to Release-12

The effort towards completion and publication of Release-8 was progressing, simultaneously planning for content in Release-9 (Rel-9) and Release-10 (Rel-10) started. In addition to extra enhancements to HSPA+, Release-9 focused on LTE/EPC enhancements [44].

The aggressive schedule for Release-8 made it necessary to limit the LTE/EPC content of Release-8 to fundamental features (supporting LTE/EPC access and interoperation with legacy 3GPP and 3GPP2 radio accesses) and high priority features (like Single Radio Voice Call Continuity (SRVCC), generic support for non-3GPP accesses, local breakout and Circuit-Switched (CS) fallback) [53].

The evolution program was motivated by the aspiration for fast marketing of LTE solutions without compromising the quality of content. 3GPP targeted a Release-9 release that would rapidly follow Release-8 to improve the initial Release-8 LTE/EPC specification. While Release-9 enhancements were being achieved, 3GPP studied new proposals for specification to be submitted to the ITU for meeting the IMT-Advanced requirements.

As a result, concurrently with Release-9 work, 3GPP made a step forward to a study item called LTE-Advanced, which defined the documentation for Release-10, to include valuable technology enhancements to LTE/EPC to satisfy the very aggressive IMT-Advanced requirements. In October 7, 2009, 3GPP suggested LTE-Advanced at the ITU Geneva conference as a new proposal for IMT-Advanced and one year later in October 2010, LTE-Advanced was approved by ITU-Radio Telecommunication Sector (ITU-R) since it met all the prerequisites for IMT-Advanced (final ratification in November 2010).

Release-11 introduced to deal with further refined topics such as Coordinated Multi-Point Transmission and Reception (CoMP), Carrier Aggregation (CA), Heterogeneous Network (HetNet) and Self-Optimizing or Self-Organizing Network (SON). To follow up these standards, 4G Americas has an annually white paper to present the latest "understanding" of the 3GPP standards work, starting in 2003 with a focus on Release 1999 (Release-99) and the publication of 4G Mobile Broadband Evolution: Release-10, Release-11 and Beyond - HSPA, SAE/LTE and LTE-Advanced.

The latter version provides deep clarifications of Release-11 enhancements and also a detailed view of the ongoing Release-12 (Rel-12) features that are nearing finalization. Release-12 continues to build, relying on LTE-Advanced and HSPA+ with further focus on downlink enhancements, strengthening the various small cell features, expanding carrier aggregation, enabling Machine Type Communications (MTC) and Wi-Fi integration, as well as looking at system capacity and stability.

The freezing date of this release is delayed from December 2014 to the first quarter of 2015 [53]. The functional freeze date is when the standard is considered finalized and no further changes or functions can be added to that release. The 3GPP project road map is shown in Figure 3.1.

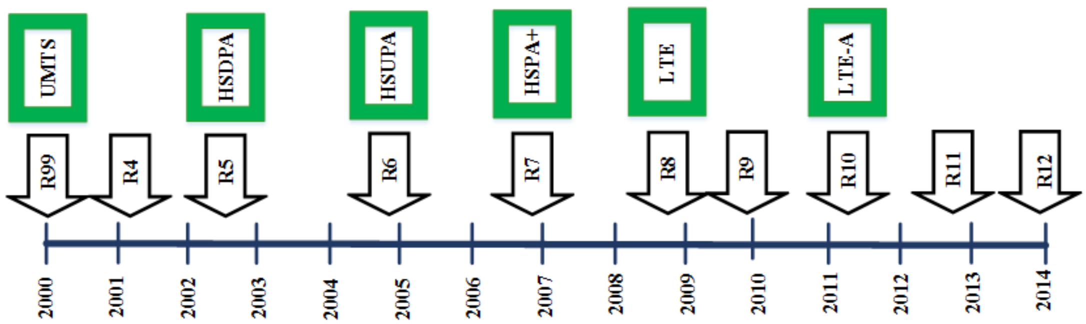

Figure 3.1 LTE-Advanced development

Table 3.1 indicates 3GPP release dates and their corresponding stage 3 completion dates; as well as, the main evolved features of each release.

Table 3.1 3GPP release dates and specifications

Release	Stage 3	Features
Rel-99	March 2000	UMTS 3.84 Mcps (W-CDMA FDD & TDD)
Rel-4	March 2001	1.28 Mcps TDD (aka TD-SCDMA)
Rel-5	June 2002	HSDPA
Rel-6	March 2005	HSUPA (E-DCH)
Rel-7	Dec 2007	HSPA+ (64QAM DL, MIMO, 16QAM UL). LTE & SAE Feasibility Study, Edge Evolution
Rel-8	Dec 2008	LTE Work item – OFDMA air interface SAE Work item – New IP core network UMTS Femtocells, Dual Carrier HSDPA
Rel-9	Dec 2009	Multi-Standard Radio (MSR), Dual Carrier HSUPA, Dual Band HSDPA, SON, LTE Femtocells (HeNB) LTE-Advanced feasibility study, MBSFN
Rel-10	March 2011	LTE-Advanced (4G) work item, CoMP Study Four carrier HSDPA
Rel-11	Sept 2012	CoMP, eDL MIMO, eCA, MIMO OTA, HSUPA TxD & 64QAM MIMO, HSDPA 8C & 4x4 MIMO, MB MSR
Rel-12	March 2013 stage 1	New carrier type, LTE-Direct, Active Antenna Systems

3.1.2 Motivation for Heterogeneous Networks

- Accelerating growth in mobile data usage - The dramatic increase in mobile data due to smart devices, applications, social networking requires capacity increase in wireless network architecture [20].
- Spectral Efficiency - Mobile data escalation being the concern, radio channel capacity in homogeneous networks is approaching the theoretical limit known as Shannon's capacity. Hence, in order to improve the network efficiency, there is a need to put more base stations. However, today's wireless cellular network is dense and adding more base stations will cause an increased amount of inter-cell interference. Therefore, we need an alternative strategy to improve spectral efficiency as well as network efficiency. With this intention, heterogeneous networks can primarily offer a greater spectral efficiency along with air interface improvements as well as advanced signal processing technologies [20].
- Service Revenue - In order to fulfill the explosive mobile data demands, cellular operators inevitably require subsidizing new network technology. Hence it is of great importance to develop fresh technologies yielding profit. Under these circumstances, heterogeneous network could be counted as a promising technology that enables capacity increase as well as supports new services revenue.

3.2 Heterogeneous Network Components

Firstly, macro cells are high power nodes and typically emit up to 46 dBm and serve thousands of customers. Secondly, pico cells are conventional base stations with lower transmit power than classic macro-eNBs. Thirdly, femto cells are low transmit power, low cost user deployed access points. They usually serve a dozen of active users in homes or enterprises. Usually, femto cell transmit power is less than 23 dBm and the coverage range is less than 50m.

Finally, relays are typically operator deployed access points. Relays route data from macro cell to the end user and vice versa. Relays are used to increase signal strength and also to improve reception in poor coverage areas like tunnels [20]. Figure 3.2 demonstrates the different components in a LTE-Advanced heterogeneous network.

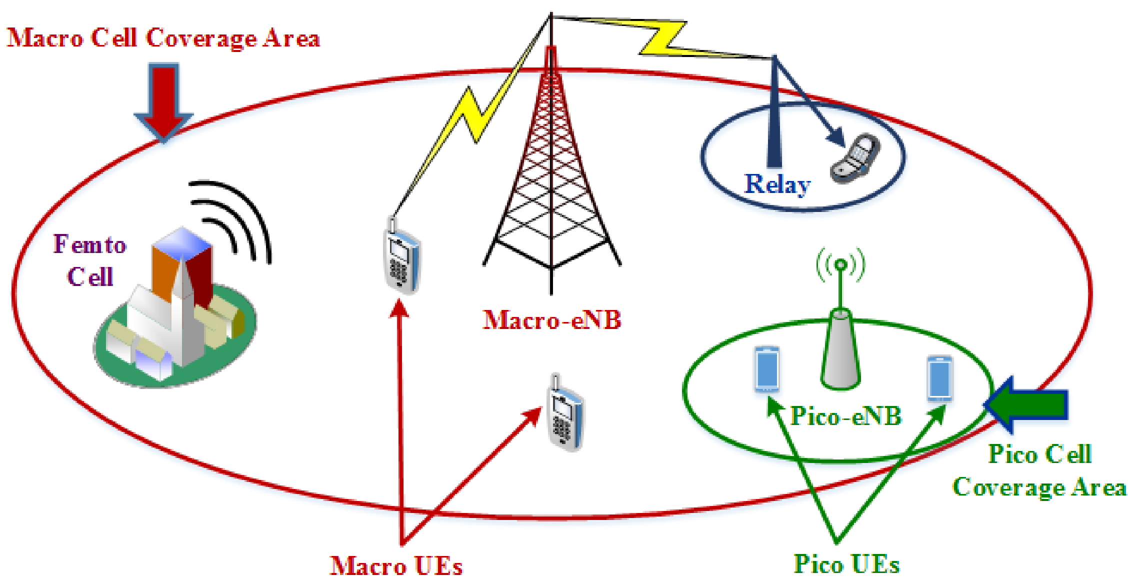

Figure 3.2 Heterogeneous Network components

This thesis focuses on downlink 3GPP LTE-Advanced multilayered network with a macro cell accompanied by a pico cell for improved network capacity and performance. The pico cell is assumed to be placed as a hotspot within the macro cell coverage area.

3.2.1 Pico Cell

Pico cell is an operator installed cell tower and it serves tens of customers within a radio coverage range of 200m or less [20]. Their transmit power is typically 250 mW to 2 W for outdoor deployments, whereas for indoor deployments it is 100 mW or less. Typically, pico cells have omni-directional antennas with the identical access attributes and backhaul as macro cells.

The placement of pico-eNBs may be more or less ad-hoc in an unplanned manner based on just a rough knowledge of traffic density and network coverage concerns. Pico cells are principally deployed for capacity in environments with inadequate macro-eNB coverage. The advantage of deploying pico-eNBs would be flexibility and ease in site acquisition because of their smaller physical size and low transmit power.

3.3 Heterogeneous Network Deployment Challenges

The main deployment challenges of HetNets considered in literature are: frequency allocation, handover, backhauling, and self-organization and interference reduction. The next subsections will briefly describe each one of them.

- **Frequency Allocation:** The allocation process is one of the major concerns in the HetNets deployment. Since the radio spectrum is a limited resource, it is recommended that macro cells and pico cells entirely share the same reserved frequency band [37]. As a matter of fact, different coverage capacities might be needed in different areas; hence it is possible to use a partial spectrum between macro cell and pico cell.

- **Handover Process:** Handovers are essential for a seamless coverage and connectivity when mobile users are moving among different cells. Moreover, handovers enable offloading the traffic from packed cells by moving the cell edge users to the less congested neighboring nodes. However, in HetNets the situation is not the same because of the large number of small cells and the diversity of backhaul links [16]. Besides, the possibility of handover failure increases the chance of user outage or signal drop. Therefore, the handover parameter settings for pico cells have to be precisely planned [33].
- **Backhauling:** is a sophisticated part in HetNets deployment due to the complex topology formed by different low power nodes deployed along with the macro cells. For example, the availability of power and network backhauling of pico cells might be tricky and costly [48].
- **Self-organizing:** Self-Organizing Networks (SONs) are the automation of mobile networks. They minimize the Operation and Maintenance (O&M) cost by using intelligent subroutines substituting human interaction without affecting network performance. For example, femto cells can be user installed and not operator installed [48] [33].
- **Interference:** In HetNets, sharing the same spectrum between different cell layers having different transmit powers causes a severe interference compared to homogeneous networks. In general, two types of interferences that occur in two-tier network architectures (i.e., a macro cell is overlaid with pico cells):

Co-tier interference: occurs among network elements that belong to the same tier in the network.

Cross-tier interference: This type of interference occurs among network elements that belong to the different tiers of the network, i.e., interference between macro cells and pico cells [47].

Regarding pico cells, the interference does not create coverage hole due to open access to all UEs, but that is not true when its coverage is extended (Please refer to **Section 3.5**).

3.4 Interference Scenarios in HetNets

Although HetNet deployment solves the problem of coverage by adding pico cells to cover areas where the macro-eNBs signal cannot reach or the areas receiving weak signal, it is also beneficial to deploy them in hotspots for bursty traffic. However, it creates the inter-cell interference. Different interference scenarios can be identified as following:

In downlink (DL): pico cells and macro-eNBs typically use the same frequency band (frequency reuse 1). Thus, a macro UE close to pico cell may receive a stronger signal from the pico-eNB than from its serving BS (Base Station) which causes low SINR and inversely for pico UEs closer to macro cell [47]. These scenarios are called macro-LPNs (Low Power Nodes) and LPNs-macro interference respectively.

In uplink (UL): the pico cell is subjected to interference from macro UEs; the farther a UE gets from serving eNB the higher power it transmits to reach the eNB. Also, when pico cell is close to macro-eNB, the pico UEs can generate interference towards macro-eNB [50].

eNBs in a HetNet setting could be in any of the three cases:

Coverage-limited environment: The cells are located far from each other. For example, the rural and high way cells. Signal levels near to the cell edges are very weak; therefore, the out-of-cell interference levels are also very low.

Interference-limited environment: The cells are packed very close to each other. Examples are dense suburban, urban or dense urban with small cells. Normally the cell edge composite signal level is very high, but the out-of-cell interference level is also very high. Accordingly, the cell edge SINR is still poor.

Environments in between: In this scenario, the cells are neither very close nor very far from each other. For instance, most light suburban cells [50].

3.5 Pico-Cell Range Extension (PRE)

A UE selects a cell based on its measurements of Reference Signal Received Power (RSRP) of the downlink signal. The highest RSRP offering eNB is being selected as the serving eNB [41]. Users of a particular operator have open access to pico cells. Open access lets users connect to the strongest cells.

Cell selection criteria based on RSRP is given by,

Serving cell selected = arg max{RSRP}

However, if the exact same notion is being applied to the heterogeneous networks with a macro-pico scenario, macro-eNB will end up enticing many UEs, since UEs will choose the higher power eNB. Whereas, pico-eNB would be serving a very few UEs due to its low transmit power [57]. The load balancing purpose would not be served if the cell selection were based on this approach.

Consequently, macro-eNB could be overloaded. pico-eNB would be under-utilized, as they are serving very few users even when they have shortest path loss distance, unevenly and unfairly distributing the traffic load in the network. Hence to balance the load between macro and pico-eNBs, a bias can be added into the RSRP measured from pico-eNB.

This offset value would, in some way act to neutralize or correct the power difference between macro and pico-eNB. Applying an offset to pico-eNB's RSRP would also make the pico coverage area wider, where pico-eNB can be connected as the serving base station [57]. Figure 3.3 explains Pico-cell Range Extension (PRE).

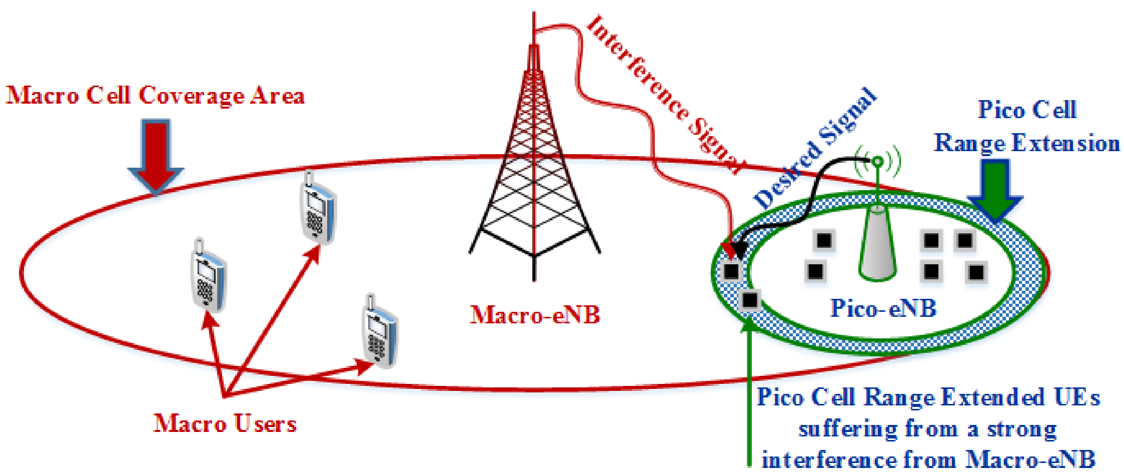

Figure 3.3 Pico-cell Range Extension (PRE)

Cell selection criteria based on RE is given by,

Serving cell selected = arg max{RSRP + ***bias***}

Where bias = 0 for macro-eNB and a few dBs for pico-eNB

On the other hand, the transmit power differences between macro and pico-eNB do not have an impact on the uplink coverage, as the transmitter is the UEs. When pico-eNB is biased with a predetermined offset, as the offset value increases, the offloaded UEs will experience severe interference from the macro-eNB [56]. That limits the offloading gain. Hence, the range extended pico UEs will experience poor SINR values as results of a strong interference from the high transmit power macro-eNB. Without any interference management solution, very small values of the range extension, a few dBs could be used for pico UEs.

The most favorable offset value depends on different factors such as, different geographical locations of macro and pico-eNBs as well as UEs and the interference levels from the macro and pico-eNBs. If the offload value is low, very few users will be connected to pico-eNB and it will be underutilized.

Whereas, if the bias is high, pico cell coverage is expanded to attract more users. In this case, due to very strong interference from macro-eNB, the range extended pico users will experience a scheduling delay as well as very low and insignificant SINR values.

Therefore, the approach under investigation would reduce the DL quality of the users in the extended pico region. However, the sole purpose of introducing pico cells in hotspots is not only load balancing but also to bring the user closer to the base stations, reduce the path loss, improving QoS and experience.

The next chapter describes the inter-cell interference analysis and the design approach taken to achieve the thesis objectives.

4 Chapter: Design Approach

In this chapter, eICIC concept is introduced. The problem being solved is presented with a macro-pico network scenario. Propagation path loss models used for macro cell and pico cell are described. The SINR calculation is explained with interference analysis. Next, SINR distribution within pico cell is studied for different scenarios such as different pico sizes and pico proximity from macro-eNB.

4.1 eICIC Concept

The purpose behind utilizing the LTE-A eICIC concept is to efficiently deploy and utilize the pico cells in an interfering macro network to increase the overall system capacity and QoS of the user, and to significantly increase the offload from macro cell to pico cell to balance the network load.

LTE-A eICIC employs time domain resource partitioning between macro and pico layers, enabling higher range extension bias values. Basically macro-eNB stops transmitting the user data during a certain sub-frames. Pico grabs the opportunity during these sub-frames, to schedule its users experiencing strong interference from macro-eNB [46] [57].

However, when macro-eNB is off for the muted sub-frames, it is not completely turned off and essentially transmits control signals. Hence, these sub-frames when macro-eNB is off are called as “Almost Blank Sub-frames (ABS)”. Macro-eNB is periodically muted with 40 sub-frames for FDD mode. This particular periodicity value is carefully chosen as being the most suited to maximize the performance of common channels such as, paging channels, synchronization channels as well as uplink Hybrid Automatic Repeat Request (HARQ). The other periodicity is for TDD mode depending on the DL/UL configuration [57].

As a result of the minimal transmission, the average transmission power of an ABS is lesser in amount than that of a regular sub-frame. It is generally dropped by roughly 10 dB. Pico UEs would experience a noteworthy dissimilar interference during a regular sub-frame and an ABS. Pico cell edge users are prioritized to schedule during an ABS, while pico cell center users can be scheduled in a regular sub-frame as well as during the ABS.

eICIC concept takes into account an accurate time synchronization of sub-frame configuration between macro and pico-eNBs in the network. The satisfactory number of sub-frames configured as ABS needs to be picked out prudently to maximize the overall network performance.

Release-10 specifications support distributed dynamic configurations of ABS muting patterns to maximize the overall network performance and the QoS of each user in the network as well. Macro-eNB is in charge of the ABS pattern selection and configuration based on the overall network scenario and traffic conditions [46]. Hence macro comes to a resolution, as which sub-frames it will configure as ABS to accommodate the minimum QoS requirements of all its users.

Users located close to the pico-eNB are called "Cell Centre UEs", and are not much affected by the macro-eNB interference as the DL received power from the pico-eNB is greater than the macro-eNB. The users located away from the pico-eNB, on the macro-eNB side are called as “Cell Edge UEs” and are highly affected by a severe interference from the macro-eNB. Figure 4.1 explains the concept of enhanced Inter-Cell Interference Coordination (eICIC) between macro and pico using Almost Blank Sub-frames (ABS).

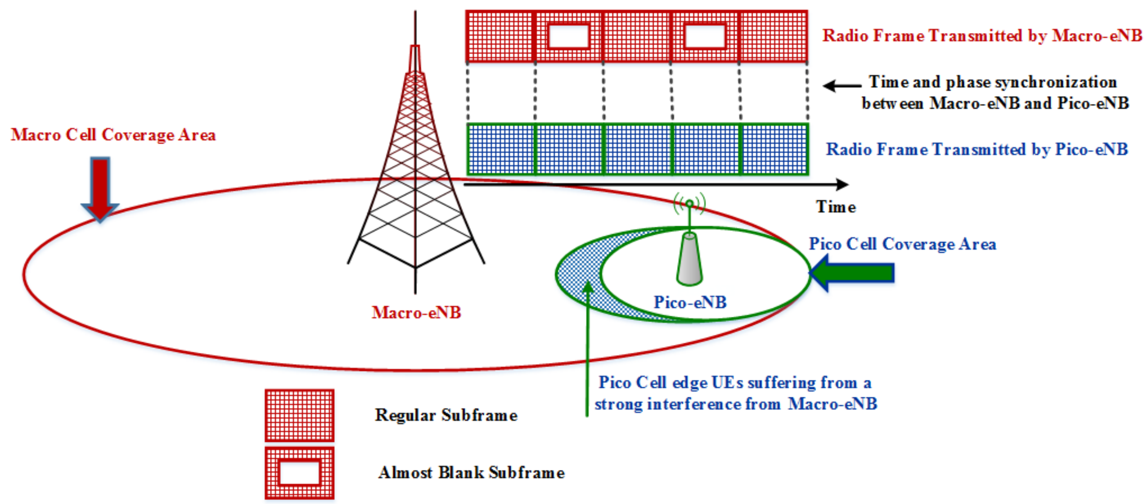

Figure 4.1 Almost Blank Sub-frame (ABS) concept

The configuration of ABS muting pattern dynamically takes place according to the variable traffic conditions and number of Cell Edge UEs in the pico Cell. The communication between macro and pico for dynamic ABS configuration takes place via X2 interface. The feedback and signaling exchange is important for ABS reconfiguration.

Figure 4.2 displays the X2 interface between macro-eNB and pico-eNB for dynamic ABS configuration.

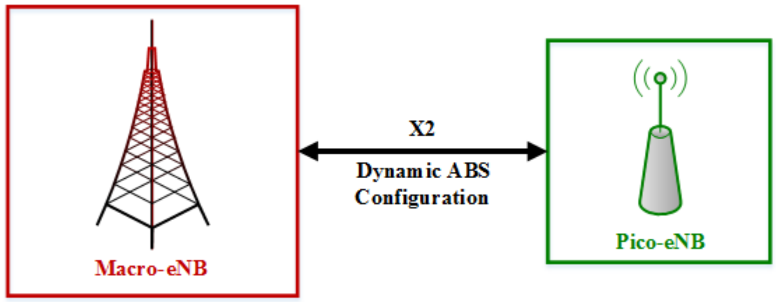

Figure 4.2 Dynamic ABS configuration on X2 interface

Pico-eNB reports to macro-eNB via X2 interface exchange messages. Pico indicates to macro that it would like to receive more sub-frames configured as ABS based on the hotspot and cell-edge interference conditions. Macro-eNB responds to pico-eNB on X2 interface with the necessary ABS information such as the currently used ABS muting pattern at macro-eNB.

Furthermore, macro-eNB can also ask for a resource status report to pico-eNB. Pico-eNB then provides a report indicating the usage of the allocated ABS resources. The status report contains useful information for macro-eNB such as, how much ABS resources are blocked at pico-eNB, is there a part of ABS resources that is not usable. This information helps macro-eNB to determine the new ABS muting pattern [46]. Hence macro-eNB configures the ABS muting pattern mutually with pico-eNB to boost up the overall network performance. Figure 4.3 shows the dynamic configuration of ABS (Almost Blank Sub-frames) based on the traffic conditions.

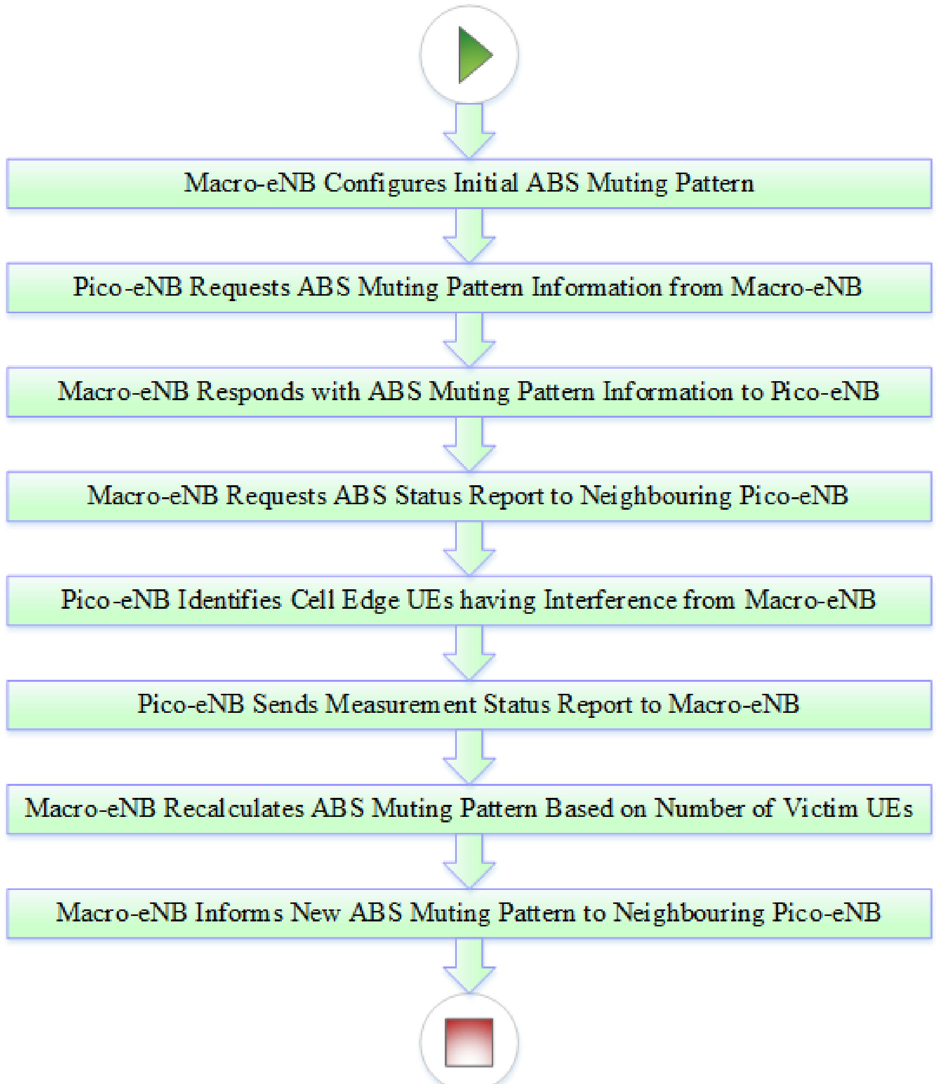

Figure 4.3 Almost Blank Sub-frame (ABS) configuration

When there are more than one pico cells deployed forming a heterogeneous network, the traffic generated by them might be different than one another. One pico may generate greater traffic and need more sub-frames configured as ABS; on the other hand, another pico might need fewer sub-frames as ABS. In this case, an algorithm to dynamically adapt to the different traffic conditions and to find an optimum ABS pattern for the overall network needs to be implemented.

4.2 Problem Analysis

In this section, the idea of integrating pico cells within the macro cell network is discussed. Study of the mutual interference between macro and pico cells as a result of sharing the same OFDM channel is being carried out.

A UE either belongs to macro-eNB or pico-eNB. For a pico UE, the signal received from the pico-eNB is the desired signal, whereas the signal received from the macro-eNB is called the interfering signal. The signal to interference and noise ratio received at a UE is being calculated under the following assumptions:

- Different path loss propagation models for the macro cell and pico cell
- Pico-eNB transmit power is much lower than the macro-eNB
- Placement of a pico cell is at the edge of the macro coverage area
- The pico and UE antennas are omni-directional

4.2.1 Macro-Pico Scenario

Consider a simple scenario to start with, as illustrated in Figure 4.4, a network consisting of one pico cell placed at the edge of the macro cell. The UE is located randomly between both base stations. The macro-eNB is carefully planned by the cellular operator considering the coverage demands and is located at the origin point (0, 0) of the Cartesian plane (X, Y). Pico cell is associated to macro cell, placed in a hotspot where there is a denser population. As stated before, pico is being mapped to the macro cell to increase the coverage and improve data rate.

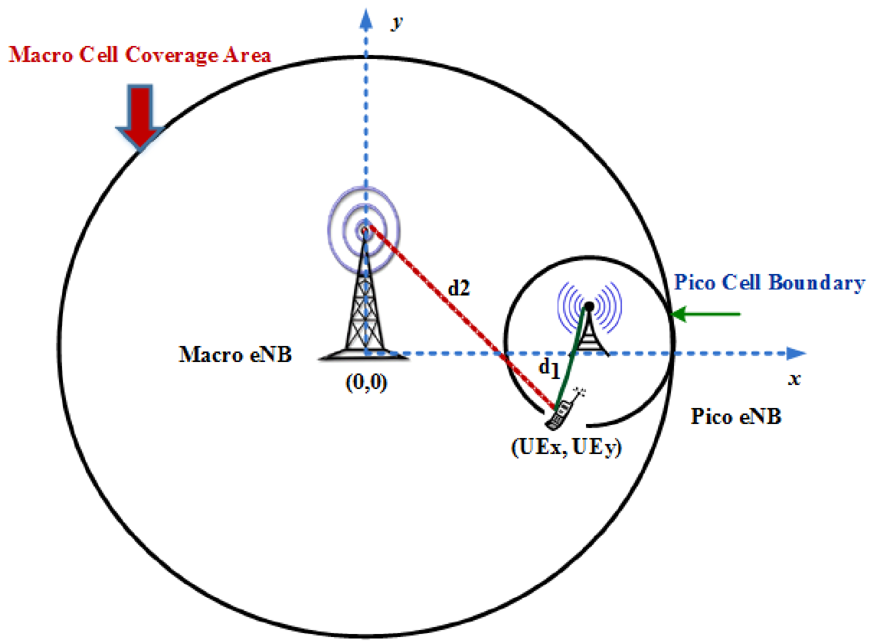

Figure 4.4 Macro-pico network propagation model

Let d_1 be the distance between UE and pico-eNB

Similarly d_2 be the distance between UE and micro-eNB

They are measured mathematically using Euclidean distance formula between two points in space, as indicated below:

$$d_1 = \sqrt{(\mathrm{PeNB_X} - \mathrm{UE_X})^2 + (\mathrm{PENB_Y} - \mathrm{UE_Y})^2} \quad (4.1)$$

$$d_2 = \sqrt{(\mathrm{MENB_X} - \mathrm{UE_X})^2 + (\mathrm{MENB_Y} - \mathrm{UE_Y})^2} \quad (4.2)$$

4.2.2 Propagation Path Loss Model

Selecting an appropriate radio propagation model for LTE is of higher importance. A path loss propagation model describes the behavior of the signal while it is transmitted towards the receiver. It is a function of the transmitter and receiver distance, and the path loss [7]. It gives an idea about the allowed path loss and the maximum cell range. Path loss depends on many factors such as the condition of environment (urban, rural, dense urban, suburban, open, sea etc.), operating frequency, atmospheric and indoor/outdoor conditions & the distance between the transmitter and receiver.

4.2.2.1 Macro Cell Propagation Model

Macro cell propagation model for urban area is applicable for scenarios in urban and suburban areas such as downtown where the buildings are of nearly uniform height [11]. Assuming that the base station antenna height is fixed at 15m above the rooftop, and a carrier frequency of 2GHz is used, the path loss L can be expressed as below:

$$L = P_{Loss}(R) = 128.1 + 37.6\mathrm{Log}_{10}(R) \qquad (4.3)$$

Where:

- R: Macro-eNB to UE separation distance in Kms

After L is calculated, log-normally distributed shadowing factor (LogF) with standard deviation of 10 dB should be added [11]. Obstacles in the propagation path between the UE and the base station node cause shadowing. Shadowing can be considered as the path loss variations induced by irregularities of the environment with respect to the average path loss obtained from the path loss model. Shadowing factor is a function of user position, as UE changes its position; the shadowing value is likely to be affected.

So that the resulting path loss with shadowing factor becomes:

$$\boldsymbol{Pathloss\_macro = L + LogF} \quad \text{..(4.4)}$$

The macro cell propagation model is valid for Non Line of Sight (NLOS) case only. It gives the worst-case propagation scenario. This model is designed mainly for distance from few hundred meters to kilometers, is not very accurate for short distances.

4.2.2.2 Pico Cell Propagation Model

The indoor propagation model expressed in dB as follows [7], that gives the identical results with the indoor model in **Appendix C.1** when a carrier frequency of 2GHz is used.

$$PL(dB) = 20\times\log(f) + 20\times\log(R) - 28dB + \sum_{i=0}^{n} P_i \quad \text{.......................................(4.5)}$$

Where:

- R : transmitter-receiver separation given in meters
- f : the carrier frequency given in MHz
- n : number of penetrated walls
- P_i : loss of wall number i

To be convenient for simulation, according to the parameters given for office environment in ITU-R P.1238, the indoor path loss model is represented by the following formula when considering a carrier frequency of 2000MHz.

$$P_{Loss}(R) = 38 + 30\mathrm{Log}_{10}(R) \ldots\ldots (4.6)$$

Where:

- R: Pico-UE separation given in meters

After L is calculated, log-normally distributed shadowing factor (LogF) with standard deviation of 6 dB is added, so that the resulting path loss becomes:

$$P_{Loss\_pico} = \boldsymbol{L} + \boldsymbol{LogF} \ldots\ldots (4.7)$$

4.2.3 SINR Calculation

The received power can be defined as the difference between the transmitted power and the path losses introduced by the environment [62]:

$$P_{Received} = P_{Transmitted} - P_{Loss} \ldots\ldots (4.8)$$

Path loss is a measurement of power loss in the transmission channel:

$$PL(d) = 10\log_{10}\left[\frac{P_t}{P_r}\right] \ldots\ldots (4.9)$$

Where P_t is the transmit power, P_r is the receive power and d is the distance the between transmitter and receiver.

The Signal to Interference and Noise Ratio is given by:

$$SINR = \frac{P_{Desired}}{P_{Interference} + N_o} \ldots\ldots (4.10)$$

Where $P_{Desired}$ is the power received by the UE from pico-eNB,

$P_{Interference}$ is the power coming from the interfering macro-eNB.

N_o is the thermal noise in dB.

The noise power at the receiver is given by a (flat) noise power spectral density and receiver bandwidth.

Noise spectral density = -174dBm/Hz (AWGN)

Bandwidth=10MHz

Hence noise power is given as:

$\boldsymbol{P_n = 3.981 \times 10^{-11}}$ mW……………………………………………………………(4.11)

Power received at UE from pico cell can be given as:

$P_{Desired} = P_{TX,pico} + G_{pico} + G_{UE} - pathloss\_pico$………………………………(4.12)

G_{pico} denotes the pico antenna gain in dBi, G_{UE} *denotes* UE antenna gain in dBi which is equal to zero.

The propagation path loss is defined according to equation (4.4), and by substitution the desired power can be expressed as:

$pathloss\_pico = 38 + 30\log_{10}(d_1)$…………………………………………………(4.13)

d_1: Pico-eNB and UE separation in meters

Similarly,

$P_{Interference} = P_{TX,macro} + G_{macro} - pathloss\_macro$…………………………(4.14)

Likewise, the path loss as per equation (4.7),

$pathloss\_macro = 128.1 + 37.6\log_{10}(d_2)$ ………………………………………(4.15)

d_2: Macro-eNB and UE separation in meters

Substituting into equation (4.9), the SINR can be written as:

$SINR = \frac{P_{TX,pico}+G_{pico}-(38+30\log_{10}(d_1))}{P_{TX,macro}+G_{macro}-(128.1+37.6\log_{10}(d_2))+Pn}$…………………………………..(4.16)

4.2.4 Interference Analysis

The UE sends CQI (Channel Quality Indicator) response as an indication of the Modulation and Coding Scheme (MCS) and data rate that can be supported by the downlink channel. Accordingly the serving base station selects a suitable modulation and coding scheme for downlink transmission for that particular UE.

The UE determines the CQI value based on measurements of the downlink reference signals. CQI corresponds to the highest modulation and coding scheme allowing the UE to decode the Transport Block (TB) with not more than 10% error rate probability. The MCS decides both the modulation alphabet and the Effective Code Rate (ECR) of the channel encoder. A UE with good receiver can report better CQI for the same downlink channel quality and thus can receive downlink data with higher MCS. Table 4.1 shows CQI index with corresponding parameters [61].

Table 4.1 SINR-CQI mapping table

CQI	Modulation	Coding Rate	Spectral Efficiency (bps/Hz)	SINR (dB)
1	QPSK	0.0762	0.1523	-6.7
2	QPSK	0.1172	0.2344	-4.7
3	QPSK	0.1885	0.3770	-2.3
4	QPSK	0.3008	0.6016	0.2
5	QPSK	0.4385	0.8770	2.4
6	QPSK	0.5879	1.1758	4.3
7	16 QAM	0.3691	1.4766	5.9
8	16 QAM	0.4785	1.9141	8.1
9	16 QAM	0.6016	2.4063	10.3
10	64 QAM	0.4551	2.7305	11.7
11	64 QAM	0.5537	3.3223	14.1
12	64 QAM	0.6504	3.9023	16.3
13	64 QAM	0.7539	4.5234	18.7
14	64 QAM	0.8525	5.1152	21.0
15	64 QAM	0.9258	5.5547	22.7

4.2.5 BLER-SINR Mapping

In LTE, the adaptive modulation and coding maintains Block Error Rate (BLER) value smaller than 10 %. The SINR-to-CQI mapping required maintaining this value can thus be obtained by plotting the 10% BLER values of the curves in Figure 4.5 and 4.6 over SNR. On the other hand, the CQI mapping on the physical layer, AWGN BLER curves are utilized in system level simulations to obtain the error probability of a received block as a function of the SINR and the MCS. When working with frequency-selective channels, an SINR averaging algorithm is required in order to compress the subcarrier SINR values into an effective SINR, which is subsequently mapped to a CQI.

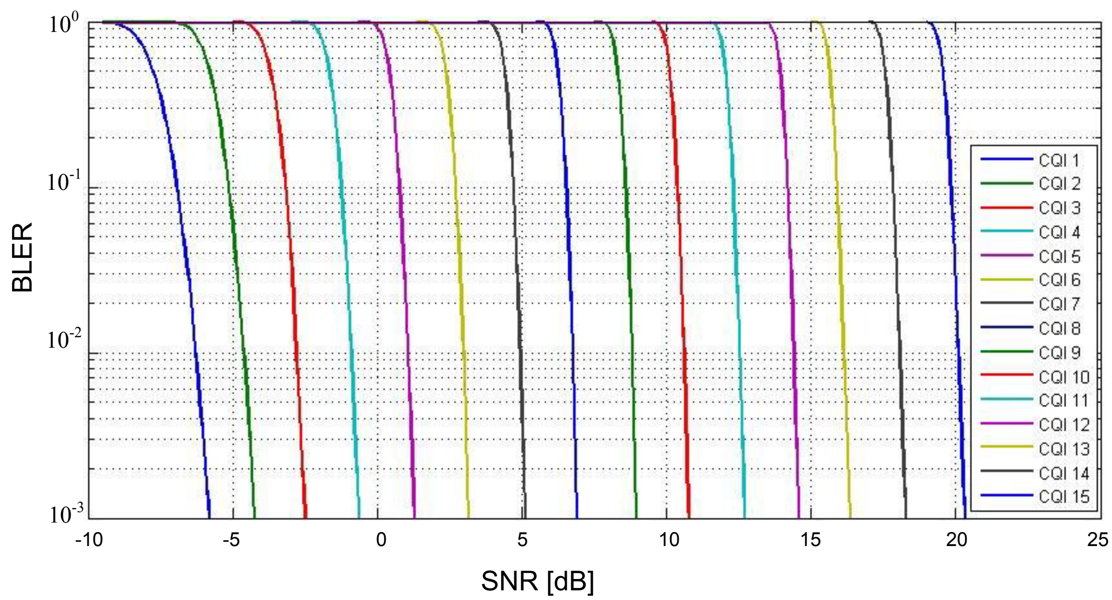

Figure 4.5 LTE BLER for CQIs 1-15

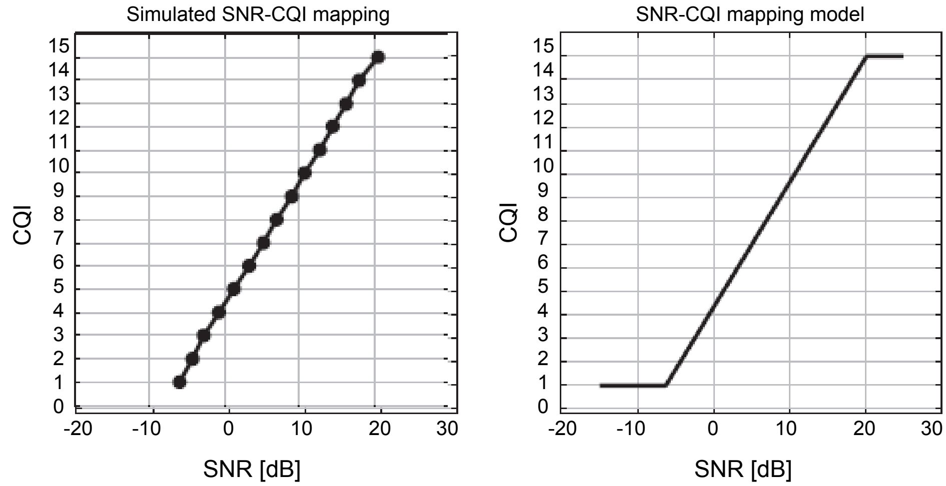

Figure 4.6 CQI mapping: BLER=10% points from the BLER curves and SINR-to-CQI mapping
Ref: C. Mehlfuhrer , M. Wrulich , J. C. Ikuno , D. Bosanska and M. Rupp "Simulating the long term evolution physical layer", *Proc. 17th EUSIPCO*, pp.1471 -1478, 2009.

4.3 SINR Distribution within Pico Cell

SINR distribution within pico cell is studied for two different situations:

1. Pico cell size is increased
2. Pico cell proximity from macro cell

For that purpose, a number of pico users are located on the pico cell edge. For each pico user the distance between its location and the pico-eNB location, also the distance between the pico user location and the macro-eNB location are calculated. The two distances are then used to calculate the signal strength received from the desired source (pico-eNB) and the interference strength received from the macro-eNB. Then the SINR of the user is determined. Next, the pico users are ranked based on their SINR from highest to lowest. Using **Table 4.1** the UEs are examined based on their SINR values. If the SINR ≥ (-6.7) dB, pico can serve the UE.

4.3.1 Pico Cell Size Effect

Reducing the cell size can increase the capacity of a cellular network [34]. Typically pico cells have cell sizes of 4 to 200 meters. Pico cells are deployed to extend coverage to areas where macro cell signal cannot reach and to add capacity to dense hotspots such as stadiums or stations. However, pico cell size plays an important role in deciding the efficient pico cell coverage [34]. The effect of different pico cell sizes on the SINR distribution within a pico cell in a macro cellular network using MATLAB simulations is analyzed. Considering pico cell sizes from 40 meters up to 70 meters with an increment of 10 meters as shown in Figure 4.7,

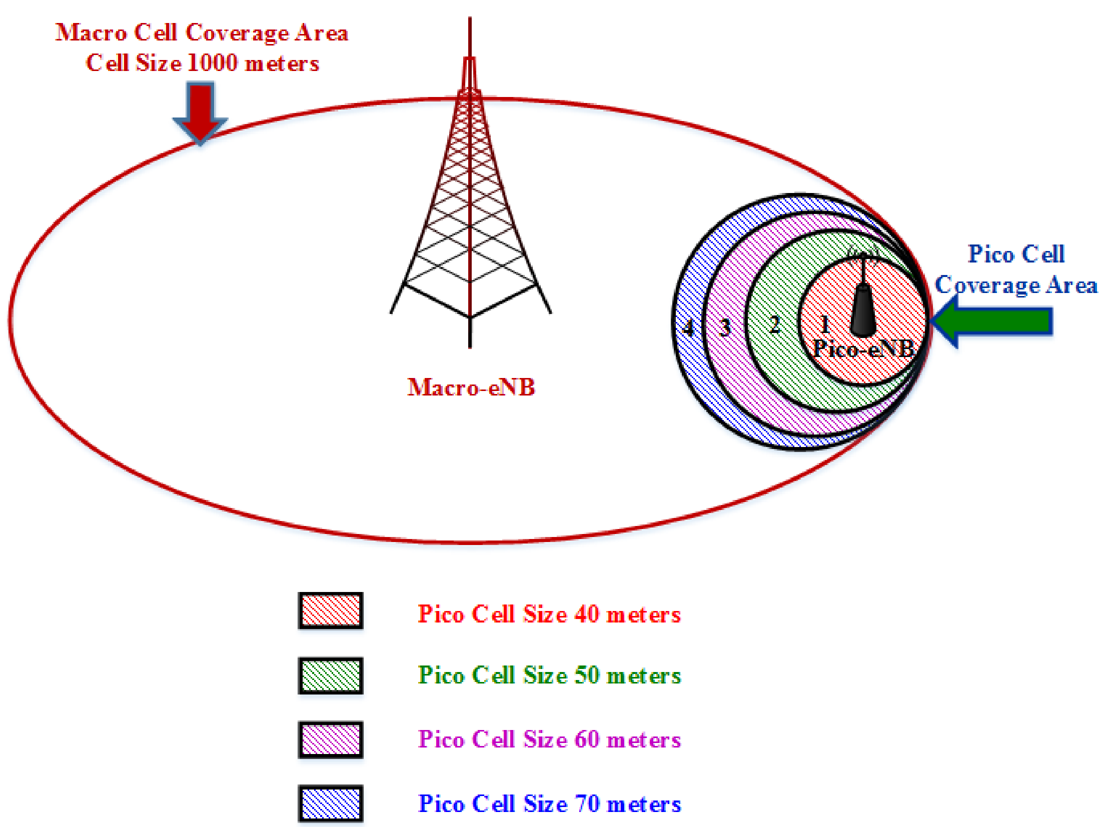

Figure 4.7 Effect of pico cell size

Four PDFs are plotted for each value of pico cell size, as shown in Figure 4.8. It can be seen from the color-coded simulation results, as the pico cell becomes larger in size the SINR drops significantly and more cell edge users suffer from a strong interference from the macro-eNB. At some point (curve 4) it becomes impossible to serve the pico users as the SINR goes below a threshold SINR value corresponding to the lowest possible CQI value (from **Table 4.1**).

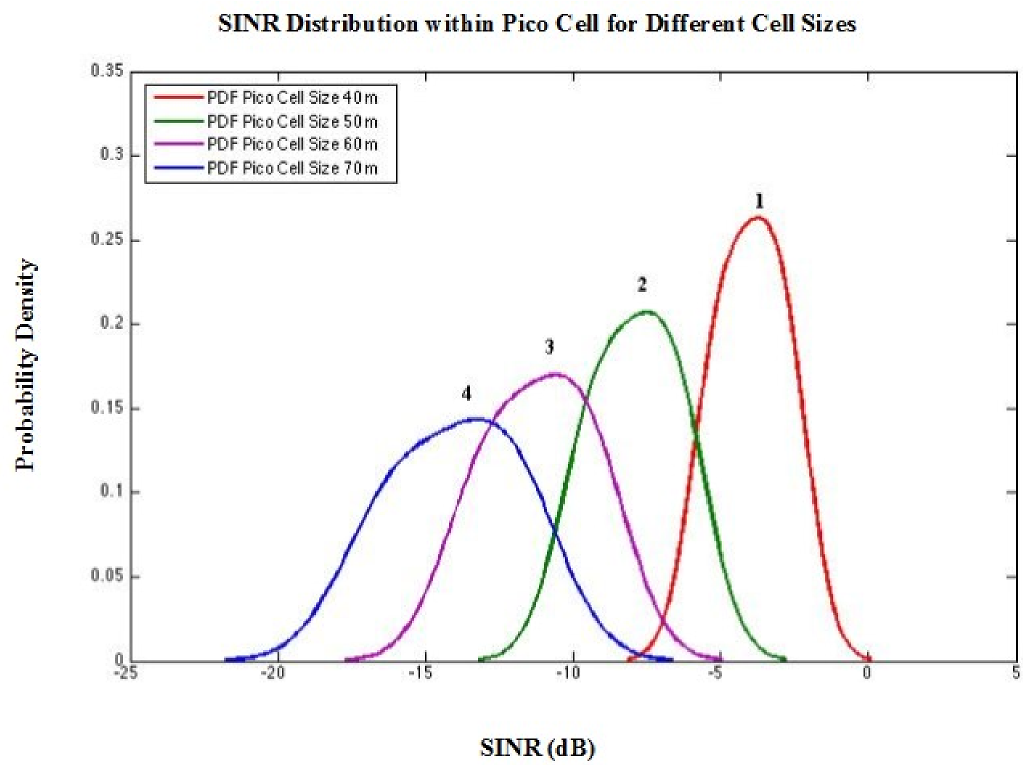

Figure 4.8 SINR distribution within pico cells with different cell sizes

If the pico cell is made too large compared to macro's coverage area, as per scenario 4, where pico size is 70 meters, the interference is overwhelming. Reasonable and acceptable SINR values can be observed within the pico cell size range of 40 meters to 70 meters within a macro cellular network of 1km.

Hence, pico cell sizes of 40 – 70 meters are believed to be finer for the considered scenario. Pico cell with a size of 40 meters is concluded to be the best among these cases, since it gives the SINR values above a threshold that can sustain the modulation and coding scheme of QPSK, as shown in scenario 1 (curve 1).

4.3.2 Effects of Pico Cell Proximity from Macro-eNB

Further, the impact of placing pico-eNB in close proximity to macro-eNB and gradually placing it at the macro coverage edge is investigated. Four different pico cell locations around macro cell within its coverage area are analyzed in terms of the pico users' SINR. The pico cell size chosen for this simulation is 40 meters. Pico cell size at all four locations remains the same. Figure 4.9 exhibits the idea of placing Pico-eNBs at different locations around the Macro-eNB.

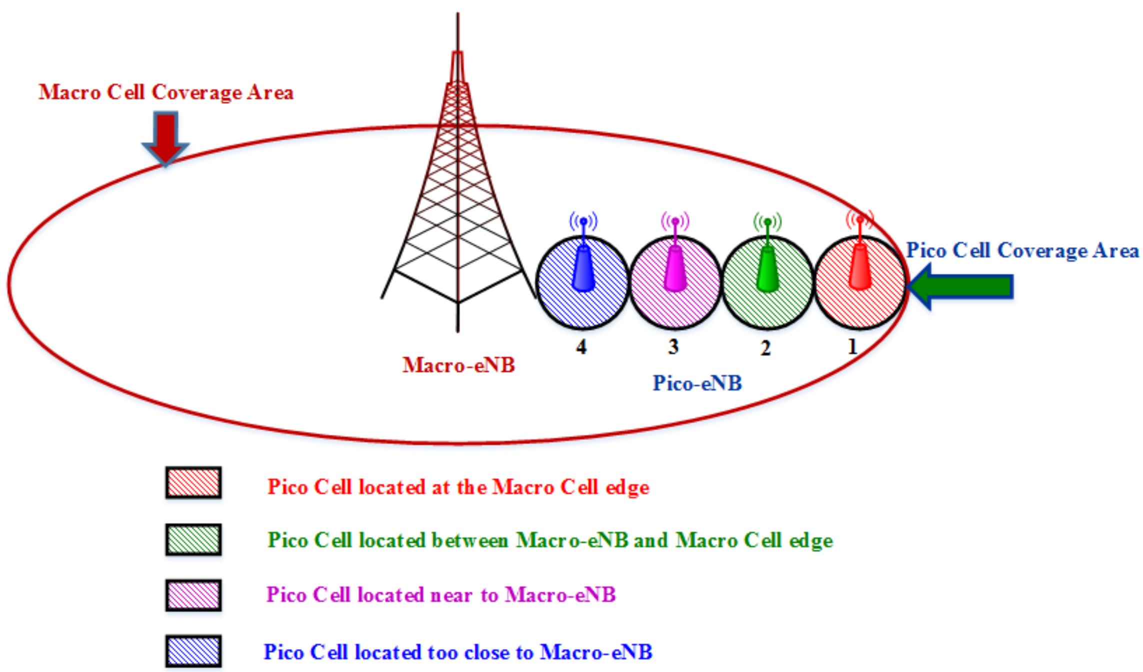

Figure 4.9 Effects of Pico Cell proximity from Macro-eNB

The simulation result gives the pico cell performance analysis in terms of the SINR distribution within the pico cell. Four PDFs are plotted for different pico cell proximity from macro-eNB. As per Figure 4.10, the closer the pico-eNB is located to macro-eNB, higher interference in experienced from the macro-eNB and SINR for pico users degrades. The SINR as can be seen from Figure 4.10 is below an acceptable value and too weak to schedule the pico users.

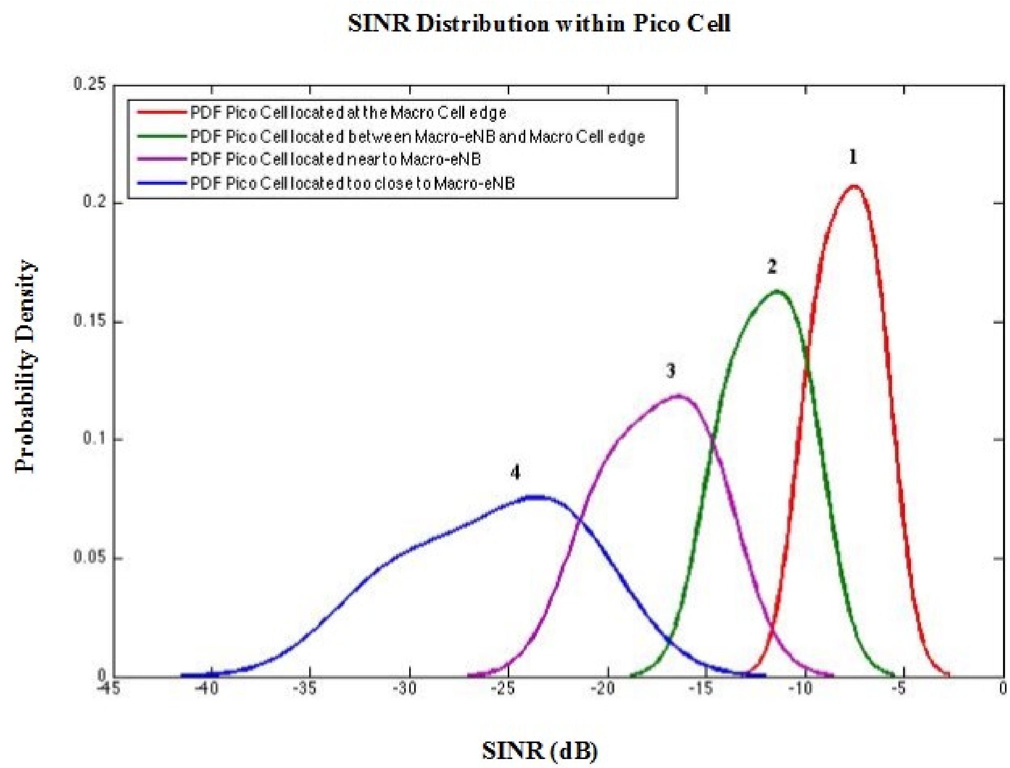

Figure 4.10 SINR distribution within Pico Cells with different cell proximity from Macro-eNB

It can be observed that, the entire curve (curve 4) has negative SINR values below an acceptable threshold for scenario 4, where the pico is located right next to macro. The pico users have SINR values that are too weak to support the minimal modulation and coding scheme (QPSK) required for scheduling the user as a result of the strongest macro inter-cell interference in that area.

Hence, the pico locations too close to macro-eNB are not suitable to be considered for simulation purposes. It can be concluded that the best location of a pico cell within the macro cellular network considered in this thesis, is at the edge of the macro coverage based on the pico cell SINR distribution studies.

From the evaluation, it can be concluded that the SINR distribution is not uniform within the pico cell coverage. The pico cell edge UEs on the macro-eNB side suffer a higher extent of inter-cell interference compared to those on the opposite side.

Hence, in this thesis, it is proposed to use adaptive array antenna for pico-eNB that will provide higher gain to the pico edge users closer to macro-eNB and a nominal gain on to the other side of the cell edge, which is safe from the interference. Instead of adding a bias to pico transmit power or changing the transmit power, it will improve the pico edge UEs' SINR by providing more antenna gain towards them, thus achieving better CQI values and be able to be served by the pico-eNB successfully.

The following chapter presents the system model developed to investigate inter-cell interference in co-channel macro-pico network, to study the effect of having ABS and pico adaptive antenna.

5 Chapter: Model of Macro-Pico Network with Smart Antenna

In this chapter, a detailed description of macro-eNB and pico-eNB interference is given. A MATLAB simulation is carried out for the following three scenarios:

1) One macro cell and one pico cell with no eICIC
2) One macro cell and one pico cell with eICIC
3) One macro cell and one pico cell with eICIC and pico cell smart antenna

The first part explains the model assumptions and simulation parameters considered, and the second part discusses the simulation results for the model described. The overall network performance is compared and analyzed for the three cases listed above. The advantage of introducing smart antennas for pico cells is evaluated.

5.1 Model Description

The basic model used for all three scenarios is as illustrated in Figure 5.1. The network layout of a co-channel deployment of macro-pico network is considered for the simulation. The model consists of one macro base station in the middle of a fairly large coverage area of 1km and one pico cell with much smaller coverage area of 40 meters and its center is located near the edge of the macro coverage area, as shown in Figure 5.1.

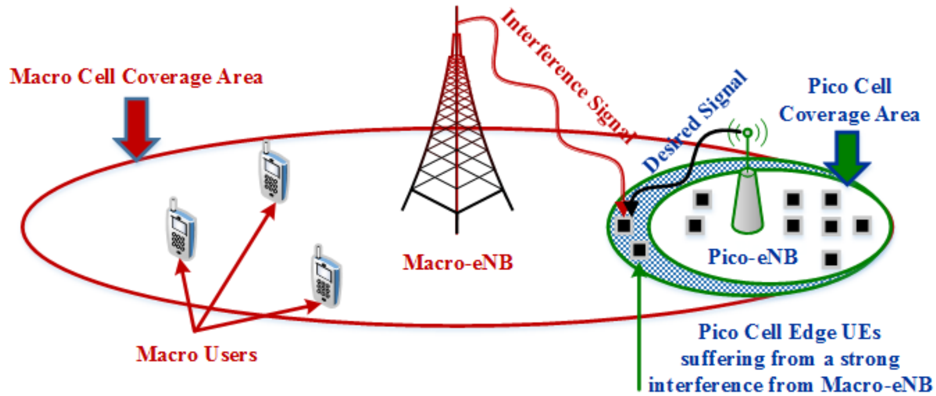

Figure 5.1 Macro-Pico network under consideration

Pico deployment has two advantages:

(1) Getting users closer to the serving base station in order to improve the data rate

(2) Help offloading some users from the macro for better load balancing.

The macro cell serves UEs scattered within its coverage area whether they are stationary or mobile. The macro cell is complemented by a pico-eNB which is acting like a hotspot. The UEs in the pico coverage area are assumed to be stationary or quasi-stationary.

5.1.1 Model Assumptions

The model under study satisfies the following assumptions:

1. All the UEs are statistically identical.
2. All UEs assumed to be LTE Release-10 compliant, which mean they individually report their CQI for ABS and regular sub-frames to their serving base station.
3. The UEs distribution within the pico cell is uniform with a user density of α_p UE/unit area, different (larger) than the user density in the rest of the macro cell coverage area.

4. Users are uniformly distributed within the macro coverage area with a user density of α_m UE/unit area.
5. The macro cell and pico cell share the same frequency channel (frequency reuse factor is unity).
6. The macro and pico have two different radio propagation models (As mentioned in **Section 4.2.2.1** and **4.2.2.2**).
7. Packets are scheduled on the basis of Round Robin protocol. Round robin is a straightforward method to schedule users by assigning them the radio resources in turn, one after another.
8. Packets are delivered on best effort basis.
9. The simulation is performed at loading level near saturation for both macro-eNB and pico-eNB.
10. Each active macro UE as well as pico UE is assumed to have an infinite buffer and that it is always loaded with data and can use any number of radio blocks allocated to it.
11. The simulation is performed on a frame-by-frame basis.
12. Traffic not sent during a frame will stay at the top of the queue for the next frame. Although, failure to be allocated any radio block in the frame doesn't increase the chance for the UE to be allocated radio blocks in subsequent frames.
13. Macro and pico are synchronized in time, i.e., the radio frame of 10 msec. begins at the same time for both macro-eNB and pico-eNB.

5.1.2 Traffic Generation

In this thesis, only downlink deployment scenario (from macro-eNB to UE and from pico-eNB to UE) is considered. The focus is on finding the weakest users (locations) within the pico cell coverage area who encounter an enormous amount of macro interference. Users for the macro cell and pico cells are separately generated. In either case, a specific number of users are generated based on the selected user's density and place the UEs at random either within the macro coverage area or pico coverage area. Users are generated according to a Poisson process. The Poisson distribution can be used to calculate the probabilities of various numbers of "successes" based on the mean number of successes. In the simulation, Poisson process generates random numbers from the Poisson distribution with mean parameter λ_m and λ_p for macro and pico respectively. The value of λ_m and λ_p is chosen to be 100 for each macro and pico cell.

The reason for selecting the value is the simulation is performed at saturation, so that the capacity will be determined by the interference only. In order to focus completely on the interference, it is important to assume that the network is fully loaded, eliminating the traffic fluctuations. It is essential to work at saturation to be able to learn the effect of interference coming from macro to pico edge users. While testing the system capacity, the average packet rate is increased to the point of generating a number of active users and packets requested by each user to fill in the entire LTE radio frame. Further, during one simulation run it is assumed that all UEs remain stationary in the same spot. Hence their average received signal strength and average values of SINR remain as is.

5.1.3 Simulation Parameters

Listed in the Table 5.1 are necessary parameters and their assumed values considered to simulate the macro-pico network in this thesis. .

Table 5.1 Simulation parameters

Parameter	Assumed Values
Network Layout	Macro cell size 1Km Pico cell size 40 meters
Transmit Power	Macro eNB: 46 dBm Pico eNB: 30 dBm
LTE Radio Frame	10 msec.
Sub-Frame Duration	1 msec.
Bandwidth	10MHz
Radio Blocks	1000 Radio blocks/ LTE radio frame for 10MHz bandwidth
Antenna Pattern	Omni and Adaptive
Antenna Gain	Macro eNB: 14 dBi Pico eNB: Variable from 1 to 6 dBi
Path Loss	Macro eNB to UE: 128.1+37.6·log10(R[km]) Pico eNB to UE: 140.7+36.7·log10(R[km])
eNB Packet Scheduling	Round Robin
Number of UEs	200 in the whole network per radio frame
UE Distribution	Macro eNB: 100 per radio frame uniformly distributed within the Macro Cell coverage area Pico eNB: 100 per radio frame in hotspot

5.1.4 Scheduling of Macro Traffic

In the simulation model, certain number of macro UEs is generated and placed at random within the macro coverage area. For each macro user the distance between its location and the macro-eNB location is calculated, also distance between the macro user location and the pico-eNB location is calculated. The two distances are then substituted in the propagation model (as stated in **Section 4.2.2.1**) and used to calculate the signal strength received from the desired source (macro-eNB) and the interference strength received from the pico-eNB. Then the SINR of the user is determined. Next, the macro users are ranked based on their SINR from highest to lowest. Each SINR is converted into a corresponding CQI using Table 4.1 and the CQI is in turn converted to the proper bit rate value. Figure 5.2 describes the scheduling process for macro users in details.

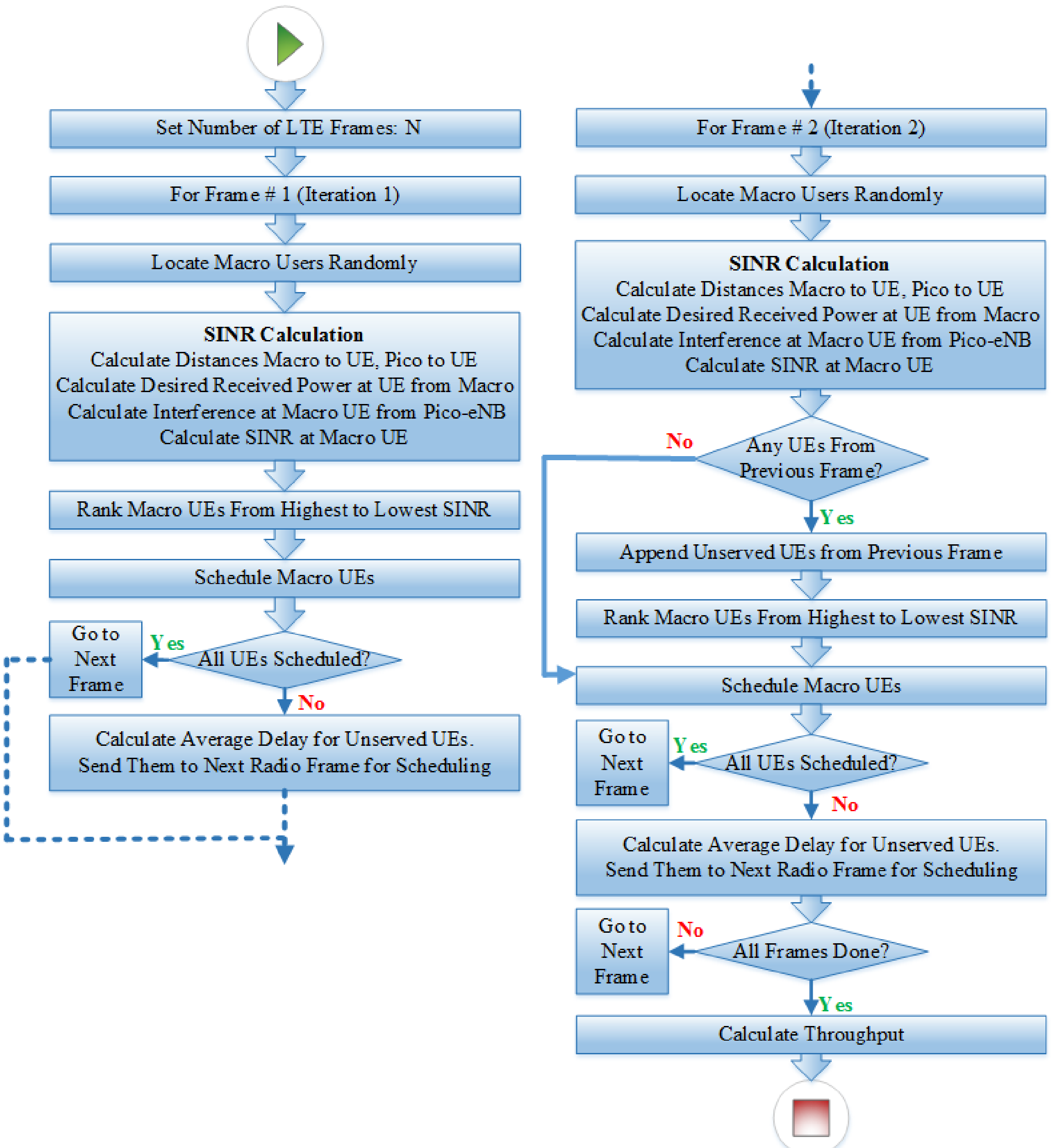

Figure 5.2 Macro traffic scheduling operation

5.1.5 Pico Cell Operation with no eICIC

In the pico scheduling routine, UE sends CQI response to indicate the data rate that can be supported by the downlink channel. Accordingly, the serving base station maps the CQI onto an applicable modulation and coding scheme for downlink transmission for that particular UE.

In a HetNet deployment scenario, if no eICIC is used and macro-eNB is continuously transmitting. This means that all time slots in the frame are used for data transmission. The system performance is poor since a lot of network traffic is served by pico-eNB and its edge users suffer strong inter-cell interference from the macro-eNB.

As a result, users at the pico center and the ones away from macro-eNB will have better SINR values and can be served efficiently with high data rates, while the pico edge users close to macro-eNB are the victims of severe macro interference and are not scheduled in the LTE radio frame.

A Monte-Carlo simulation is performed for a certain number of LTE radio frames (N). A number of pico users are generated and are placed at random within the pico coverage area. For each pico user the distance between its location and the pico-eNB location, also the distance between the pico user location and the macro-eNB location are calculated. The two distances are then used to calculate the signal strength received from the desired source (pico-eNB) and the interference strength received from the macro-eNB using pico path loss model (as stated in **Section 4.2.2.2**).

Then the SINR of the user is determined. Next, the pico users are ranked based on their SINR from highest to lowest. Each SINR is converted into a corresponding CQI using Table 4.1 and the CQI is in turn converted to the proper bit rate value. Then, the UEs are examined based on their CQI values. If the CQI ≥ 1, that UE is eligible to be served in the current radio frame, otherwise, it will be blocked.

These unserved UEs will be sent over to the next radio frame along with the newly generated users for that frame. This operation will be continued. This case helps to study the impact of high macro interference on the pico edge users and the delay it causes in their service without use of eICIC.

Figure 5.3 demonstrates the pico cell operation. It is assumed that there is no eICIC used. Macro remains ON all the time and no sub-frame blanking is employed in this case. In this particular case, the delay associated with scheduling a user with high inter-cell interference is considered to be infinite. The foremost assumption that supports the infinite delay is the stationary and/or quasi-stationary pico user. During a run of simulation for N number of radio frames, the pico user is assumed to remain in the same position. Hence the effects of the shadowing can be unacknowledged. In that case, the pico user facing the macro side and experiencing huge inter-cell interference would always have the exact same average value of the signal strength and average SINR as it won't move and the average path loss wouldn't change.

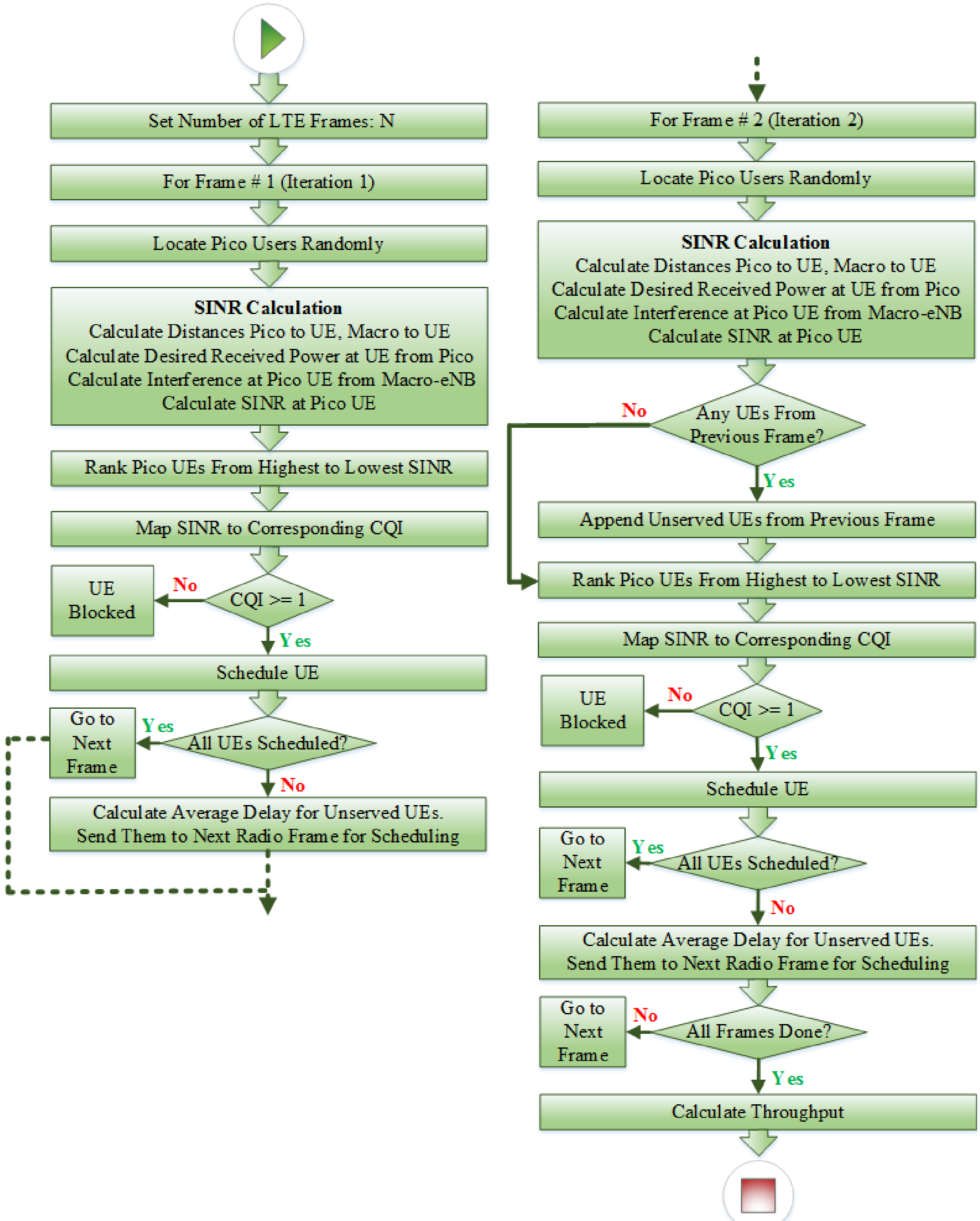

Figure 5.3 Pico cell operation when no eICIC is used

5.1.6 Introducing eICIC technique in the Model

The pico operation with eICIC is different as compared to that of without eICIC. The pico cell center users are allowed to be scheduled anytime during a radio frame, while pico cell edge users are only allowed to be scheduled in the ABS.

During an ABS, the macro-eNB is muted partially. It won't transmit user data; however it will be engaged in supporting control signaling activities. As a result, the transmit power from macro-eNB during an ABS is much lower and can be effectively handled at pico cell edge UEs. The users who could not be scheduled in the previous scenario when macro was ON all the time, will be now scheduled based on their CQI index values.

With the help of eICIC muting of a certain sub frames, the overall network performance improves, since the pico cell edge users have a chance to get scheduled on to the radio frame.

In the simulation, the scheduler schedules the victim UEs during ABS, although not all of them could be scheduled within the allocated ABS. Hence some of them will wait for the following frame to get scheduled. As previously stated, the scheduling criterion takes into account the CQI values as reported by UEs to their serving base station. UEs being LTE Release-10 complaint can report individual CQI values for a regular sub-frame and for an almost blank sub-frame. Macro continues transmitting the control signals necessary for network support during an ABS. However, macro won't transmit any user traffic.

In the simulation run, the pico cell edge users who weren't scheduled in the current LTE radio frame are being carried forward to the next radio frame and are considered again for scheduling based on their CQI value. This introduces a delay in serving the pico cell edge UEs. Since the simulation is performed at saturation and all the users are allocated equal number of radio blocks in a frame, the delay is either zero or infinite.

If CQI $\geq$ 1, then the UE will be served in the regular sub-frame. Otherwise the UE will have to wait until the macro-eNB is muted for a certain period during the frame and experiences a delay. In the worst-case scenario, the UE might end up waiting for an infinite time to be served under high interference conditions from macro-eNB.

Obtaining the suitable muting pattern for macro depends on the number of unserved pico users subjected to high inter-cell interference and poor SINR values. Hence verifying the network performance by muting macro from 10% of the radio frame to 90% of the radio frame is highly important. Different parameters contributing to the appropriate ABS pattern for a particular case of the heterogeneous network deployment are pico cell edge users, macro cell users, macro cell size and pico cell size.

Macro has to find a balance between remaining silent in order to let pico effectively schedule its inter-cell interference affected users and also to successfully support its own users at the same time. Figure 5.4 shows the steps during pico cell operation with eICIC.

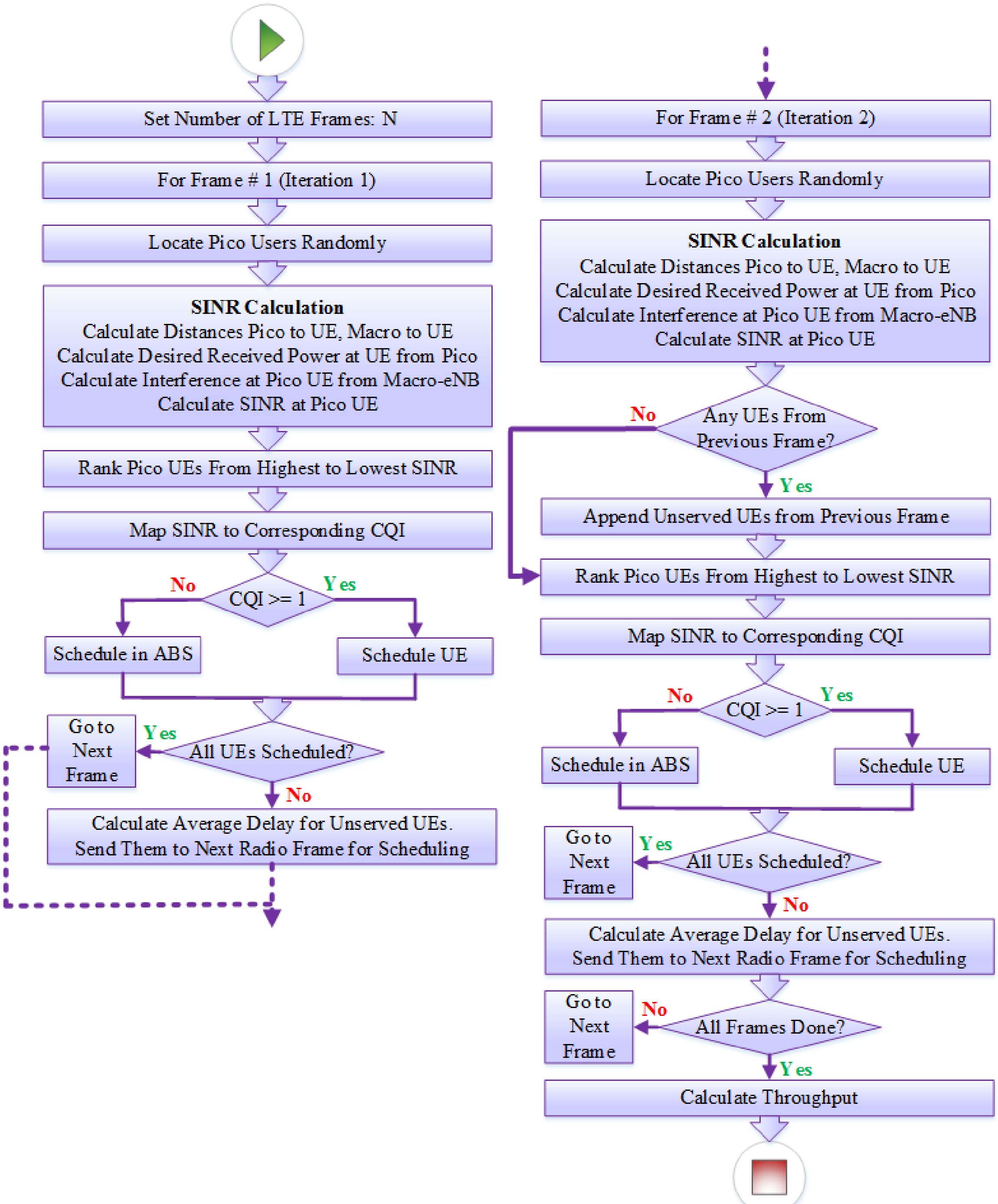

Figure 5.4 Pico cell operation with eICIC

5.2 Simulation to find Optimal ABS Ratio

In this section, the ABS ratio for which Macro is muted is found out that maximizes the overall cell throughput. A simple macro-pico scenario as shown in Figure 5.1 is simulated to study the importance of eICIC and to find the satisfactory ABS muting pattern. The suitable ratio is determined by means of simulations. First the performance of the macro-pico scenario when macro transmits all the time is observed. Then the throughput of this case is compared with the following cases to find the best among them.

1) Macro 10% ON and 90% muted of the LTE radio frame.
2) Macro 20% ON and 80% muted of the LTE radio frame.
3) Macro 30% ON and 70% muted of the LTE radio frame.
4) Macro 40% ON and 60% muted of the LTE radio frame.
5) Macro 50% ON and 50% muted of the LTE radio frame.
6) Macro 60% ON and 40% muted of the LTE radio frame.
7) Macro 70% ON and 30% muted of the LTE radio frame.
8) Macro 80% ON and 20% muted of the LTE radio frame.
9) Macro 90% ON and 10% muted of the LTE radio frame.
10) Macro always ON

The macro operation is as described in Figure 5.2 and pico operation as per Figure 5.4. The pico cell edge users closer to macro-eNB have a tremendous amount of interfering signal coming from macro-eNB. As a result, their SINR is below an acceptable value and are unable to be scheduled. To enable their scheduling, macro-eNB mutes certain sub-frames and lets pico-eNB schedule these victim users in coordinated way.

Figure 5.5 summarizes the throughput plots for the case considered 100 macro users uniformly distributed within macro coverage area and 100 pico users uniformly distributed within pico coverage area. Pico cell is highly denser than macro cell.

It can be observed that, macro is ON 80% and muted for 20% of the radio frame case gives the highest throughput for the complete cell. The 80% ON – 20% OFF is considered as the optimum ABS muting ratio that maximizes the overall network throughput. Throughput is calculated in terms of information bits transmitted per LTE radio frame (10 msec.).

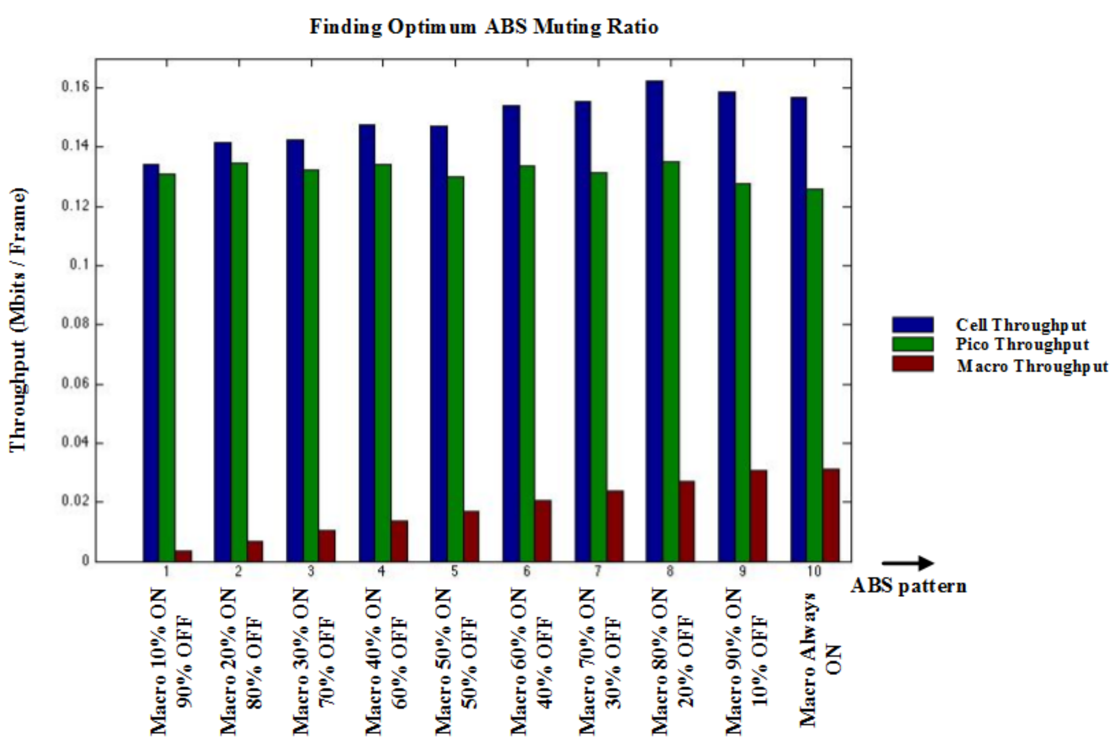

Figure 5.5 Finding appropriate ABS muting ratio for 100 macro users and 100 pico users

The pico cell throughput levels are greater as compared to the macro cell throughput levels, despite the fact that both of them have identical number of average users per frame. The reason is macro covers a wide area of 1km, the macro users are widely scattered around macro-eNB. The transmitter-receiver separation distances for macro users are large as compared to the separation distances between pico cell and pico users.

Hence macro users have lower SINR values and lower data rates as a result of a greater path loss as a function of their separation distances. Pico cell being deployed as a hotspot, the total traffic load carried by pico cell per unit area is much higher than that of macro cell traffic per unit area. Therefore, macro cell has much lower capacity when compared with pico cell's capacity.

5.3 Introducing Adaptive Antenna to Pico-eNB

The novel enhancement introduced in this thesis as an extension to eICIC is having an adaptive array antenna installed at pico-eNB. The smart antenna will provide a higher antenna gain in the direction of the macro site such that this will improve the SINR values of the victim UEs closer to the macro site and allow them to be scheduled on the regular sub-frames as well. The delay associated with waiting for an ABS to be served for the pico cell edge UEs will be significantly reduced, as the UEs with better SINR and CQI are eligible to be served on a non-ABS sub-frame. The overall network performance improves.

On the other hand, the adaptive antenna would provide a lesser antenna gain towards the pico centre UEs and edge UEs who are away from macro-eNB and are not much affected by the interference.

The antenna gain pattern setup process is based on the detailed examination and observation of pico cell users. pico cell edge users SINR is monitored continuously from 0° to 360° along the circular pico coverage area. The objective is to find out points (locations) exhibiting strong SINR and points (locations) exhibiting weak SINR. Then the pico coverage is adjusted by antenna. The SINR behaviors at cell edge are observed over a long period of time to come up with an adaptive pattern.

The rest of the section describes the system level simulation run for the three conceptual scenarios discussed above. The results are validated for the different setups.

5.3.1 Pico Transmit Adaptive Antenna

The Signal to Interference and Noise Ratio (SINR) for a pico UE is given by:

$$SINR = \frac{P_{Desired}}{P_{Interference} + N_o} \quad \text{.......(5.1)}$$

Where $P_{Desired}$ is the power received by the UE from pico-eNB,

$P_{Interference}$ is the power coming from the interfering macro-eNB.

N_o is the thermal noise in dB.

5.3.1.1 General Model

The work was started by developing a framework of a general case, considering the layout shown in Figure 5.6. The pico cell of interest establishes a desired circular coverage is as shown. It is assumed that there are several interference sources including the macro cell that covers the pico cell of interest. Other sources of interference could be other pico and macro cells as illustrated.

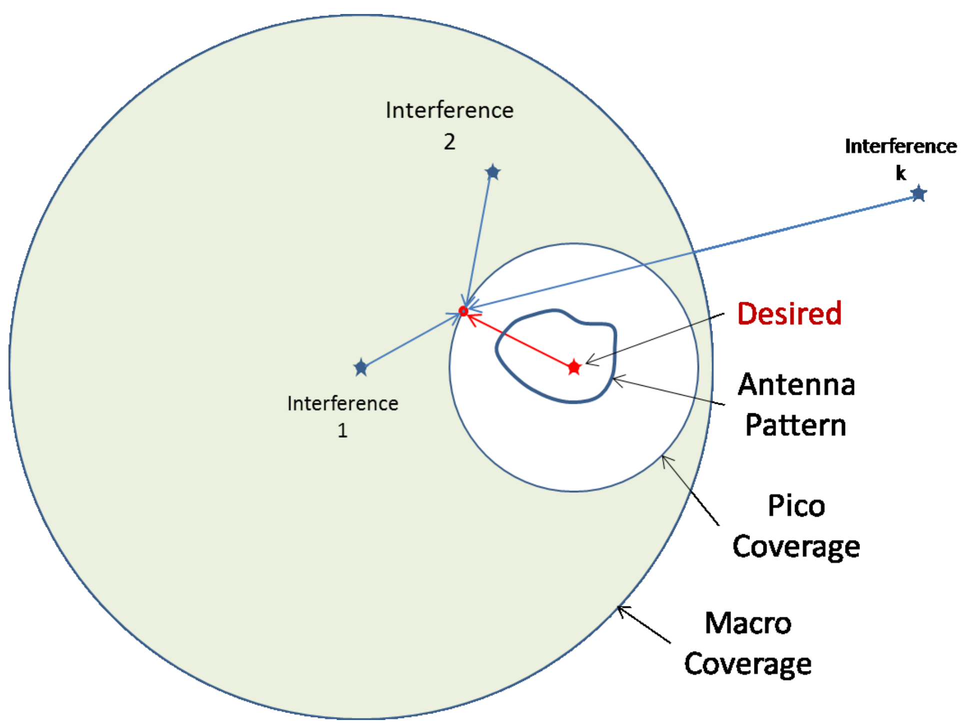

Figure 5.6 General model for pico with smart antenna

The basic idea is to find an optimal antenna pattern that equalizes the SINR along a circle at the edge of the desired pico coverage area. This means that more gain will be placed at directions where the interference is coming from and less gain in directions where there is little interference.

Now, Eqn. 5.1 can be modified to account for the pico antenna gain:

$$SINR(\theta) = \frac{P_0(R).G(\theta)}{\sum_k I_k(\theta)+N_o} \qquad (5.2)$$

Where,

θ is the azimuth angle.

$P_0(R)$ is the average desired received power at distance R (the coverage radius of the pico cell).

$I_k(\theta)$ is the interference received from interference number k at angle θ at distance R from the pico center.

The antenna pattern that equalizes the SINR along the coverage edge of the pico cell is obtained by choosing a fixed value for $SINR(\theta) = SINR$ then,

$$G(\theta) = SINR\ \frac{\sum_k I_k(\theta)+N_o}{P_0(R)} \qquad (5.3)$$

There are several questions regarding Eqn. 5.3. Such as,

(1) How can the constant SINR be determined?

(2) How can the antenna pattern be realized in practice? And

(3) How can a pico cell estimate the interference environment?

The value of the SINR determines the bit rate at the edge of the pico cell. Therefore, one needs to establish the minimum spectral efficiency at the edge of the pico cell and translate that into the corresponding SINR. The minimum value is the SINR required to sustain the QPSK.

The second question concerning possible implementation strategies, it is stated that there are several possibilities but the implementation is outside the scope of this thesis. The implementation approach could be:

(a) Sectored Cell: where the Pico is divided into N sectors and each sector has a gain {g(k); k=1, 2, 3 ….N}. Each gain element would be adjusted based on the interference environment experienced in the sector; or

(b) Adaptive Antenna Array: where digital beam forming techniques are used to adjust the gain using N degrees of freedom, where N is the number of antenna elements. The beam forming strategy would be a long-term gain adjustment to fit the pico into the specific environment. Initially, the adaptive beam would be an omni-directional pattern but as interference is sensed from different directions, the antenna elements adjust their gain to increase the gain in high interference direction and lower the gain in low interference directions to equalize the SINR around the pico center.

The third question is also treated as a long term interference estimation to smooth out the temporal variations of signal attenuations from different interference sources. The interference angular estimation can be coupled with a smart antenna concept as described in point (b) in the second question discussion.

5.3.1.2 The Pico-Macro Case:

In the present work, the focus is on the case of a single interference source to the pico cell represented by the original macro cell. In this case the power received at a pico UE from pico-eNB can be expressed as,

$$P_{Desired} = P_{TX,pico} + G_{pico(variable)} - pathloss\_pico \quad (5.4)$$

Where

$P_{TX,pico}$ is the pico-eNB transmitted power (30 dBm)

$G_{pico(variable)}$ is the pico transmit adaptive array antenna variable gain (1 to 6 dBi)

$pathloss\_pico$ is the path loss from pico-eNB to UE (dB)

Interference power received at a pico UE from macro-eNB can be given as,

$$P_{Interference} = P_{TX,macro} + G_{macro} - pathloss\_macro \quad (5.5)$$

Where

$P_{TX,macro}$ is the macro-eNB transmitted power (46 dBm)

G_{macro} is the macro transmit antenna gain (14 dBi)

$pathloss\_macro$ is the path loss from macro-eNB to pico UE (dB)

Scenario described in Figure 5.7 is simulated to study the effect of adding adaptive smart antenna to a macro-pico network scenario with eICIC. In this scenario, pico UEs are located right at the edge of pico cell along the pico coverage circle. The SINR analysis for this case suggests that pico UEs in the vicinity of macro-eNB are the victims and are subjected to a huge inter-cell interference from macro-eNB, whereas the pico UEs farther away from macro-eNB are least affected by the inter-cell interference. The scenario is used for simulation purposes in this thesis, besides this; in general there may be more than one inter-cell interference sources.

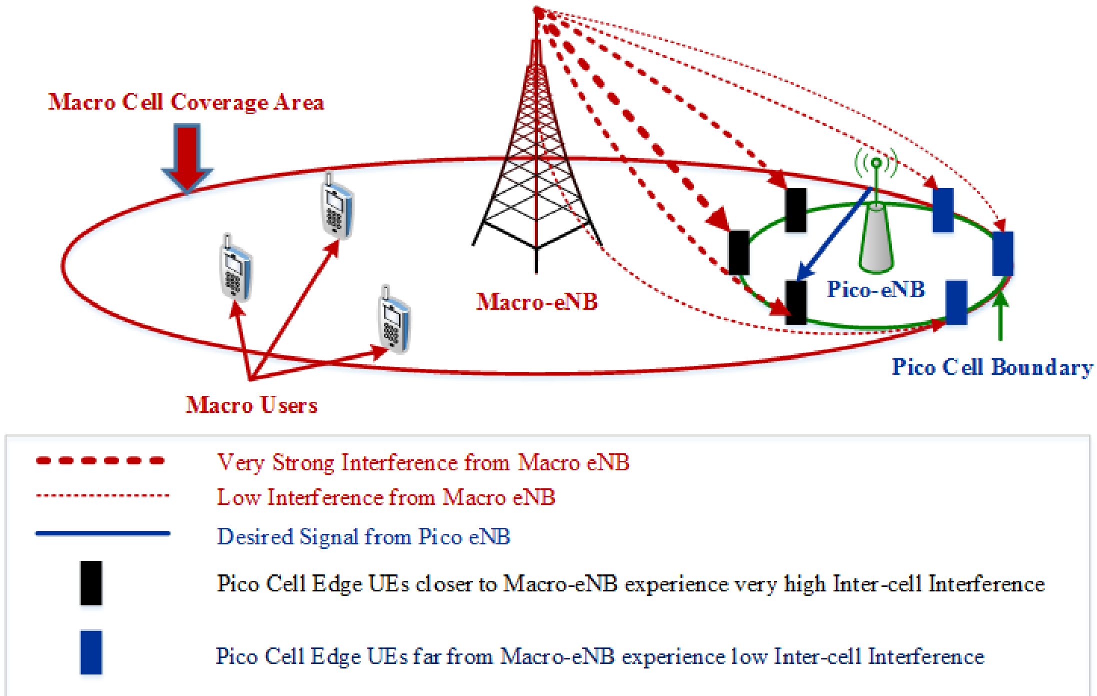

Figure 5.7 Interference conditions at pico cell edge

Hence it can be concluded that, adjusting the pico-eNB transmit antenna gain more towards the victim UEs along with eICIC solution is more beneficial.

5.3.2 Cell Edge User's SINR Distribution within Pico Cell

The following section verifies and validates the concept discussed above. First the SINR values of the pico cell boundary users are analyzed with respect to their separation distances from macro-eNB for a comprehensive understanding of the concept introduced in this thesis. The comparative analysis is carried out for three cases of no-eICIC where there will be no interference coordination or interference cancellation, eICIC where macro will be muted for a certain sub-frames and eICIC with pico transmit smart antenna where antenna variable gain equalizes the pico edge users' SINR and then the interference is coordinated using ABS.

The SINR pattern of the pico edge users is calculated in a macro-pico co-channel downlink deployment. The pico users are located right on the edge of pico cell boundary on every 5° from 0° to 360° along pico-eNB circular coverage. Figure 5.8 demonstrates the scenario under investigation. The pico transmit antenna pattern is omni-directional before using the adaptive antennas at pico. The SINR values for the pico edge users facing the high inter-cell interference side cannot sustain the lowest modulation and coding scheme employed in LTE. Hence, when using eICIC technique in this case, more ABS needs to be allocated in order to serve all of these victim users. Macro needs to remain muted for a longer duration in a frame that will affect the scheduling of high mobility micro users.

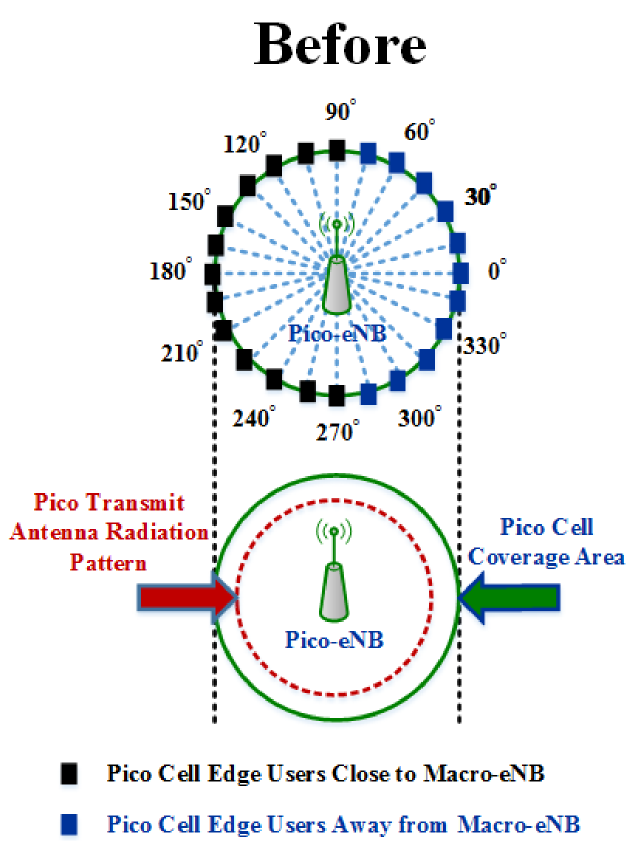

Figure 5.8 Pico-eNB antenna pattern before using smart antenna

Figure 5.9 displays the pico cell SINR (average) distribution as a function of the pico user location. It can be observed that, in a simple co-channel deployment of a macro-pico network, very few pico users have an acceptable SINR and CQI value. The SINR distribution within the pico cell in a macro cellular network is not uniform as observed from the plot.

The pico edge users residing on the macro side have high levels of the inter-cell interference as compared to those on the other side of pico who are not facing the macro. Therefore, interference preventive measures need to be taken more for the pico edge users facing the macro side so that macro can be muted for a little while without affecting the macro user scheduling operation.

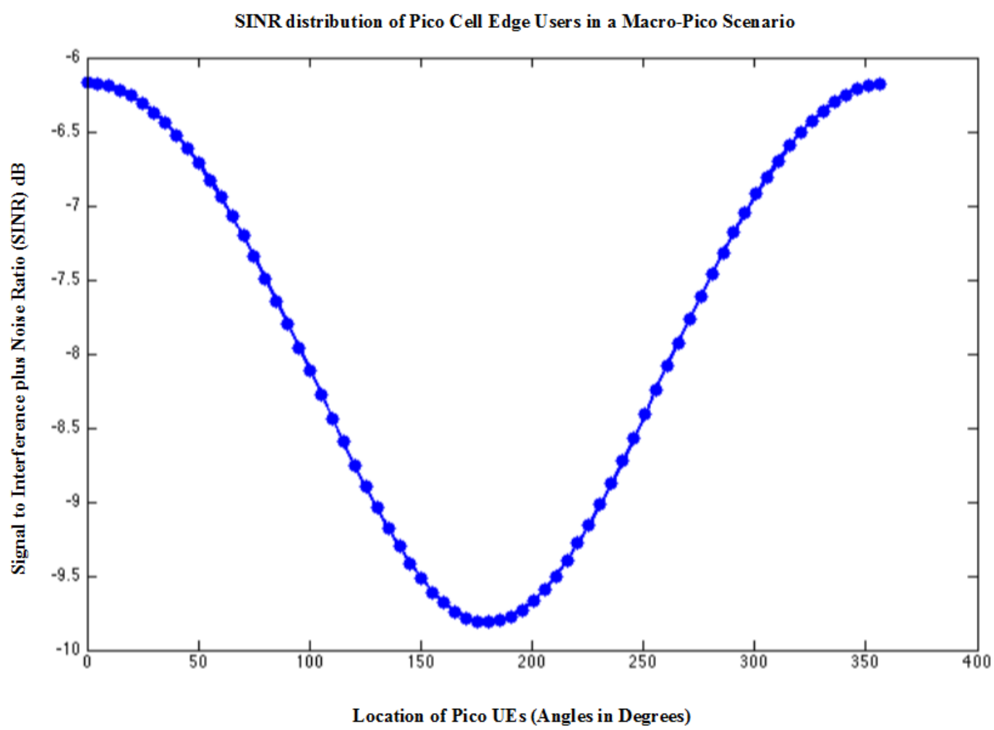

Figure 5.9 SINR distribution of pico cell edge users in a macro-pico network

After the SINR distribution vs. pico edge user location analysis has been performed, the pico-eNB transmit antenna gain is adjusted that will bring the SINR throughout the pico edge coverage to an equal value. Based on the SINR values obtained above, it is determined in which direction of the pico we can utilize more antenna gain to raise up the SINR values and in which direction the SINR values are acceptable and no higher gain needs to be provided. For that purpose, pico transmit antenna gain is provided from 1 dBi to 6 dBi in the steps of 1 dBi and the SINR behavior for each and every value of pico transmit antenna gain was observed. Here, it is found that the gain values that will equalize the SINR throughout the pico coverage area. Figure 5.10 shows the pico transmit antenna pattern after gain adjustment.

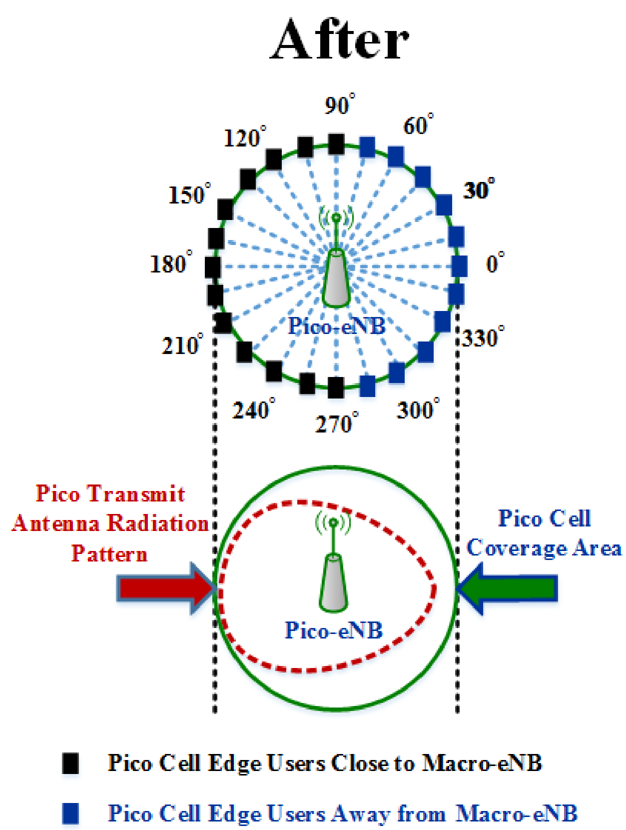

Figure 5.10 Pico-eNB antenna pattern after pico adaptive antenna

The simulation results give a substantial idea of the performance gain enhancements of the overall macro-pico network with eICIC with pico-eNB adaptive antenna. Figure 5.11 summarizes the cell net throughput along with macro cell throughout and pico cell throughput. The ABS muting pattern where macro is 80% ON and 20% OFF is identified as the highest throughput achieving muting pattern through simulations. The simulation results convey that, the system performance with eICIC pico-eNB smart transmitting antenna scheme is improved as compared to the sole eICIC scheme.

The macro cell throughput has lower values of bits transmitted per frame when compared to pico cell throughput levels of each ABS muting ratio. Because of the fact, pico carries a larger network load being deployed as a hotspot. The overall cell throughput levels consist of both macro and pico throughput combined.

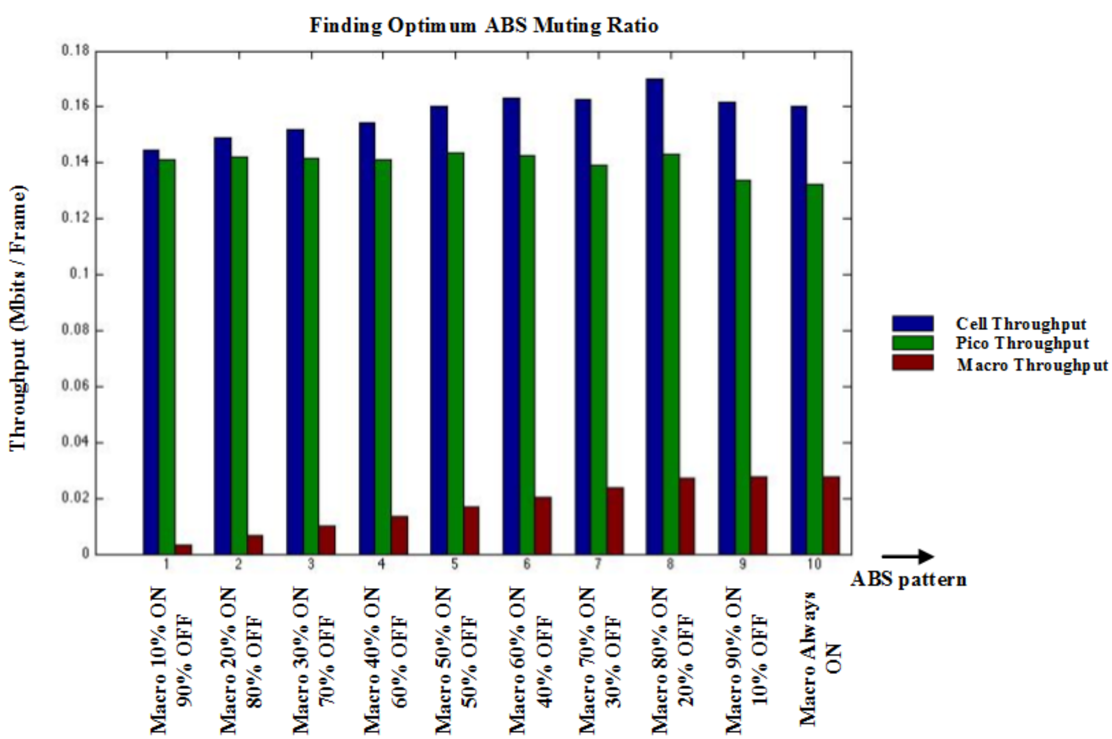

Figure 5.11 Network throughput levels with eICIC and pico adaptive transmit antenna

Figure 5.12 demonstrates pico cell throughput levels comparisons for eICIC and eICIC with pico transmit variable antenna gain. It can be seen that pico cell throughput is greater than that of eICIC for all ABS muting patterns when adaptive antenna is used at pico cell. However, when macro is muted for the 20% of the radio frame, gives the highest pico cell throughput value with variable antenna gain as well for the macro-pico network scenario considered in this thesis.

Equalizing pico users' SINR values by using adaptive transmit antenna at pico saves the serving delay of the pico users in the high inter-cell interference region. The key idea is that, pico users on the high interference side can have a fair chance to be scheduled on a regular sub-frame with their SINR values made equal or greater than the threshold SINR that can support the lowest modulation and coding scheme in LTE.

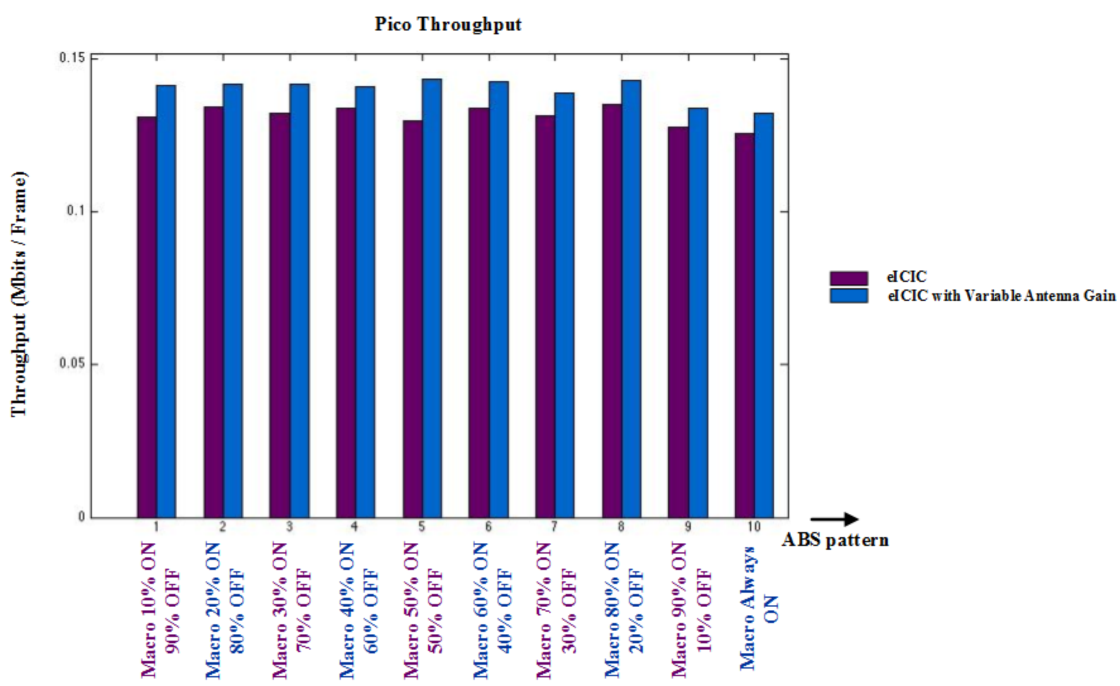

Figure 5.12 Pico cell throughput comparisons with eICIC and eICIC with adaptive antenna

In Figure 5.13, the overall macro-pico cell throughput levels are plotted for eICIC scheme and for eICIC with pico variable gain transmit antenna. The comparative plot exhibits that; there is a noteworthy gain in overall network throughput levels for ABS muting patterns.

Both macro cell and pico cell contribute in computing the overall network throughput per frame. Using adaptive antenna at pico makes it possible to obtain higher throughput per frame with the exact same network configuration parameters for all the muting patterns. The key difference is that pico's transmit antenna doesn't provide an omni-directional gain within pico's coverage area. The gain pattern is adaptive. The SINR distribution is adjusted within the pico based on the inter-cell interference conditions.

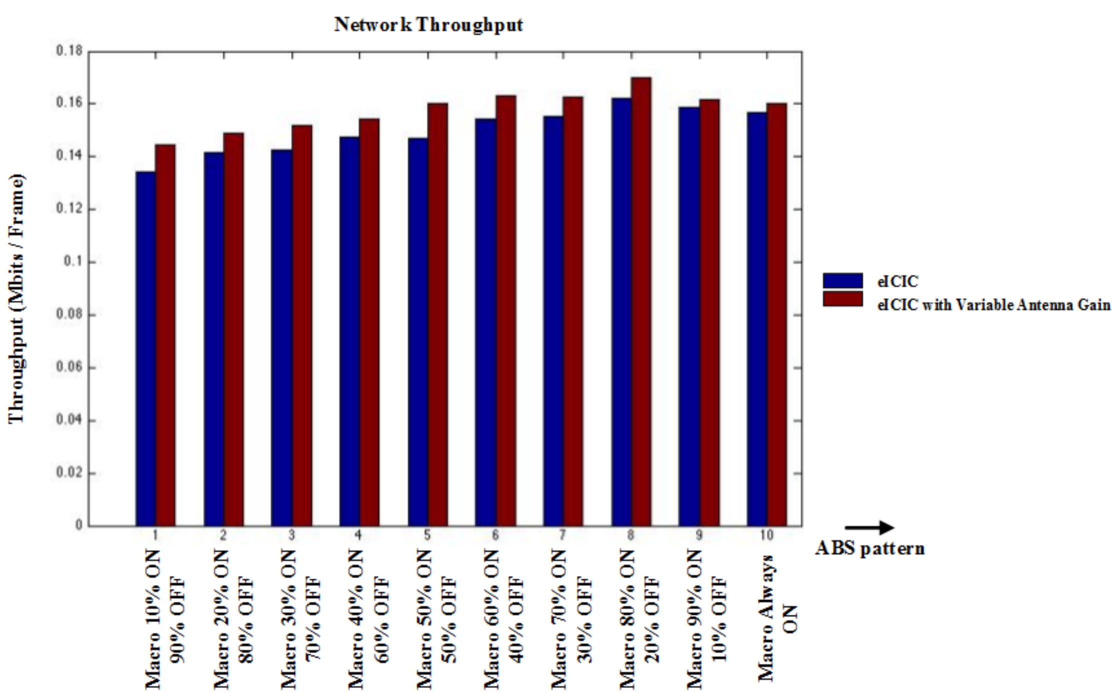

Figure 5.13 Overall cell throughput comparisons with eICIC and eICIC with adaptive antenna

The most important performance analysis is that of pico edge users' who are constantly being subjected to a higher extent of inter-cell interference. It is motivated to improve pico cell edge performance in the presence of inter-cell interference. In other words, pico center users are safer than pico edge users, because center users are close to the serving base station and far away from the interfering base station. Hence, in this thesis the analysis of pico cell edge user throughput is carried out in order to verify if the proposed scheme is effective enough to encourage pico edge users' scheduling.

Figure 5.14 explains the pico cell edge user throughput for eICIC and eICIC with variable gain pico transmit antenna. It can be observed that adjusting the antenna pattern towards pico edge users suffering with strong macro interference is beneficial. The pico edge user throughput has increased to a notable extent with the help of smart antennas.

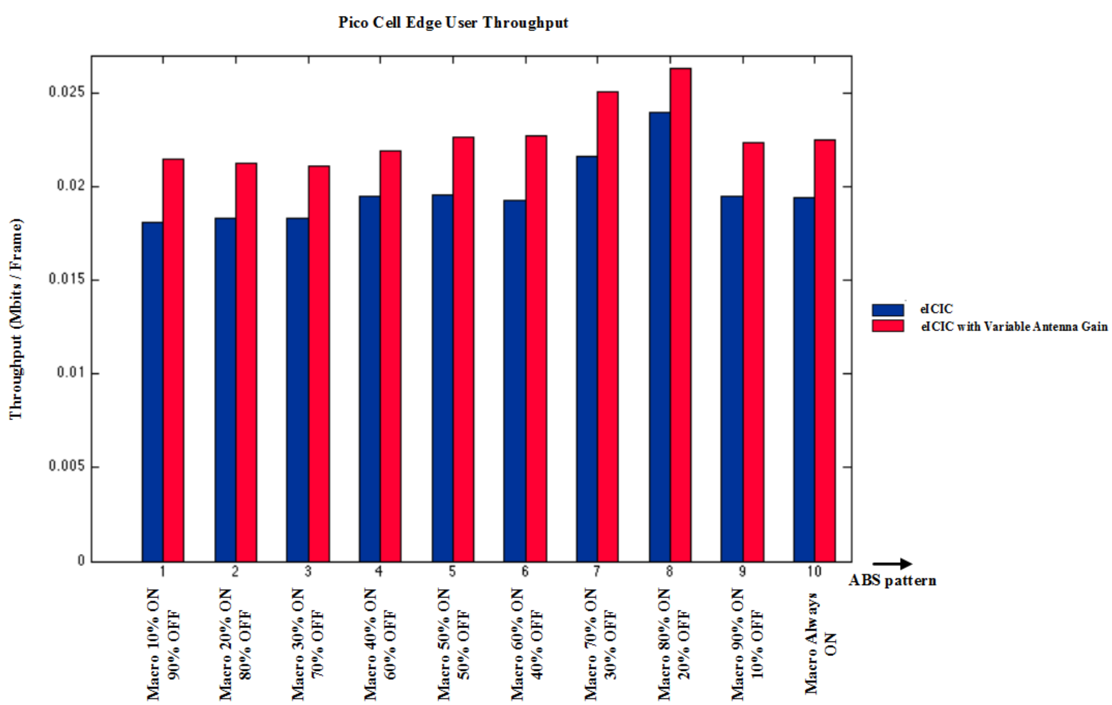

Figure 5.14 Pico cell edge users' throughput comparisons: eICIC and eICIC with adaptive antenna

6 Chapter: Conclusions and Future Research

6.1 Conclusions

In this thesis, the mutual interference between a macro cell and a pico cell within the LTE/LTE-A frame work is studied. In particular, it is assumed that a pico cell is located within a macro cell and that they share the radio resources. The purpose of this research was to further enhance what is known as “Enhanced Inter-Cell Interference Coordination” (e-ICIC) by allowing the pico cell to use adaptive smart antenna to modify the signal to interference ratio distribution within its coverage area. Using adaptive antenna radiation pattern use the antenna pattern of the pico cell to improve the overall system performance.

In this thesis simulations are performed, to note the dissimilarity between the existing Pico-cell Range Extension (PRE) technology and the newly introduced pico adaptive antenna technology. Range extension causes expanding the pico cell size beyond its predefined boundary. When the range extended users suffer a tremendous interference from the high power macro, the eICIC concept comes into picture and macro has to be muted for a while to allow scheduling of pico’s range extended users. Whereas, when the adaptive antenna is used at pico cell, the pico cell edge users’ SINR rises up to fairly decent values and they can be scheduled on regular sub-frames also. The delay action until macro is muted can be omitted when adaptive antenna is used to reshape the SINR distribution within pico cell.

In this thesis, a study was conducted about the state-of-the-art of LTE and LTE-Advanced networks. Despite the fact that boosting the spectral efficiency of the cellular system is a requirement for both operators and end users, it is understood that this demand introduces a severe interference into the network.

Inter-cell Interference Coordination (ICIC) schemes are mitigation/scheduling procedures invented for the uplink/downlink of OFDMA-based cellular networks in order to alleviate interference problem, in such a way that edge users in different cells are assigned, when desired, to complementary segments of the spectrum.

The development of interference mitigation techniques from Release-8 to Release-12 was discussed in this work. The study pointed out that interference is a major issue in LTE networks and the key solutions implemented in literature at the terminal end can be very much effective. Introducing pico base stations to form HetNets have the potential to considerably boost network performance. The key idea is to reduce the transmitter-to-receiver separation distance and enable better spatial reuse of the spectrum.

This thesis focuses specifically on the computation of the suitable Almost Blank Sub-frames (ABS) allocation ratio and dynamic distributed configurations of ABS based on the network traffic in LTE-Advanced heterogeneous networks. It is concluded that the ABS pattern is dependent on both the number of macro users and pico users in the network.

Also the impact of pico cell location within a macro network and pico cell size on the SINR distribution of pico cell has been studied comprehensively and validated using simulation results. A straightforward system level simulator is built up using the Monte- Carlo simulation method. Further, simulations have been carried out to study the effect of employing a variable gain adaptive array antenna as a pico transmit antenna to boost the SINR value of the interference affected pico UEs. The comparison among the performance analysis results of no-eICIC, e-ICIC and smart antenna interference coordination tools have shown a performance enhancement in terms of cell edge throughput. Thus, the objective of this thesis of achieving pico cell edge user throughput performance improvement is achieved successfully.

6.2 Recommendations for Future Research

The natural extension to the work presented in this thesis is to examine the general case of multiple pico cells and macro cells and to develop built-in algorithms that adjust the antenna patterns for each pico cell to optimize its own coverage in the presence of multiple interference sources.

The second extension of the work concerns the CRS (Cell Specific Reference Signal) which is considered to be a major source of interference in a HetNet scenario. Hence CRS interference cancellation is an important area of focus for future studies. Some CRS solutions are being studied to prevent CRS interference such as Successive Interference Cancellation (SIC) or the puncturing of CRS resource elements, these solutions are still being worked upon and will be a part of the Further Enhanced Inter-Cell Interference Coordination (FEICIC) in LTE Release-11.

For advanced networks beyond 4G, research and standardization work is still in progress and not yet finished. 3GPP team is currently finalizing Release-12 and developing new features in Release-13 aiming to further resolve interference problems especially the once caused by emerging of small cells.

Appendices

Appendix A Orthogonal Frequency Division Multiplexing (OFDM)

A.1 OFDM Concept

OFDM can be thought of as a hybrid of multicarrier modulation [63]. R.W. Chang first described it in 1966 at Bell Labs. An OFDM signal consists of a number of closely spaced modulated carriers. When modulation of any signal is applied to a carrier, then sidebands spread out either side. It is essential for a receiving end to be able to receive the entire signal to effectively demodulate the data.

When signals are transmitted close to one another they must be spaced so that the receiver can distinguish them using a filter and there must be a guard band between them. Although the sidebands from each carrier overlap, they can still be received without the interference since they are orthogonal. This is achieved by having the carrier spacing equal to the reciprocal of the symbol period [64].

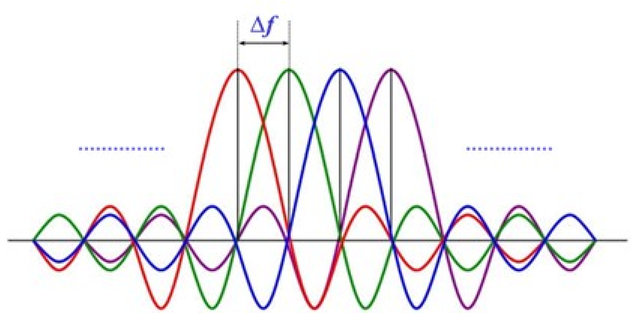

Figure A.i OFDM spectrum

A.2 OFDM Architecture

The data to be transmitted on an OFDM signal is spread across the carriers of the signal, each carrier taking part of the payload. This reduces the data rate taken by each carrier.

As shown in Figure A.ii, an efficient OFDM implementation converts a serial symbol stream of PSK or QAM data into a size M parallel stream. The required spectrum is then converted back to its time domain signal using an Inverse Fast Fourier Transform (IFFT); such that, the M streams are modulated onto M subcarriers via the use of size N $(N \leq M)$ inverse FFT. The N outputs of the inverse FFT are then serialized to form a data stream that can then be modulated by a single carrier. Note that the N-point inverse FFT could modulate up to N subcarriers.

When M is less than N, the remaining N -- M subcarriers are not in the output stream. Essentially, these have been modulated with amplitude of zero. A guard interval is inserted between symbols to avoid Inter-Symbol Interference (ISI) caused by multipath distortion (denoted by CP: Cyclic Prefix). The discrete signals are converted back to analogue. Although it would seem that combining the inverse FFT outputs at the transmitter would create interference between subcarriers, the orthogonal spacing allows the receiver to perfectly separate out each subcarrier [65].

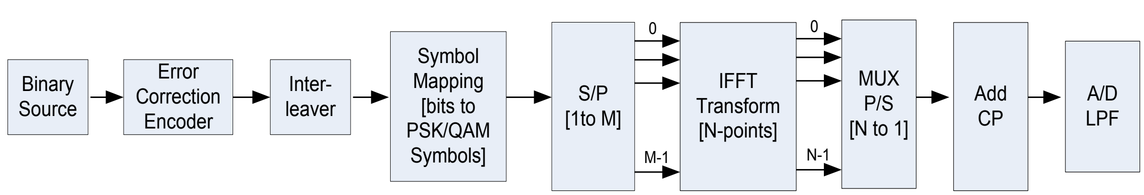

Figure A.ii General OFDM transmitter

Note that CP represents an overhead resulting in symbol rate reduction, and having a CP reduces the bandwidth efficiency but the benefits in terms of minimizing the ISI compensates for it.

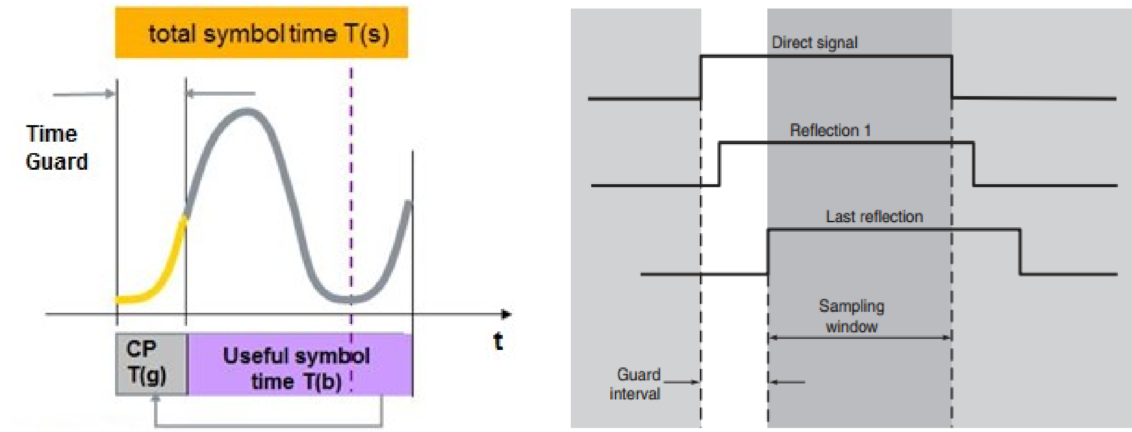

Figure A.iii   Guard interval

Figure A.iv displays the general OFDM receiver. The receiver performs the inverse operation of the transmitter. The received data is split into *N* parallel streams that are processed with a size *N* FFT. The size *N* FFT efficiently implements a bank of filters each matched to the *N* possible subcarriers. The FFT output is then serialized into a single stream of data for decoding. Note that when *M* is less than *N*, in other words there are fewer than *N* subcarriers are used at the transmitter; the receiver only serialized the *M* subcarriers with data.

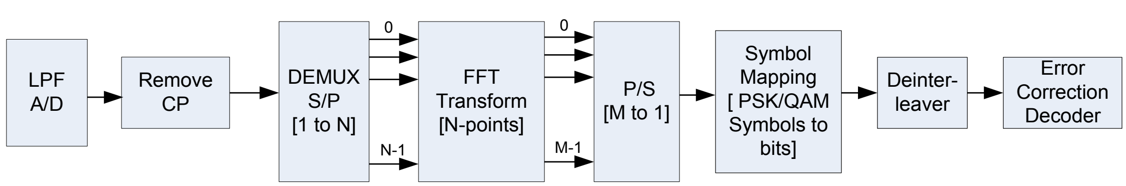

Figure A.iv   General OFDM receiver

Appendix B Modulation and Coding in LTE Release-8

LTE uses Adaptive Modulation and Coding (AMC) to improve data throughput. This technique varies the downlink modulation-coding scheme based on the channel conditions for each user. When the link quality is good, the LTE system can use a higher order modulation scheme (more bits per symbol), which will result in more system capacity.

On the other hand, when link conditions are poor due to problems such as signal fading, the LTE system can change to a lower modulation scheme to maintain an acceptable radio link margin [66]. The allowed modulation schemes for DL and UL are shown in the following tables.

B.1 Downlink

Downlink channels	Modulation scheme
PCH	QPSK
PDCCH	QPSK
PDSCH	QPSK, 16QAM, 64QAM

Physical signals	Modulation scheme
RS	Orthogonal sequence modulated by binary pseudo random sequence
P-SCH	
S-SCH	

B.2 Uplink

Physical channels	Modulation scheme
PUCCH	Based on Zadoff-Chu
PUSCH	QPSK

Physical signals	Modulation scheme
Demodulation RS	Zadoff-Chu
PRACH	U^{th} root Zadoff-Chu

The channel coding is turbo coding with coding rate of $^1/_3$ (for every bit that goes into the coder, three bits come out), based on $^1/_3$ turbo encoder used in 3GPP Release-6.

B.3 Downlink Frame Structure

Two radio frame structures are defined in LTE: frame structure type 1, which uses both FDD and TDD duplexing, and frame structure type 2, which uses TDD duplexing. Frame structure type 1 is optimized to co-exist with 3.84 Mcps UTRA systems. Frame structure type 2 is optimized to co-exist with 1.28 Mcps UTRA TDD systems, also known as TD-SCDMA.

Figure B.i shows frame structure type 1. A DL radio frame has duration of 10 msec. and consists of 20 slots with slot duration of 0.5 msec. Two slots comprise a sub-frame. A sub-frame, also known as the Transmission Time Interval (TTI), has duration of 1 msec. compared to 2 msec. TTI for HSPA systems. Shorter TTIs reduce the latency in the system and will add further demands to the mobile terminal processor.

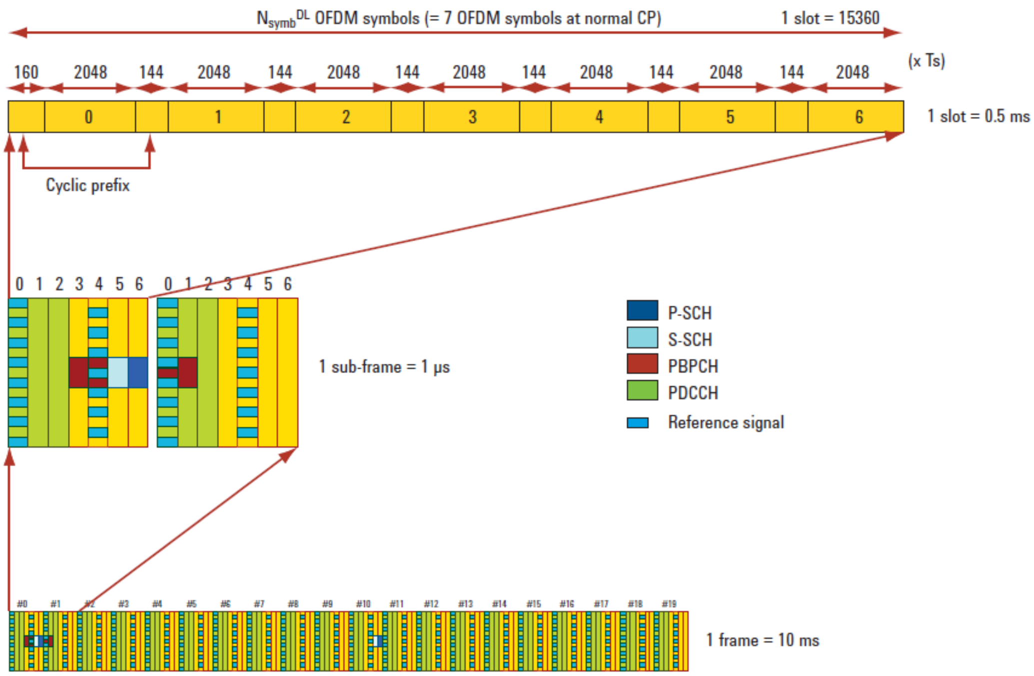

Figure B.i Frame structure type 1

As shown in Figure B.i, the physical mapping of the DL physical signals are:

• Reference signal is transmitted at OFDM symbol 0 and 4 of each slot. This depends on frame structure type and antenna port number.

• P-SCH is transmitted on symbol 6 of slots 0 and 10 of each radio frame; it occupies 72 sub-carriers, centered around the DC sub-carrier.

• S-SCH is transmitted on symbol 5 of slots 0 and 10 of each radio frame; it occupies 72 sub-carriers centered around the DC sub-carrier.

• PBCH physical channel is transmitted on 72 sub-carriers centered around the DC sub-carrier.

B.4 Downlink slot structure

The smallest time-frequency unit for downlink transmission is called a Resource Element (RE), which is one symbol on one sub-carrier. A group of 12 contiguous sub-carriers in frequency and one slot in time form a Resource Block (RB) as shown in Figure B.ii. Data is allocated per User Equipment (UE) in units of RB.

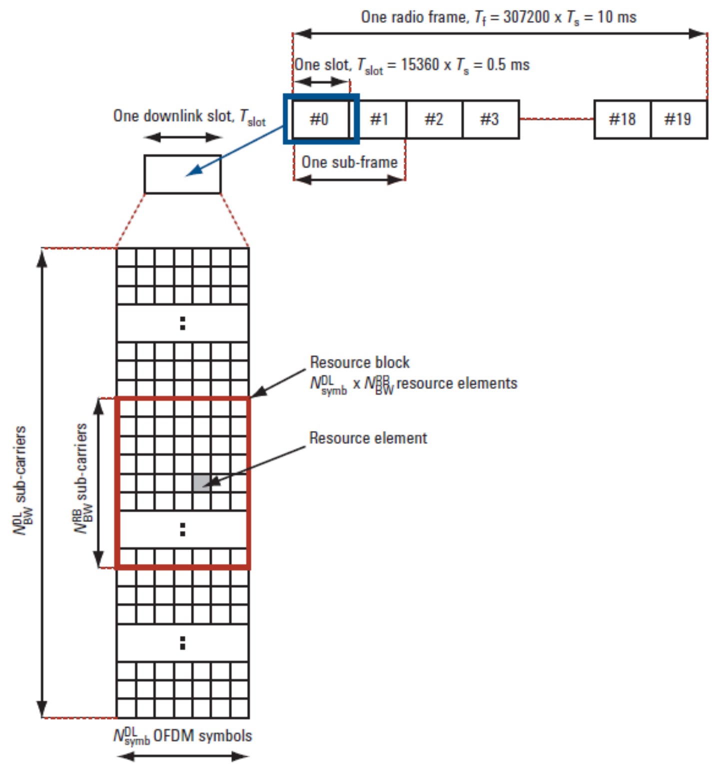

Figure B.ii Downlink resource grid (Ref 3GPP TS 36.211 V8.0.0 Figure 6.2.2-1)

For a frame structure type 1 using normal Cyclic Prefix (CP), a RB spans 12 consecutive sub-carriers at a sub-carrier spacing of 15kHz, and 7 consecutive symbols over a slot duration of 0.5 msec. as shown in Table B.i.

A CP is appended to each symbol as a guard interval. Thus, a RB has 84 resource elements (12 sub-carriers x 7 symbols) corresponding to one slot in the time domain and 180kHz (12 sub-carriers x 15kHz spacing) in the frequency domain. The size of a RB is the same for all bandwidths; therefore, the number of available physical RBs depends on the transmission bandwidth. In the frequency domain, the number of available RBs can range from 6 (when transmission bandwidth is 1.4MHz), to 100 (when transmission bandwidth is 20MHz).

Table B.i Resource block parameters (Ref 3GPP TS 36.211 V8.0.0 Figure 6.2.3-1)

Configuration		N_{symb}^{DL}	N_{symb}^{DL}	
			Frame structure type 1	**Frame structure type 2**
Normal cyclic prefix	Δf=15 kHz	12	7	9
Extended cyclic prefix	Δf=15 kHz		6	8
	Δf=15 kHz	24	3	4

Appendix C Pico Cell Deployment and Modeling

C.1 Pico Outdoor Model

According to [7], Pico Cell is modeled as a 2-dimensional rectangular block (100x100 meters) as seen in Figure C.i.

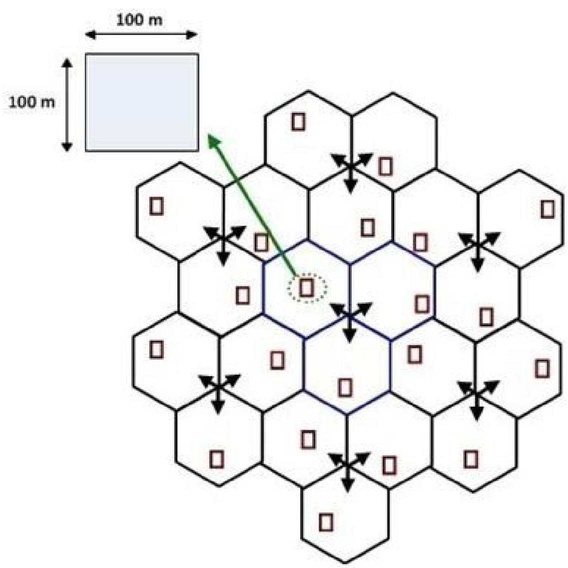

Figure C.i   Outdoor Pico Cells deployment within Macro layout

- Propagation path loss model:

PL (dB) =140.7+ 37.6log$_{10}$(R)), R in Km…………………………………………….(C.1)

C.2 Pico Indoor Model

The model is a large office building with an open floor plan layout [46]. Figure C.ii demonstrates an idea of the environment. The parameters of the pico environment are the following:

- Building size = 100x100 meters

- Room size = 23x20 meters

- Corridor width = 4 meters

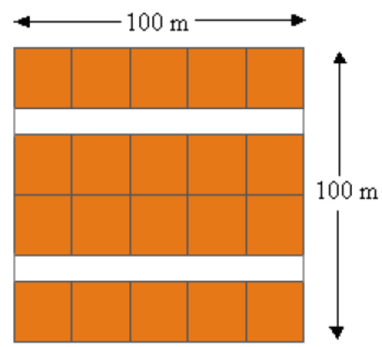

Figure C.ii Pico indoor model

- Propagation path loss model:

PL (dB) = 38 + 30 log10 R, R in meters……………………………………………(C.2)

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