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Performance evaluation of eICIC algorithms in LTE HetNets

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Dedication

To the loving memory of my father Demeke Tsegaye, who allowed me to perceive the value of education.

And

To: Netsanet, Dave, Nigus, Benjamin, Lydia and TGye for their love, support and encouragement.

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First and for most, I would like to THANK GOD for giving me the strength and courage through all the hard times and for blessing me with friends and family that always have been by my side and helping me when I needed it the most. Well, praising God goes without saying for me, for it will be a very long list of "Thank You God ...", even if I had to mention very few of them.

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Abstract

It is not a hidden fact that, in today's wireless and cellular networks, businesses and end users have clearly become dependent on mobility and the freedom of being always online. Smart phones, tablets and other devices are expected to be connected all the time and the applications on these devices are required to run smoothly. That is, for a mobile network to even be considered to have the minimum requirements from its users today, network problems like dropped calls, choppy videos and slow downloads should be out of the question. However, with the fast growth rate of wireless communication devices competing for spectrum, the mobile access networks that we have today will soon reach their maximum capacy. To address these high expectations, mobile network operators are employing new strategies in densely populated areas and commercial buildings where spectrum scarcity is highest. 3GPP has been working on LTE Advanced (Long Term Evolution - Advanced) in order to improve the spectral efficiency by employing Heterogeneous Networks (HetNets). HetNets improve the business model for mobile network operators and users by introducing network topologies which are less costly and are able to increase the capacity and coverage provided by the traditional macro cell mobile networks. HetNets are comprised of macro cells and low cost - low power base stations like picocells, femtocells, relays and other small cells along with WiFi-APs and distributed antenna systems (DAS). With HetNets a significant network capacity gain and uniform broadband experience can be provided to the users anywhere and at low cost, since the spectrum can be re-used across the multiple tiers in the network. However, HetNet deployments come with a lot of challenges and advanced interference control and management techniques are required to get the highest possible benefit from these networks. The enhanced Inter Cell Interference Coordination (eICIC) technique has been studied previously to address the interference problem that these small cells experience from macro cells. This thesis will concentrate on the performance improvement achieved when eICIC mechanisms are introduced to a simple HetNet. The eICIC approach as described in 3GPP's Release 10 involves two mechanisms, which this thesis also tries to take into consideration. These are the CRE (Cell Range Expansion) acheived through cell bias adjustments and ABS (Almost Blank Subframe) ratio. A discussion about the importance eICIC in SON - Serlf Organizing Networks will also be done.

Keywords: Almost Blank Sub-Frame,ABS, Enhanced Inter Cell

Interference Coordination, eICIC, Heterogeneous Networks, HetNets, Cell Range Expansion, CRE

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Part I

Introduction to HetNets and eICIC

Chapter 1

Introduction

This Chater will be an introductory part outlining the basic reasons of why we needed HetNets. This will be followed by a short problem statement about the work done in this thesis and finally, a description of the structure of the rest of the thesis will be presented.

The continuous exponential growth in distribution and usage of smart phones, tablets and other mobile communication devices together with the electronic devices we use in our everyday activities (like smart TVs, ATMs, indoor and outdoor appliances and transportation devices) are generating a continuous and enormous growth of bandwidth requirements for mobile networks and applications. Although, there has been considerable improvements in the broadband technologies today(like WiMAX and LTE) aiming at a much better performance in the 3G and 4G cellular technologies that are currently being used, they will definitely be unable to compensate or meet the expected increase of mobile traffic in the very near future. As shown in Figure 1.1, the monthly mobile voice and data traffic measured by ericsson proves that the data traffic increase observed in Quarter 1 of 2014 is more than 3X compared to how it was in Quarter 1 of 2012, while the voice traffic change is not as significant as the data traffic.

Following the direction 3GPP has introduced in Release 10 [[16] Section 16], within the long-term evolution-advanced (LTE-A) specifications, heterogeneous networks (HetNets) which involve the use of existing macro - cells and small-range (i.e., pico, micro, and femto) cells, seem to be one of the very few possibilities to follow towards finding the future solution in order to address the enormously growing bandwidth demand. Small cells could maneuver the enhancement in the coverage and capacity in densely populated areas inside the traditional macro-cell deployment. 3GPP has also made special consideration to femto-cells for providing a better broadband coverage in home and office installations, and also for outdoor deployments where a small geographical coverage is required. Femto-cell deployments have actually become of more interest for mobile network operators, since studies show that home and commercial environments will be the the ones that would generate most of the data and voice communications in the near future. However, the deployment of HetNets does not come without inferring bigger challenges. In fact, HetNets nature of includ-

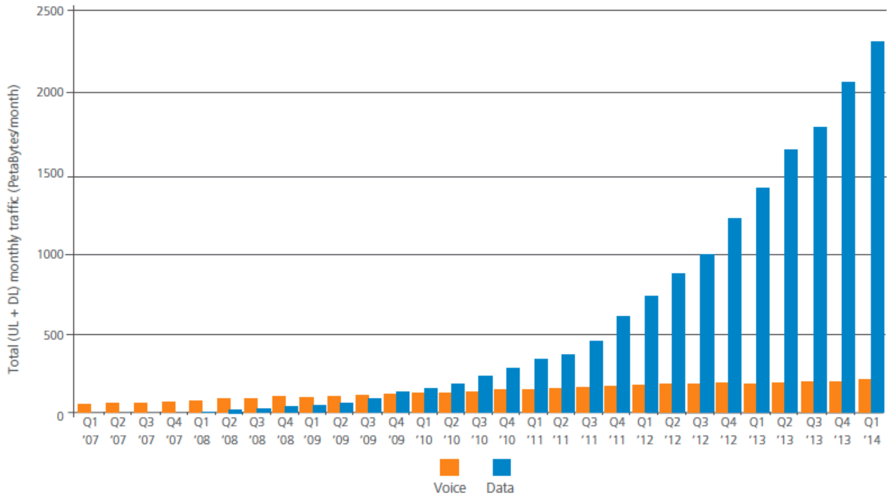

Figure 1.1: Total monthly mobile voice and data measured by Ericsson

ing several type of low power small-cells overlaid in the macro-network, would create a great deal of macro to small - cell or small - cell to small - cell interferences.[4] Apparently, an accurate and precise simulation and performance evaluations of the proposed Inter-cell Interference coordination and management mechanisms has become inevitable in order to decide the most appropriate deployment scenarios of small-cells in the existing broadband cellular networks.

1.1 Statement of the problem

A lot of studies have been made in the past to point out the importance of eICIC (Enhanced ICIC) algorithms in achieving the best possible performance improvement of Heterogeneous networks (HetNets). However, the exact implementation of the ABS (Almost Blank Subframe)mechanism for eICIC is left for operators. And since the Self Organizing approaches followed by each network operators differ greatly in different parts of their network, so does the appropriate association and decision rules for CRE (Cell Range Expansion) and Resource Block allocations also. Determining the radio resource allocation schemes and patterns by using ABS techniques and evaluating the results that could be obtained by using these schemes is, therefore, a very important part of HetNet deployments. To achieve acceptable results, the methodology followed in this thesis work is:

- Background study to get a good understanding of the problem and learn about the different approaches that are being used/are proposed to be used for inter - cell interference coordination and management in HetNets.
- Get familiar with the LENA - LTE/EPC network simulator which

is based on the popular open source internet systems simulation platform (NS - 3).

- Implement ABS mechanisms in a simple HetNet scenario to address the Inter - cell interference problems in these type of networks, (eICIC mechanism), in LENA - LTE simulator.
- Evaluate and compare the simulation results obtained with the theoretical assumptions or other previously done studies on this topic.
- Draw conclusions based on the observations made and suggest a preferable path to future enhancements and HetNet deployments.

1.2 Description of remaining chapters

The rest of the thesis is organised as follows:

Chapter 2 - Background and Review of Literature: will be focused on the background study that has been carried out as a basis for this thesis work. LTE network architecture, LTE HetNets and the importance of eICIC mechanisms in LTE HetNets has been studied.

Chapter 3 - LENA LTE/EPC and NS3: This section of the thesis is about getting to know what the LENA project and the LTE/EPC simulator done in conjunction with NS - 3 was about. An X2 interface or messaging module modification has been done and some time was spent to go through these changes and understand what has been done in this context.

Chapter 4 - Methods of Inter - Cell Interference Coordination: This chapter discusses about the different Inter - Cell Interference coordination and management mechanisms that have been proposed and standardized by 3GPP. The different types of ICIC mechanisms mentioned could be implemented to give acceptable results in different deployment scenario, but ABS technique for eICIC has been proven to be better in HetNets and it has been discussed in detail.

Chapter 5 - ABS and CRE for eICIC implementation in NS3: This chapter concentrates on the implementation details that has to be carried out in order to realize ABS for eICIC. The topics outlined in this section include: Cell selection and Cell Range expansion (CRE), Victim UE selection and Protection, packet scheduling strategies and Scheduler modification made in the course of this thesis, and finally the ABS mechanism and implementation in detail.

Chapter 6 - Simulation Results and Conclusion: This chapter covers the results obtained in the simulation process of ABS technique for a simple HetNet scenario and make some conclusions based on the results. A suggestion of what could be done in the future has also been done.

Appendices are also included in the end:

Appendix A - Glossary: A list of abbreviations used in this thesis.

Appendix B - Files: A description of files that follow with this thesis.

Appendix C - Source Code: An outline of the source files and organization of these files if one wants to set the simulation up as it is done in this thesis.

Chapter 2

Background and review of litrature

This chapter will focus on describing the basic theoretical aspects which are relevant for this thesis, which are LTE Advanced network, Heterogeneous Networks (HetNets) and enhanced Inter Cell Interference Coordination techniques as standardized by 3GPP.

In Heterogeneous Networks (HetNets), both the macro-cell base stations and the underlying small-cell (low powered) base stations are often called eNodeBs or eNBs; and these base stations can be using similar technologies (like LTE) or different technologies (such as, the Macro using LTE while the small-cell base stations would be using WiFi). In order to achieve the purposes of HetNets in increasing the overall network capacity, provide enhanced coverage and customer experience, some mechanisms should be in place to allow operators to dynamically deploy small-cells for better coverage and efficiently offload the Macro eNB data traffic. This is done by considering different parameters of the network such as traffic characteristics, QoS demand, network congestion and so on. In order to make a good basis for the interference coordination techniques in the coming chapters, the next sections of this chapter will discuss some of the most basic theoretical aspects of Heterogeneous Networks and eICIC. It's worth mentioning that by the time this thesis is conducted there has already been extensive studies and towards the deployment of Heterogeneous Networks and evaluations of the techniques to cell coordination for these type of networks.[4][24][14]

2.1 LTE Network Architecture

In order to address the problems or demands caused by the enormously growing mobile data traffic, the 3rd Generation Partnership Project (3GPP) standardized a new broadband technology in its release 8 in march 2009 and named the technology as Long Term Evolution (LTE). The introduction of new features (like flat network architecture and flexible spectrum) in LTE made it possible to give the current cellular networks a much better performance compared to the networks which were based on previous standards from 3GPP (like HSPA+ which is also called Evolved 3G), especially when considering down link (DL) and up link (UL) peak data rates, spectral efficiency and latency.[21] At the end of 2010, 3GPP made a lot of improvements to the previous release of LTE and came up with LTE-Advanced (LTE-A). This release is submitted in order to meet the requirements of the International Mobile Telecommunications - Advanced requirements that were published in 2008.[8, 26]

The enhancements that were made in order to come up with the LTE technologies include the modification of the Radio Access Network (RAN) and the core network itself. This resulted in a new core network called as Evolved Packet Core (EPC) and a new and modified RAN called as Evolved Universal Terrestrial Radio Access Network (E-UTRAN). Figure 2.1 shows a high – level overview of the LTE architecture along with the standardized interfaced. Here, we will only discuss only some of the components making up the LTE architecture which are specifically related to the work in this thesis.

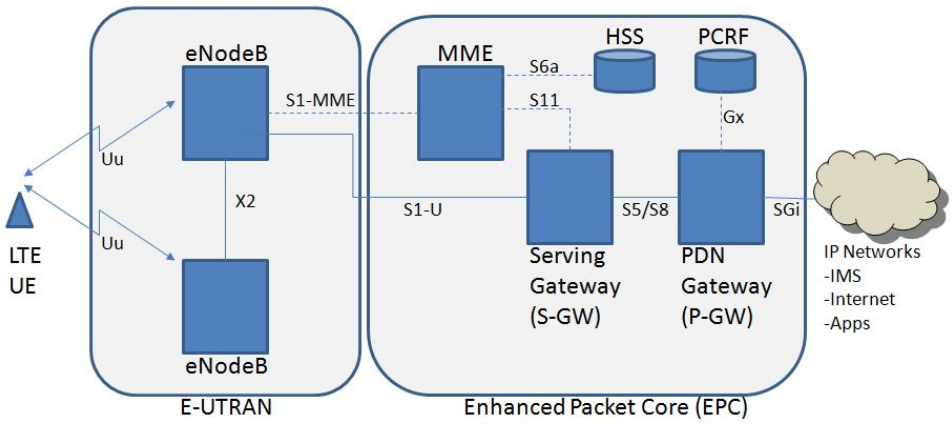

Figure 2.1: LTE Network Architecture with its standard interfaces (Image taken from [20])

E - UTRAN: carries out the task of providing the radio communication need to connect the UEs (User Equipments) to the Evolved Packet Core (EPC). And the Evolved Node Bs (eNodeBs) are equivalent to the the traditional base stations but with much more enhanced features. The eNodeBs use the S1 interface in order to relay data from the UEs to the EPC. In addition to macro eNodeBs (MeNB), which have a high Tx power, the E - UTRAN also has other alternatives of eNodeBs with lower Tx power. This includes eNodeB variations like Pico eNode (PeNB), Femto eNodeB (FeNB) and so on. These lower power eNodeBs are underlaid in the E – UTRAN in such a way that they would complement the high transmission power eNodeBs. The PeNBs for example are deployed outdoors in city center or metro areas where as FeNBs are deployed indooers to provide and enhance coverage in home and office installations.[16] In addition to relaying data to the EPC, the following are some of the additional functionalities of eNodeBs:

- **Radio Resource Management (RRM):** this functionality is to carry out the administration of radio resources, scheduling (dynamica allocation of UL or DL resources).
- **Radio Mobility Management (RMM):** this is to carry out tasks of measuring, and analyzing mobility in order to make handover decisions.
- **Radio Resource Control (RRC):** is about the functionality of facilitating the reserving, modifying or allocating resources for the transmission between the UEs and eNodeBs.

The X2 Interface: is a logical interface that interconnects two eNodeBs. In the practical E – UTRAN the logical point to point link between two eNodeBs should be possible even if there is no physical direct connection between the eNodeBs. This interface is mainly used for the exchange of signaling information between the eNodeBs, which helps the network acheive some of the features of the E - UTRAN mentioned above. The X2 interace model that has been implemented in the LTE – LENA simulator depicts a point to point link between the eNodeBs. That means a point – to – point device is created in both eNodeBs and both point – to – point devices are attached to the point – point – link.[2] More on the X2 interface and the modification made to the LENA X2 interface messaging module in the course of this thesis is presented in chapter chapter 3 - The LENA LTE Project and NS-3.

2.2 LTE HetNets

As it has been mentioned in the previous chapter, a systematically studied network planning is the key approach to addressing the enormous increase in the mobile broadband subscribers and services that are continuously becoming bandwidth – sensitive in terms of the limited radio resources available. Operators have been reacting to these challenges by continuously enhancing the capacity by introducing new radio spectrum, adopting modulation and coding scenarios that are more efficient and also finding a ways to implement new multi-antenna schemes. However, these techniques and scenarios alone will not suffice in addressing the challenges in areas where mobile broadband subscribers are densely populated or around cell edges where the network performance decreases very fast. Therefore, operators have also started actively researching and deploying small – cells and carefully integrate them with their existing macro networks to help with traffic offloading, performance improvement and QoS while re – using the spectrum in the most efficient way.

Keeping the macro – network in its homogeneous state and trying to expand it by adding more macro – cells (MeNBs) could have been one way of adding more performance to the network. But, decreasing the macro – to – macro distance is only possible to a certain limit. And Moreover, it would be very difficult to deploy more MeNBs, both cost wise and location wise. Specially, in city centers and metro areas. An alternative solution operators are implementing to address these problems is using small – cells by using low – power (low – range) base stations (such as eNBs, PeNBs, HeNBs or Relay Nodes (Rns)) and Remote Radio Heads (RRHs) in to the existing Macro – cell (MeNB). The resulting network with this kind of approach will be a Heterogeneous Network (HetNet) which brings a new kind of topology to the network, where MeNBs covering large area with underlaying small – cells that help the macro – cell to achieve higher bit rates in a unit area. Figure 2.2 shows a typical LTE HetNet architecture.

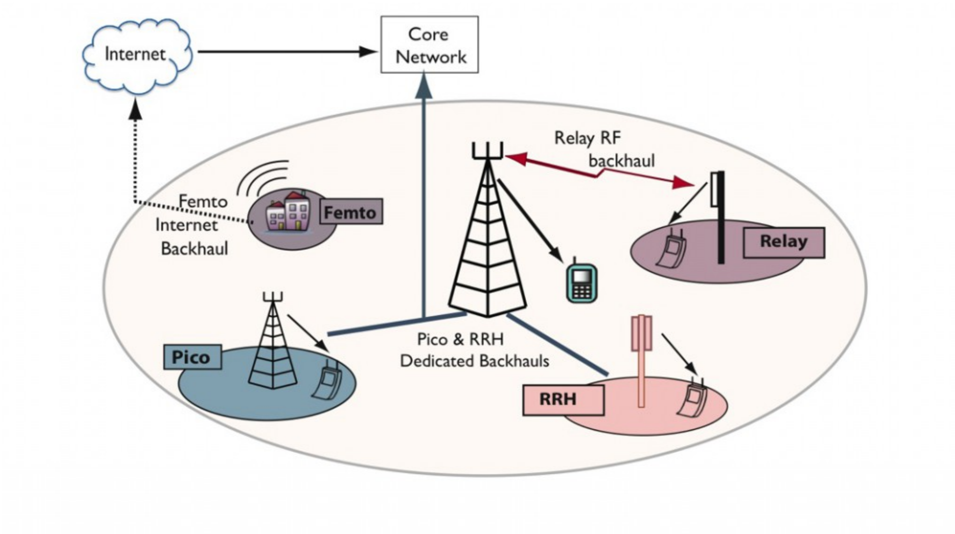

Figure 2.2: LTE Hetnet Achitecture with macro and small cells
(Image taken from [7])

As it is depicted in Figure 2.2, In decreasing transmission power these small – cells of HetNets are called as macro - , micro - , pico - and femto – cells and the corresponding cell sizes doesn't only depend on the transmission powers of the eNodeBs, but also on the deployment environments and antenna positioning. (such as indoor, outdoor, metro, city and rural sites). The Femto eNodeBs (FeNBs) that were introduced in LTE Release 9 [21] are designed with a primary purpose of serving and enhancing indoor coverages (such as commercial building deployments). The unplanned mass deployment nature of FeNBs and the fact that they are privately owned by home and office owners makes them create the so called Closed Subscriber Group (CSG); and thus FeNBs are only accessed by specific set of UEs in that subscriber group. This creates another level of interference between the surrounding FeNBs combined with the interference from other cells in the area. A variety of femto – cell interference management solutions have been studied depending of the physical layer technology and specific deployment scenarios. Most of the approaches followed in this case require the FeNBs to frequently communicate with the MeNB and the PeNB so that UEs suffering from interference could be identified through the backhaul and an interference management will be done. This thesis will not consider the femto – cell interference coordination scenarios but there are a lot of references that could help in the implementation if one is interested on that area.[27]

Another type of small – cell in HetNets is the Relay Node (RN), which is also a low – power eNB which was standardized in LTE Release 10 [16]. The RN is connected via the Un radio interface to the eNB from which it relays the signal. The RN thus faces interference when the Uu and Un are using the same frequency. RN interference management is also not covered in this thesis, but the reader can get more information about this from the the studies and implementations which have already been done in this aspect.

2.3 LTE HetNets and eICIC

As we have discussed in the previous sections of this chapter, the true advantage of HetNets over the traditional homogeneous networks comes with the use of different types of low – power small – cells effectively deployed with macro - cells. However, the expected performance improvement of HetNets would almost be impossible to achieve if the proper interference coordination mechanisms are not in place. In Release 8 and 9 of 3GPP, an Inter – Cell Interference Coordination (ICIC) mechanism was introduced. And ICIC helped to some extent in achieving the high frequency reuse factor set by the LTE standards. Cell edge users in homogeneous networks benefited a lot more when ICIC was implemented since the mechanism implemented different types of frequency reuse schemes to allow cell edge UEs use different sub carriers or resource blocks (RBs). Which resulted in an improved SINR levels to the cell edge UEs. But since ICIC technique allocates different sub carriers only when delivering data channels and control channels are not transmitted through different sub carriers, this caused interference from the control channels used by the neighboring cell edge users. Enhanced ICIC (eICIC) on the other hand is not a frequency domain interference coordination mechanism, instead it uses the time domain to allow cell edge UEs to use the resource blocks in different time domains. Therefore, eICIC is a more preferred technique in the interference management in HetNets. A detailed comparison between the ICIC and eICIC mechanisms is made in the section 4.1.

Part II

Methodology

Chapter 3

LENA - LTE/EPC with NS-3

This chapter will be about the simulation environment used in this thesis. The LENA-LTE/EPC project is based on NS-3 network simulator and it is the simulation evironment used in this thesis and an overview of both of them along with the X2 interface module modification that has been done in the course of this thesis.

3.1 LENA-LTE/EPC project

LENA is an open source and Long Term Evolution – Evolved Packet Core (LTE – EPC) simulator which is developed based on the well known discrete network simulator (NS – 3) for mobile and Internet systems. It provides operators with a test bed to design and evaluate the performance of algorithms for SON, HetNet and ICIC solutions. The version used in this this thesis is the LENA V8 which is also included in ns-3.19 release [19] as an all-in-one distribution. Building the stable N3 - 3 all in one distribution or cloning the development version from the official repository is well documented in the NS-3 website.[13]

The LENA project is a product – oriented simulation environment that is designed based on the industrial API – Small Cell Forum MAC Scheduler Interface and it aims mainly on creating a favorable and publicly trusted simulation platform for designing and evaluating high level requirements such as:

- Inter – cell interference coordination and management solutions.
- DL and UL packet schedulers.
- Traffic Offloading (Load balancing) and mobility management.
- HetNet solutions.
- End – to – End QoS provisioning , between a UE and a Remote Host for example.

And the models that are developed under the LENA project include:

- **MAC and Scheduler Model:** in this scheduler module the resource allocation type used is Resource Blocks that might be grouped in to RBGs if needed. The model has also an Adaptive Modulation and Coding and Transport Block model. The schedulers that are developed as part of the LENA project are Round Robin (RR) and Proportional Fair (PF) schedulers but other schedulers are also included in the official release of NS-3. All the different algorithm apply for the DL only, but for the UL all current implementations use RR.

- **The HARQ Model:** uses the combined subsequent transmission attempts to determine the overall success probability of transmissions and that enables a faster recovery from errors. HARQ is handled by the Scheduler.

- **PHY layer Model:** The biggest assumption in this model is that it only models FDD with a frequency domain granularity of Resource Block (RB).The time domain granularity is 1 TTI which is further divided in to DL (control + data) and UL (control + data, SRS). The model also provides CQI feedback and error model in order to evaluate the correctness of the transmissions and different frequencies and bandwidth for eNBs.

- **Radio Propagation Models:** are the models that deal with radio propagation topics, such as Buildings model, Path Loss model, Fast fading model and Antenna models. Most of these models were developed inside the LENA project but are not specifically devoted to LTE, i.e. they can also be used in simulating other wireless solutions, like WiFi for example.[19]

3.2 NS-3 Overview

NS - 3 is also a GPLv2 license open – source discrete – event simulator written in C++ with optional python bindings for wired, wireless Internet systems and with LENA – LTE simulator API added, it became one of the very few real – world alike LTE simulators. NS – 3 can simulate a complete communication system with detailed modeling from MAC layer (Layer 2) up to Application layer (Layer 7). At the PHY layer (Layer 1), NS – 3 has more or less a simplified modelling. This mainly is because of the need to make the simulator scalable to larger simulation scenarios, for example, with 100s of eNBs and 1000s of UEs. If it had to have very detailed modelling at the PHY layer with detailed signal processing, then such large simulation scenarios would have been difficult to run and would take very long time to finish. Therefore, NS – 3 and most of the network simulators out there have the model granularity to a ' packet ' level, where as other system level simulators have a granularity level of 'session' and link level simulators have a granularity of 'PHY symbol' and the Radio level granularity of the LENA LTE model is 'resource block'. NS – 3 has no official GUI and IDE, it is expected to be run from the command line an if one wants to write simulations, then one has to write the C++ or Python scripts in ones preferred programming IDE. And depending on what we put inside the node container in NS – 3, a node can be anything from a base station, laptop, mobile phone, sensor node and so on. And for every type of NetDevice that is put in a node (Ethernet Net Device, LTE NetDevice, Wifi NetDevice and so on), there is a corresponding channel model that goes with it. One exception to this in NS – 3 is the Spectrum Channel, which is used by different kinds of NetDevice models, i.e. the spectrum channel model can be used by Wifi NetDevice or Bluetooth and so on. This makes it possible for different network devices to share the spectrum channel (as it is in the real world) and that the interferences that occur by having different kinds of these Net Devices in this channel can be computed and evaluated more realistically.

NS – 3 has a modular architecture. In addition to its main modules (Core, network, internet and applications modules), NS – 3 has a collection of several other simulation models, like wireless model, antenna model, propagation, aodv, olsr, lte and so on, that allow us to simulate different scenarios of our interest. And as part of the X2 interface messaging module modification, some part of the lte – module was modified in the course of this thesis and a new module had to be added in the local NS - 3 installation. An overview of the modified files of the 'lte' model and the new model added is given in Appendix C 7.2 and a short explanation related to the X2 interface modifications done is given in Section 3.3.

Simulation Outputs : can be in one of the following KPI (key performance Indicator) formats:

- For Channels – SINR maps and Path loss matrices
- For PHY – TB (Transport Block) tx/rx traces and RSRP/RSRQ traces
- MAC – UL/DL scheduling traces

3.3 X2 Interface/messaging Modification

As described in Section 2.1, the X2 interface is a logical link between eNBs is in HetNets that is mainly used for the exchange of signaling information between the eNBs.[13] See also Figure 5.3 To achieve this goal, the LENA project has modelled the interface in to two planes, which are:

X2 – U (Data Plane) : IPv4, GTP, and UDP are implemented with point – to – point links. (ns3::PointToPoint)

X2 – C (Control Plane) – supports handover primitives that are used for X2 based handover and SON primitives which are used for Self – Organizing Network solutions (in our case eICIC). These SON primitive categories are LOAD INFORMATION and RESOURCESTATUS UPDATE.

In order to make use of these SON primitives and exchange information, like the traffic load at the PeNB, number of CRE – UEs that are under interference, and RLC buffer size between the MeNB and

PeNB, a modification of the X2 model has been done where new messages were introduced to achieve this information exchange. See also Section 7.2. The CSB added to the PeNB in order to account for the Cell Range Expansion, can also be sent to the MeNB over the X2 interface but also over the backhaul to the neighboring eNBs to help the UEs in taking efficient handover measures.

Chapter 4

Methods of Inter - Cell Interference Coordination (ICIC)

This chapter will describe the different type of cell interference coordination and management methods that are bing implemented. And finally focuses more on the eICIC ABS mechanism implementation.

4.1 ICIC vs eICIC

ICIC that was introduced to HetNets in 3GPP Release 8 [15] and to mitigate inter – cell interference for cell edge UEs, the eNBs can communicate via the X2 interface. The X2 Application Protocol (X2AP) message is used to "load information" from neighboring cells. The X2AP LOAD INFORMATION message received from a neighboring eNB indicates the UL interference level on all of its physical resource blocks (PRBs) and also if the transmission power is high or low for all of the UL PRBs. When the message is received by the other eNB, it will make use of the information to schedule the cell edge UEs in the available Pysical Resouce Blocks (PRBs). That means, two neighboring eNodeBs will not be using the same set of PRBs at the same time. This scheme is one of the preferred ones in ICIC implementation schemes. See Figure 4.1.

This mechanism of ICIC allocating different sub carriers for delivering data channels resulted in a better interference level for the DL data channels or traffic channels. The problem with ICIC is that it requires some of the resource blocks to be reserved resulting in lower throughput for the cells. ICIC also limits the range expansion mechanism (explained in Section 5.1). On the other hand, eICIC helps in reducing the interference in both the data channel and control channels.

Enhanced ICIC (eICIC), that was introduced in 3GPP release 10 [16] on the other hand, does not not require any resource blocks to be reserved for the transmission of either the control or user data. The major shift from ICICs is that eICIC uses time domain. The realization of eICIC is done through the use of ABS (also termed as Almost Blank Subframes). That is,

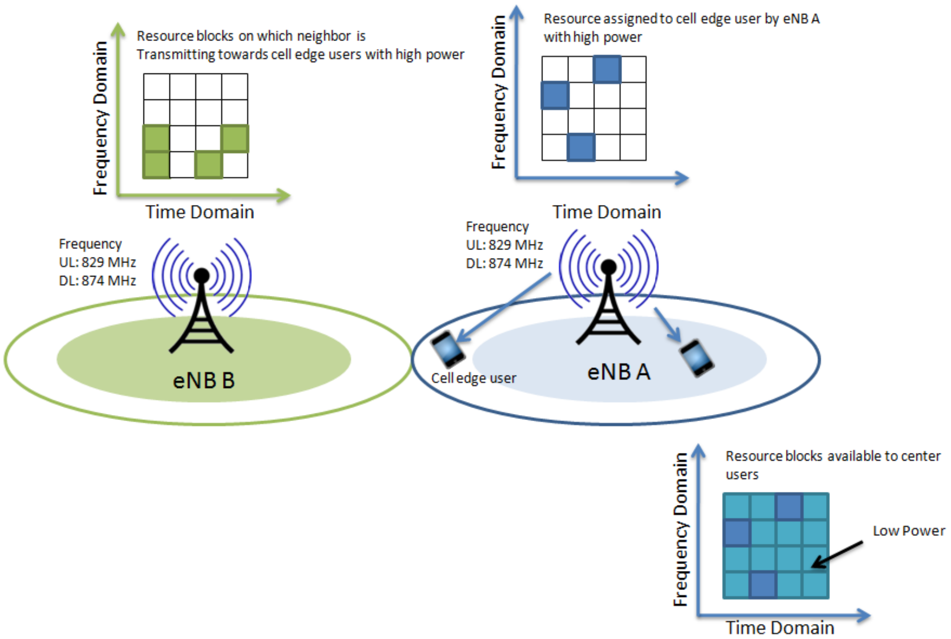

Figure 4.1: ICIC with Resource Block assignments
(Image taken from[9])

the macro eNB almost "silences" some of the subframes in the the DL radio frame. These silenced subframes contain only control channel and cell – specific reference signals and no data. Thus, cell edge UEs can get both control and user data during ABS. And this flexible usage of frames among MeNBs and small-cells (like PeNBs) makes eICIC easily responsive to load variations. As it was in ICIC, the Macro eNB will use the X2AP messages to LOAD INFORMATION or send out ABS patterns to the neighboring small – cell eNBs. Figure 4.2 shows a cell edge UE (UE1) being scheduled during the ABS periods.

Further enhanced ICIC (FeICIC), has also been introduced in 3GPPs Release 11. [17] The major enhancement from eICIC is that UEs can also participate in the inter – cell interference management by canceling interference signals for their control channel. This capability of UEs' in cancellation of interference for control signals would make it possible for even larger cell range expansion.

4.2 Carrier Aggregation - CA

CA is one of the most useful interference management mechanisms that are being used today. Carrier Aggregation (also called Channel Aggregation) that was standardized in 3GPPs Release 10 [16] and is compatible with R8 and R9 compatible UEs. It is the mechanism by which we combine carriers of same or different bandwidths (often referred to as component carriers – CCs) in order to improve the total transmission bandwidth. CA can be implemented using either FDD or TDD and each serving cell has a

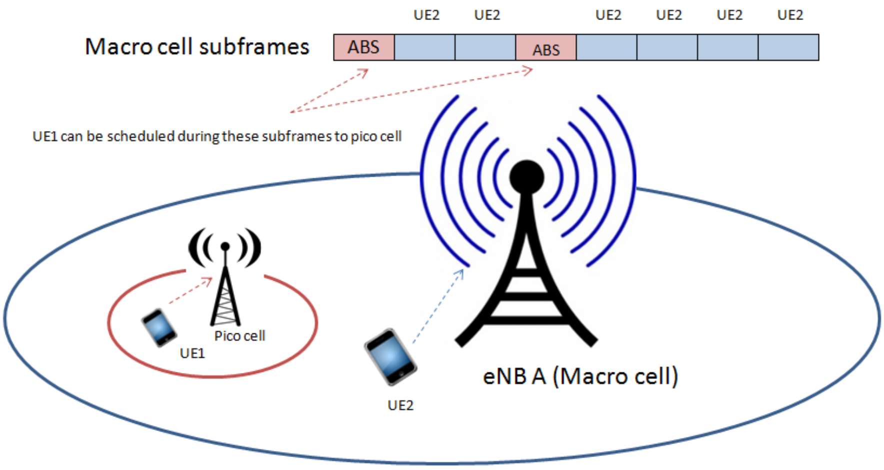

Figure 4.2: eICIC mechanism with ABS
(Image taken from[9])

component carrier (CC). One of the serving cells is designated as primary serving cell (PSCell) and is responsible for management of the carrier aggregation processes and configuration, while the rest of the other serving cells are referred to as secondary serving cells (SSCell) . LTE Advanced UEs that are capable of CA can be assigned to use resources on all the existing CCs, but R8 and R9 compatible UEs can only be assigned to use resources on a single CC.[18] A mechanism called Cross – Carrier scheduling is used to allocate Physical DL control channels (PDCCH) on different CCs both in macro and small neighboring cells. PDCCH carries DL control information (DCI) which is used for scheduling by the cell edge UEs. This phenomenon of using different component carriers for transmission of PDCCH than the normal traffic channels helps in reducing the download control channel interference in the neighboring small cells. Some small cell types, however, need different timing advance (TA) in order to do the CA process (eg. RRHs), and starting from Release 11 [17], it has been made possible to have serving cells that differ in their timing advance and belong in different timing - advance - group.

4.3 Coordinated Multi Point - CoMP

After the introduction of CoMP in 3GPP Release 11 [17], the data transmission rates in HetNets can also be increased by using a MIMO (multiple – input – multiple – output) technologies for UEs. CoMP allows UEs to utilize the best transmission and reception signals from different eNBs in the HetNet deployment by combining multiple antennas both in the cell center and around cell edges for UL and DL. Thus, improving the coverage, spectral efficiency and cell – edge throughput. The reason for this is that when CoMP is enabled, cell edge UEs can choose to have their UL through the small cell and the DL through the macro – cell. But this, however, is possible only when the MeNBs and the small – cells are synchronized efficiently by exchanging the coordination schemes through the backhaul. There are different approaches of CoMP for the different scenarios involved and the reader can read more about the implementations and evaluations of these schemes for further research evaluation. [12]

Chapter 5

ABS and CRE for eICIC implementation in NS-3

In this chapter we will discuss about Cell Selection and Cell Range Expansion along with UE Protection and ABS implementation to realise eICIC in NS - 3.

5.1 Cell Selection and Cell Range Expansion (CRE)

In this section we will have a look at the key enablers of HetNets which are Cell Selection and CRE.

5.1.1 Cell Selection

As described in the previous section, in areas where it is hard to find coverage from MeNBs or whenever the need for offloading the MeNBs arises, HetNets have small – cells like Pico base stations (PeNBs) to efficiently improve the overall performance of the network while all of the eNBs are using the same frequency carrier. One of the challenges in this type of networks is, for example, making the PeNB layer work with the MeNB layer as efficiently as possible. In other words, a mechanism should be in place to decide which base station the UEs can be connected to at any given time. In LTE HetNets cell selection is mostly done using RSRP or RSRQ. [8] These measurements are also used when a cell re - selection or handover decisions are made.

- **RSRP (Reference Signal Received Power):** is the average power that is received by UE and it is measured based on RSSI (Received Signal Strength Indicator) that is obtained from resource elements that carry cell specific reference signals spread over the whole bandwidth. This measurement is done by UEs and is periodically reported to the eNB. RSRP measurement values are in the range: (-140dBm < RSRP <= - 44 dBm). That is the UE reports value 0 to the base station if the value of the measured RSRP is less than -140dBm and an integer value in the range (0 to 97) if the RSRP measured shows a 1dBm difference from

Reported value	Measured quantity value	Unit
RSRP_00	RSRP < -140	dBm
RSRP_01	-140 ≤ RSRP < -139	dBm
RSRP_02	-139 ≤ RSRP < -138	dBm
…	…	…
RSRP_95	-46 ≤ RSRP < -45	dBm
RSRP_96	-45 ≤ RSRP < -44	dBm
RSRP_97	-44 ≤ RSRP	dBm

(a) RSRP reporting scheme - 3GPP standard

Reported value	Measured quantity value	Unit
RSRQ_00	RSRQ < -19.5	dB
RSRQ_01	-19.5 ≤ RSRQ < -19	dB
RSRQ_02	-19 ≤ RSRQ < -18.5	dB
…	…	…
RSRQ_32	-4 ≤ RSRQ < -3.5	dB
RSRQ_33	-3.5 ≤ RSRQ < -3	dB
RSRQ_34	-3 ≤ RSRQ	dB

(b) RSRQ reporting scheme - 3GPP standard

Figure 5.1: 3GPP's RSRP (a) and RSRQ (b) schemes [18]

-140dBm to -44dBm. And value 97 will be reported if the measured RSRP is greater than -44dBm. Figure 5.1a shows the RSRP reporting schemes as standardized in 3GPP.

- **RSRQ (Reference Signal Received Quality):** used when RSRP measurement is not sufficient enough or a more sensitive calculation has to be done in order to make cell selection, re – selection or handover decisions. It is calculated by:

$$RSRQ = \frac{N * RSRP}{RSSI}, \text{ Where N = the number of resource blocks.}$$

  The measurements of RSRQ range is between -19.5dBm to -3dBm. And for each of the 0.5dB variations measured the UE reports a number from 0 to 34 to the base station in an increasing order. Figure 5.1b shows the 3GPP standardized RSRQ reporting scheme.

In the implementation for the simulation part, there is a vector *mMeasuredRsrqs* which is intended to hold each entry of RSRQ measurements for every UE. More description in chapter 7.2

5.1.2 Cell Range Expansion (CRE)

The PeNBs in HetNets, due to their low – power transmission, cover a relatively small area than the MeNBs and since UEs select the cell they want to connect to based on the received signal strength, they tend to automatically connect to the MeNBs unless they are very close to the PeNBs (or are in the PeNB cell center area). However, operators want to offload the the data traffic from MeNBs as much as possible in order to gain from the benefits of using small – cells. And one of the mechanisms to achieve

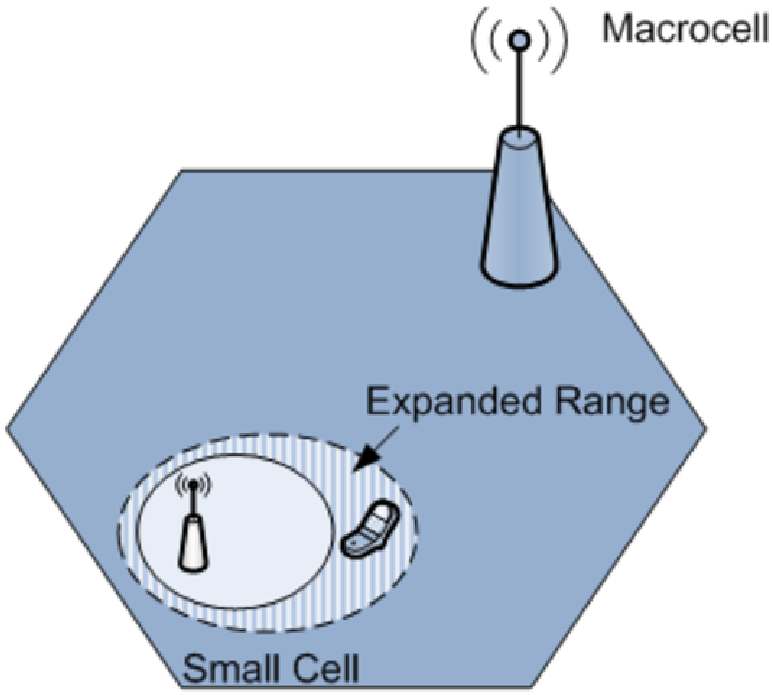

Figure 5.2: A simplified HetNet deployment with CRE

this work is by using Cell Range Expansion (CRE). Figure 5.2 shows a simplified HetNet deployment to illustrate CRE.

From previous studies on PeNB and MeNBs, we know that the DL quality is better when the UE is in the cell – center areas of either the PeNB eller the MeNB. However, in the UL, it is the terminal output power that determines in which area it is better to connect to the PeNB. The UL coverage area is usually larger than the DL coverage area. And by virtue of being closer to the pico - cell, the UEs can get a better UL if they connect to the PeNB. Therefore, to increase the area covered by the PeNB and thereby helping the MeNB in offloading the UL channel, a CRE method is used. Which is a mechanism of adding a positive cell selection bias (CSB) to the signal power received from both the PeNB and MeNB. (i.e. Macro RSRP and Pico RSRP). Thus, the preferred cell selection, based on the signal power measurements that we have discussed in the previous sub – section, can be calculated as:

$$PreferedCell = argmax(Macro_{RSRP}, Pico_{RSRP} + CSB)$$

The CSB coefficient setup and decision making process needs a lot more careful observation. It is up to the mobile network operators to decide the magnitude of the CSB used; which is based on the scenario that fits their networks for a better load balancing or traffic offloading from the MeNBs. The amount of CSB will vary based on the network load, the position of the eNBs, number of small – cells and macro – cells and so on. Thus, The Preferred Cell according to the equation above will either be the Pico or the

Macro cell, depending on which one has the strongest signal power. But, in the CRE area, the PeNB has a stronger signal power than the MeNB, which then makes the UEs in this area to be connected to the Pico – cell in the UL. In the DL, however, the UEs in the CRE area will get a lot of interferences from the Macro – cell. One solution can be to use inter – cell interference management techniques to have a coordination between the PeNB and the MeNB so that the UE in the CRE area can be connected to the PeNB in the UL and to the MeNB in the DL. This coordination helps to bring a significant network performance gain but that depends on how the signals from these base station are combined or coordinated. One of these coordination techniques is the ABS (almost blank subframes) mechanism for eICIC and it is described in section 5.4.

5.2 UE selection and protection

When UEs connected to the PeNB or other small – cells in HetNet start moving to the edge of the cell with which they are associated to, i.e. in to the CRE area, they will start to experience interferences from the neighboring cells. Which means that the SINR (Signal – to – Interference – and – Noise Ratio) starts to drop low. In order for the ABS and other interference coordination mechanisms to be sufficiently implemented, identification of the UEs, that are under interference, would then becomes very vital. For this purpose, the thesis will make use of a victim UE detection algorithm that has been proposed and evaluated in [11]. The algorithm that was proposed also considered SINR as an effective measure to check for the interference level. Even though, the 3GPP standardisation states that the SINR level of a DL control channel to be – 6dB or – 4dB, the authors suggest the threshold to be – 3dB which is simuliar to CQI feedback of 3. Moreover, the article sets the detection period to be 50ms to account for the fact that the SINR might not stay below the threshold for a longer period. The algorithm that is dependent on the wideband CQI filtering is given as:

$$CQI_f[n] = [\alpha CQI[n] + (1 - \alpha).CQI_f[n-1]]$$

Where $CQI_f[n], CQI_f[n-1]$ are the filtered CQI values at time instants n and n - 1. While $CQI[n]$ is CQI at time instant n, α is the constant variable that should be set accordingly.[11] And the most important assumption made by the article was that CQI feedbacks are reported in the next subframe for the SINR measurements during ABS and that the feedbacks are sent constantly in an appropriate period.

In the implementation for the simulation part we keep track of the CQI measurements for both the aggressor and victim UE, using dual reporting both during ABS and non – ABS. This is because the aggressor cell UE and the victim cell UE will measure different levels of SINR depending on if they are in ABS or non – ABS periods, and it also allows us to keep track of the CQI measurements for both data channel and control channel during ABS and non – ABS and then make the decision to protect and label the UE as interference victim or not. The dual CQI reporting in DL is introduced in the 3GPP's Release 10 enhanced ICIC section. [16]

For this purpose a vector *menbProtectedUesVec* holding RNTI values of the protected UEs for every eNB has been defined in order keep track of the list of protected UEs and schedule them during the obtained ABS periods. More on this in chapter 7.2.

5.3 Scheduling Strategy and Scheduler Modification

Scheduling is one of the most important areas to be considered when thinking of ABS or any of the interference coordination mechanisms, since one has to have an optimal scheduling mechanism in place in order to maintain the overall network throughput at the maximum level possible. When dealing with interference management and coordination we will always end up sacrificing the use of some resources on the MeNBs side or any side of the cells involved in the interference. Therefore, the process of making the efficiency loss on one side of the network to count for the better of the overall performance obtained in the network will greatly depend on the scheduling mechanism used. 3GPP has left the implementation and adaptation of the packet scheduling algorithms to the network operators, but in general the major requirements in a scheduler used for an LTE HetNet include: [10]

- **Packet Scheduling:** is used in RRC connected mode and takes care of the process of providing access to air interface resources on 1ms – TTI basis for all the active UEs being considered.

- **Power Control:** Provide an achievable level of the required data rate by adjusting the SINR level to the desired level. Also controls the interference to the neighboring cells.

- **Link Adaptation:** Takes care of the optimal selection process of MCS parameters like Modulation, Channel coding and Transmission schemes.

- **Resource Assignment:** Air Interface resources should be assigned to the selected UEs based on TTI.

- **Rate Control:** Takes care of the process of allocating resources for the different radio bearers of the UE which are available at the eNB for the DL and at the UE for the UL.

- **HARQ (Hybrid Automatic Repeat Request) (ARQ + FEC):** Responsible for error recovery by using link adaptation.

The article [10] also suggests, based on the evaluations made, that PFS (Priority first Scheduling) is better in achieving significant overall throughput than the other two types of schedulers mentioned. That is, the Round Robin (RR) scheduler which schedules all UEs equally in a round robin manner and the Max – CQI scheduler which schedules UEs with the highest CQI first. The PF scheduler creates the balance between the RR and Max – CQI schedulers by considering fair resource allocation and maximization of overall cell throughput. And this is they type of scheduler used in this thesis. To attain the basic goal of having schedulers, which is to efficiently assign shared channel (data) resource amongst the UEs in consideration, the MeNB and the small – cells (such as PeNBs) are required to be synchronised down to 1ms which in turn is equal to the duration of one sub – frame in time domain. And for the ABS implementation to work, we want the MeNBs to almost keep silent during and ABS period and the scheduler shouldn't grant any of the MeNB UEs an UL or DL during ABS, except that MeNB can transmit some synchronisation and control signals during this period. For the implementation of ABS in this thesis, a modification of the $pf - ff - mac - scheduler$ of the LENA LTE – NS3 module was done as part of the X2 interface modification phase. The $pf - abs - mac - scheduler$ files in this thesis have the following modifications in addition to the above mentioned scheduler requirements which were already implemented with LTE NS-3 module:

- Takes care of HARQ processes.
- $RefreshDlCqiMaps()$: to decrement the timers by 1 and deøete CQI when the timer reaches 0.
- Check the ABS pattern of the MeNB and don't grant UL or DL on ABS subframes.
- If the UE is a CRE – UE and if the subframe is not ABS, then do not schedule the UE.
- If the UE is a CRE – UE and if the subframe is ABS, then schedule the UE at the existing PRBs and update the CQI, TTI, HARQ and other values. (CQI == 0 means that the UE is out of range according to TS 36.213.)
- For more detailed implementation of the $pf - ff - mac - scheduler$ see Appendix C - Source Code in chapter 7.2 and the source code bundle companying this thesis.

5.4 ABS mechanism and implementation

Basically, ABS mechanism in HeTNet is the phenomenon by which a MeNB mutes some of its subframes in order to allow UEs in neighboring cells (specially UEs in CRE area) to do the data transmission in those silenced subframes, i.e. by transmitting their data in a different time range than the MeNB. Cell center UEs can do their data transmissions using all the subframes at any time, which makes the ABS method specially targeted for cell – edge UEs. Moreover, the usage of ABS for inter – cell interference coordination, as time domain mechanism, also solves the cell – edge interference problems that could not be addressed by using ICIC in frequency domain. And since ABS works in the time domain, all the neighboring eNBs which are in the same geographical area should be synchronized in time and phase to a small fraction of 1ms, as the duration of one sub – frame is 1ms. Figure 5.3 shows the steps or signalling done during an ABS setup and synchronization between a MeNB and a PeNB. The X2AP (X2's application protocol) $LoadInformation()$ messaging is used for this purpose over the X2 interface. See also Section 4.1

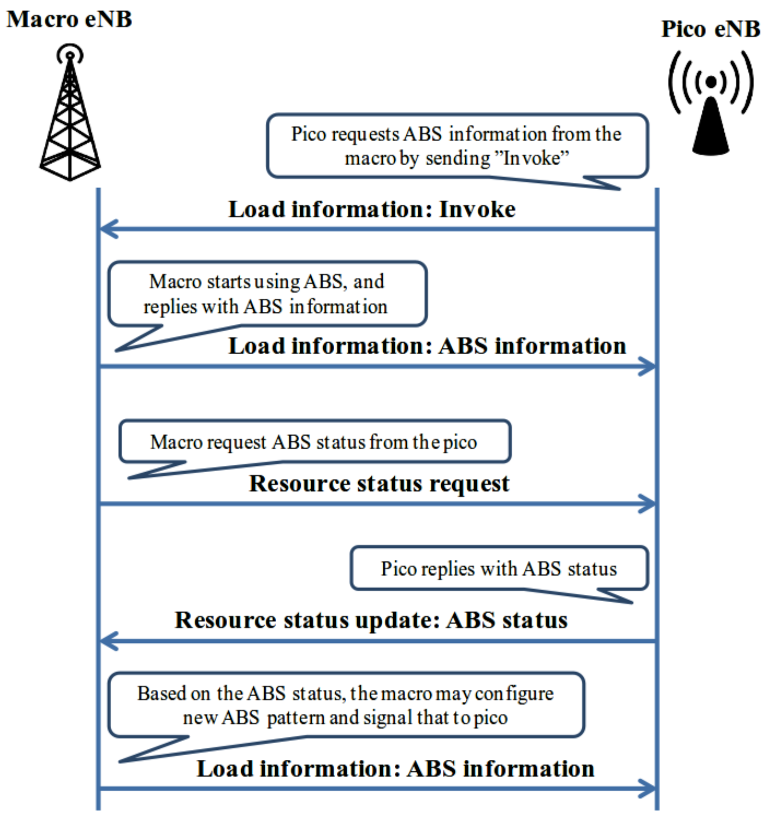

Figure 5.3: X2 signaling for Macro - Pico ABS coordination [9]

As shown in Figure 5.3 and from discussions in section 5.3, before the packet scheduling and link adaptation phases are reached, a subframe muting pattern must be arranged by the MeNB. The MeNB arranges the ABS pattern by dynamically analyzing the traffic load, interference conditions and service requirements made by the neighboring cell – edge UEs. For this purpose, 3GPP's Release 10 [16] has mechanisms that are put in place to let Macro - and Pico – cells to exchange information over the X2 interface in a distributed manner, so that the MeNB can make decisions on whether it needs to silence some of the subframes and which subframes to silence, with the main focus of increasing the overall network performance. After the decision of the ABS pattern is decided then the MeNB will inform which pattern the neighboring PeNB should use by sending a *LoadInformation* message. In addition to Macro – Pico communication over the X2 interface, MeNBs in the same geographical area would inform each other about what ABS muting patterns they are using over the X2 interface. This allows the neighboring MeNBs to use overlapping ABS patterns so as to maximize the benefit of eICIC.[23]

During an ABS period, the MeNB will only be transmitting signals that are required for synchronization methods (like Common Reference Signals (CRS)) and therefore the signal power from MeNBs during this period will be around 9% og the normal transmission; meaning that cell – edge users would still experience interference due to the transmission of these signals. However, the signal power is very low that it is still possible to get a tremendous amount of throughput gain for CRE – UEs by using ABS technique as eICIC. 3GPPs Release 11 [17] has introduced a feature called CRS cancellation by which advanced UEs that are capable of canceling the CRS interference from MeNBs will almost get zero interference from CRS when ABS method is used.

An example ABS pattern set by a MeNB is shown in Figure 5.4 along with an illustration of how the information is exchanged over the X2 interface and how the Macro UEs, CRE – UEs (cell edge UEs) and Cell – Center UEs will be scheduled to use radio resources according to the ABS pattern set by the Macro – cell.

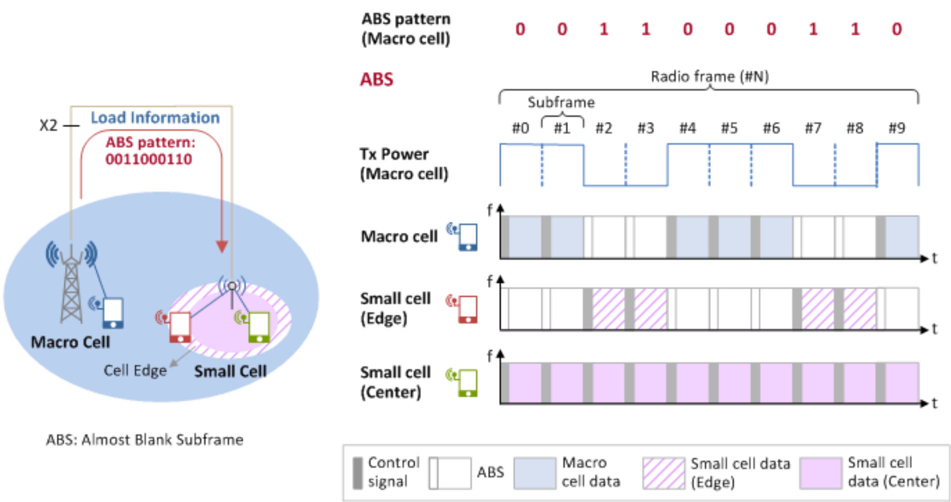

Figure 5.4: ABS mechanism for eICIC
[6]

The ABS mode, however, will be deactivated if, for example, the CRE – UE moves closer to the cell – center and its SINR level becomes above the CQI threshold. This is accomplished by using the same mechanism the MeNB has used to decide ABS pattern and inform it to the neighboring cell. If the MeNB receives the Load Information messages and the CQI measurements for a UE are above the defined threshold, then the MeNB will inform the neighboring PeNB to stop scheduling that UE in ABS mode.

Note that: For implementation purposes in this thesis we will be using static ABS patters for the CRE – UE scheduling.

Part III

Simulation Results and Conclusion

Chapter 6

Results and observations

This chapter describes the simple simulation scenario implemented, the assumptions made and discusses the results observed.

6.1 Simulation Assumptions

The following are some of the major assumptions that has been done while setting up the simple HetNet scenario.

- **UE Mobility:** There are different kinds of mobility models in NS – 3. However, the assumption for the initial simulation of this simple HetNet scenario is the Constant Mobility Model that is invoked by:

  $mobility.SetMobilityModel("ns3 :: ConstantPositionMobilityModel");$

  One argument for choosing to start with the constant mobility model is that UEs in a HetNet scenario and specially the ones served by small - cells benefit mostly when they are not moving or changing positions so often. This is because when the UEs are moving from cell to cell then they might suffer from delays caused by cell re - selection and handover.

- **UE attachments to the Network:** attaching UEs to the eNBs in NS – 3 simulation is done by calling the $LteHelper :: Attach$ function after the $LteHelper :: InstallEnbDevice$ and $InstallUeDevices$ have been called first. This can be done in two ways:

  Manually: this is done before the simulation begins and each UE needs to know which eNB it belongs to. Distance of the UEs from the eNBs can be considered to decide to which eNBs they can be connected to. In real life, UE will automatically decide which eNB to connect to.

  $lteHelper- > Attach(ueDevs, enbDev);//$Attach UEs to a single eNodeB

  Automatically: Based on the received signal strength which is done in the initial cell selection process, UEs can automatically choose which eNB to attach to.

$lteHelper->Attach(ueDevs);$ //attach one or more UEs to the strongest cell

Note: The UE attachment method used for this simple scenario was the Manual one.

- **Static ABS patterns:** According to 3GPP's standardizations and as it has been described in the previous chapters of this thesis, the neighboring MeNB and PeNB should exchange channel and UE information over the X2 interface, before the MeNB decides and generates the ABS pattern to be used. But for the simulation scenario considered in this thesis a static ABS pattern has been used.

6.2 Simulation Setup and Parameters

This section will point out the simulation setup and parameters used for the simple HetNet scenario deployment considered for the simulation of the ABS - eICIC method. The DL of the HetNet scenario has been simulated following the LTE - Advanced specifications. The MeNB and the PeNB are deployed in a 1km^2 area with the USs attached to the respective eNBs manually. Three of the PeNB users are deliberately made to be situated at a point where they will be in the CRE area of the PeNB and that they will get an interference from the MeNB. An illustration of the simulation parameters is listen in Table 6.1 and a visualization of the deployment in NetAnim can be seen in Figure 6.1.

Parameter	**Value**
System	LTE - Advance HetNet scenario at 2000MHz, Carrier bandwidth = 5MHz, deployed 1050 m x 1050 m area
Macro Cell	MeNB with a radius of 400m deployed at (400,525) into the area with an omnidirectional antenna
Pico Cell	PeNB with a radius of 150m deployed at (950,525) into the area.
Scheduling Scheme	Proportional Fair ABS MAC scheduling.
Macro Cell Subscribers	2 UEs, that are attached to the the MeNB; 1 of them on the PeNB side
Pico Cell Subscribers	The MeNB serving 1 UE in the cell - center area and 3 CRE - UEs at a CSB equivalent to 100m.
ABS pattern	1/8.
Simulation measures	Simulation time 10 - 50 secs to observe different situations.

Table 6.1: Parameters for the simulation scenario

6.3 Simulation Observations

A repeated simulation of the proposed simple HetNet scenario has been done. To visualize the HetNet deployment and simulation that is done in LENA - LTE/EPC simulator and process the observations, the NetAnim offline animator. NetAnim animates the simulation done in NS - 3 by using XML trace files that are configured and collected in the duration of the simulation. See Figure 6.1.

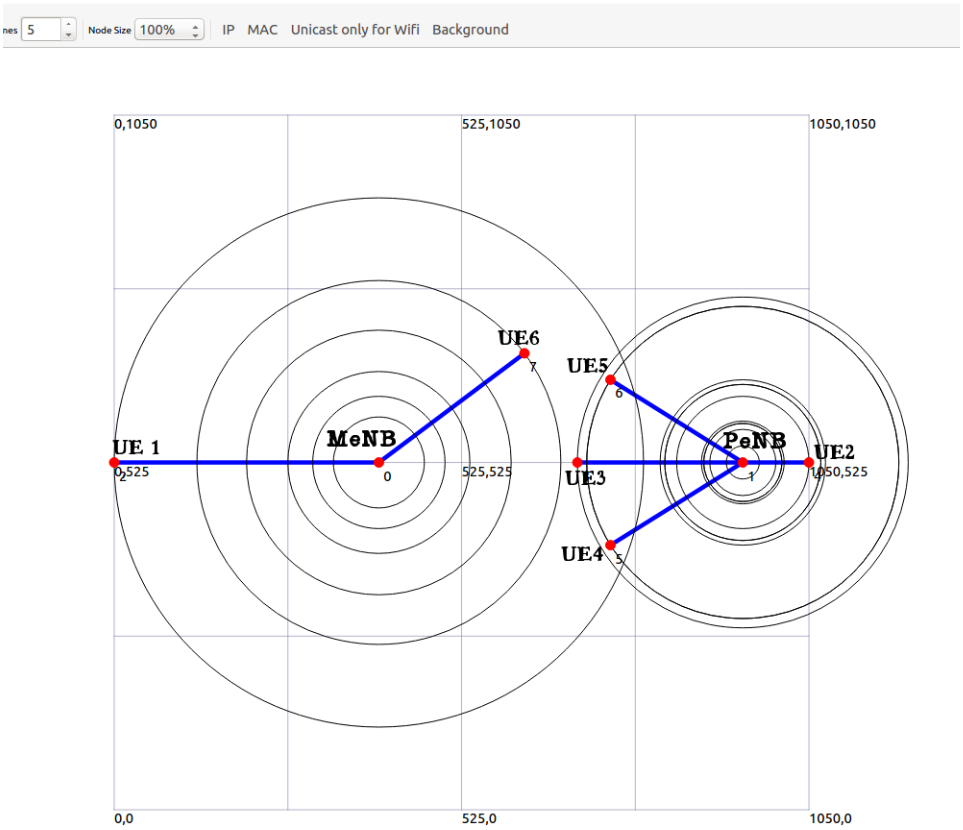

Figure 6.1: NetAnim visualization of a simple HetNet deployment in NS -3

The simulation was run first without enabling the eICIC mechanism and the UEs that could normally be served by the PeNB in the CRE area were attached to MeNB so that we could compare the overall network performance improvement with the results found at the next run of the simulation with the cell edge UEs attached to the PeNB, a CSB added to the PeNB in order to cover these UEs as CRE - UEs and the ABS eICIC mechanism enabled.

The ABS pattern used in the simulation was a static and not generated by the MeNB after negotiating with the PeNB based on the traffic load and other information from PeNB over the X2 interface. The reasons for this is that there was a need for additional parameters that needed to be added to the X2 interface messaging module implemented and there was no more time to continue working on this module instead of continuing with the rest of the thesis work and consider to use a static ABS for testing purposes.

Figure 6.2 shows the average throughput of the MeNB with one PeNB. We can see that the throughput is better when the simulation is run with out ABS mechanism applied. The reason for that is, the MeNB doesn't need to sacrifice any resources during the no ABS scenario. On the other hand, the average throughput of the MeNB with ABS enabled poor since the MeNB has to blank some of the subframes, giving away resources.

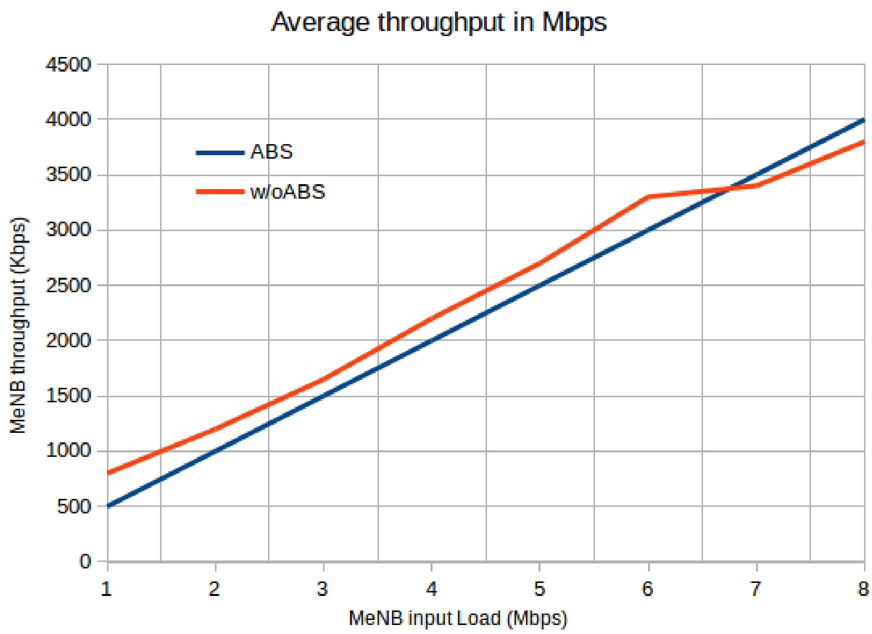

Figure 6.2: MeNB average throughput

The main reason behind the modification of the scheduling algorithms is to find a balance between the throughput loss caused when the MeNB sacrifices some resouces and the throughput gain by using PeNB together with existing MeNBs, using ABS - eICIC as a coordination mechanism. In order to see the results obtained by using ABS mechanism see figure 6.3

Figure 6.3 shows a throughput distribution of UE3 which is a CRE - UE attached to the PeNB as in figure 6.1. It can be observed that the throughput for the CRE - UE is better with ABS enabled. The reason is, as described in previous section of this thesis, a static ABS pattern is used, where the MeNB is made to mute some of its sub - frames. That gives the CRE - UEs like UE3 to get less interfernce from MeNB and they would be scheduled to use resource blocks during this 'silenced' subframes.

However, not all of the results obtained from the simulation were as per the specifications and previous studies on this topic. It could be the simulation scenario that has been considered or the implementation on the eNB synchronization module (the X2 interface) or ones own programming approach or the way the HetNet devices have been configured in the

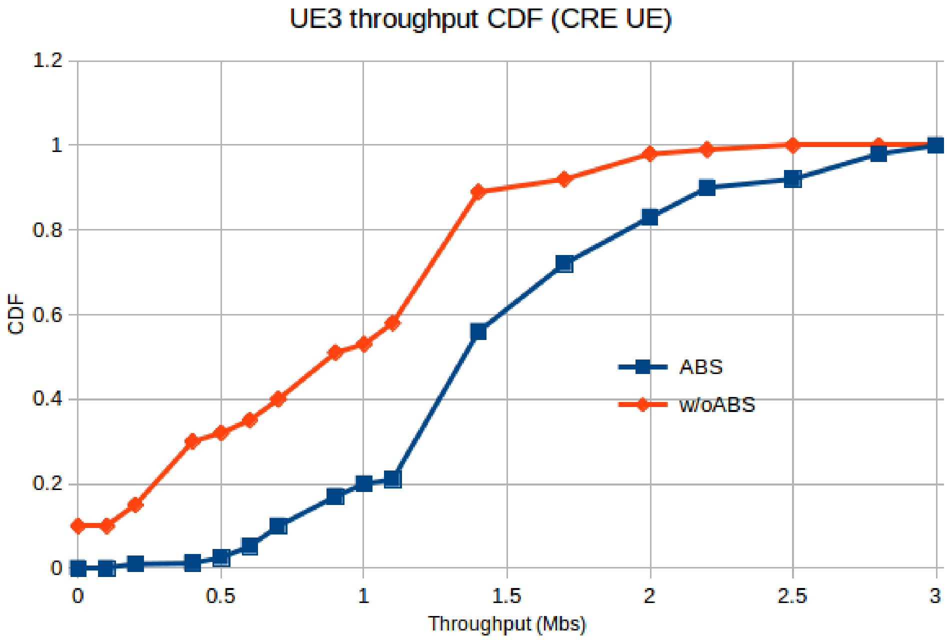

Figure 6.3: CRE-UE throughput with and without ABS

scenario considered or the methods that were used to evaluate the simulation trace files. The simulation was run several times with considerable improvements made in the code implementation for each run.

The results obtained from the simulation run with the ABS eICIC enabled showed, in some cases, no improvements to the SINR, RSRP or RSRQ measured by the CRE - UEs. And in some measures, the over all throughput was actually less than the one observed with out the ABS eICIC enabled. However, this can be accounted to the fact that there is only one MeNB and one PeNB with a few UEs attached to each one of them. Which is very different from the situation in real HetNet deployments. Because, the main improvement comes when there are a lot of PeNBs overlayed in a MeNB network, since that makes the interference level higher.

Chapter 7

Conclusion and Future Work

In this Chapter, we will draw some conclusions from the discussions in the previous chapters and observations in the simple HetNet scenario simulation done in the end of this thesis. These observations have been compared with the researches and implementations carried out before this work. A section that will point out the work left undone in this thesis and the possible future work, which can be carried out based on the work started in this thesis, is also included in the end.

7.1 Conclusion

In today's world of communication systems where mobility, fast and reliable access to the internet and a network with a capacity of handling high quality voice and video services, is becoming a basic necessity to our day today lives. Providing a network that can cope with the exponentially growing mobile users' database, is the main goal of every single mobile network operator. Therefore, operators worldwide are working towards addressing the high data traffic demands. Operators could consider to add spectral efficiency, just as we did from 2G to 3G and 4G but we are reaching the limits of Shannon's law with out really being advanced. It has been studied by 3GPP on how get significant capacity increases and the only realistic way to follow right now is by increasing the number of cells; sectors or cell - sites or small - cells. HetNets introduce a major paradigm shift in the way we design and deploy mobile networks, and provide us with the possibility to add network capacity and greatly improve the overall performance of the network. In HetNets a large number of small - cells are tightly deployed inside the existing macro - cell network; all sharing the same frequencies. However, the deployment process of HetNets comes with some challenges, one of them being the Inter - Cell Interference Coordination. And it is when we can properly coordinate and control these cells, that we get the best of both worlds. ABS (almost blank subframe) technique as an enhanced inter - cell interference coordination is one of the techniques to meet these interference - coordination challenges. And, the fact that we have an accurate simulation environment, as NS-3 LENA - LTE/EPC simulator,makes it easier to evaluate the performance of eICIC algorithms in different kinds of HetNet deployments. The LENA LTE/EPC simulation model has a granularity to the level of resource blocks but can still be used to simulate eICIC algorithms since the results are based more on the higher layers, like the MAC scheduler layers, than the Spectrum channel or the PHY layer.

The ABS - eICIC scheme requires that the neighboring cells be tightly coordinated in time domain and in phase, and an X2 interface is used while negotiating the considered network parameters with the Pico cells, based on which the ABS pattern will be decided by the Macro cell. The CSB added to the PeNB to extend the cell coverage range of the small cells can also be sent over the X2 interface. A modification of the X2 interface module has been done, even though it needs more improvement in order to have the parameters needed for the information negotiating between the macro cell and small - cells.

In addition to ABS mechanism, the CRE method would make the PeNBs or other small cells to extend their coverage area so that the UEs which are closer to the small - cells would get a better received signal strength while also helping to offload the macro - cell traffic. The CQI feedback that is experienced by each UE for each cell is used in selecting the best cell to which it is best to connect to.

Scheduling is one of the main requirements in the inter - cell interference coordination and management, as the best possible scheduling should be there to make sure that the resource or performance loss by the macro - cell should be compensated by the over - all system performance gain. For this purpose the a scheduler modification had been done. The scheduler uses the CQI measures and checks if the UE is a CRE - UE among other things before deciding the best possible transmission schedule for that UE.

7.2 Future work

The starting point or idea of the thesis was to implement eICIC algorithms that have already been proposed in papers like [5] and evaluate and compare the network throughput observed to the HetNet scenario with out an eICIC algorithm or mechanism implemented. However, due to the fact that the X2 messaging module modification, that had to be done before starting the implementation of the algorithms, took a longer time than expected and that after the eICIC algorithms realisation opened up for more parameters to be considered in the X2 messaging module, a slight direction change of the thesis had to be done. Thus, instead of directly implementing eICIC algorithms from the articles, examining the network performance improvement by using some predefined ABS patterns for the cell - edge user equipments (UEs) was suggested as an easier direction to follow with respect to the time limit there was in this short thesis work. It's my belief that implementing some of the tested eICIC algorithms as whole would make the results and conclusions more enriched and reliable for future implementation of HetNets and that helps mobile network providers in decision making and direction planing to the future new era of HetNet deployments.

The ABS muting/pattern setting done statically in this thesis, but by making the macros decide the ABS pattern based on the load, position and service requirement of the UEs in the CRE area of the neighboring cell, over the X2 interface, the performance could be improved even more. Another point to consider in future improvements to this would be use a bigger simulation scenario where a number of MeNBs and PeNBs would be included so that they would create a higher level of interference. The overall network performance improvement gain by using ABS - eICIC compared to no eICIC would then be more sigificant.

Appendix A - Glossary

3GPP	Third-Generation Partnership Project
ABS	Almost Blank Subframes
CA	Carrier Aggregation
CC	Carrier Components
CQI	Channel Quality Indicator
CRE	Cell Range Expansion
CRS	Common Reference Signals
CSI	Channel State Indicator
DL	Downlink
eICIC	enhanced Inter - Cell Interference Coordination
eNodeB	Evolved NodeB
FDD	Frequency Division Duplexing
FeICIC	Further enhanced ICIC
HARQ	Hybrid Automatic Repeat ReQuest
HetNets	Hetrogeneous Networks
ICIC	Inter - Cell Interference Coordination
KPI	Key Performance Indicator
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MeNB	Macro Evolved NodeB
MCS	Modulation and Coding Scheme
PeNB	Pico Evolved NodeB
RB	Resource Block
RNTI	Radio Network Temporary Identifier
RS	Reference Signal
SINR	Signal-to-Interference-and-Noise Ratio
SRS	Sounding Reference Signal
TDD	Time Division Duplexing
TDM	Time-Division-Multiplexing
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink

Appendix B - Files

This Appendix is about the list of files that follow with the thesis and can be used to re - create the simulation set up for ABS - eICIC algorithm evaluation.

As the simulation was done using the latest NS -3 LENA - LTE/EPC simulator and one can download the latest simulator from LENA project website [19] a tutorial on how to install the simulator is found in the documentation [13]. After downloading the simulator, create a new module in your NS - 3 installation (i.e. in the /src folder); a tutorial on that can be found at the NS - 3 manual - new module section [22]. Then, Extract the files included in the zip folder to your desired location, but distribute the files included in each folder according to the following guideline:

- **helper:** these files should be copied to the 'helper' folder of the new module you have created.
- **model:** These files should be copied to the 'model' folder of the new module you have created.
- **lte-model:** Copy these files to the 'lena/src/lte/model' folder.
- **spectrum - model:** Copy these files to the 'lena/src/spectrum/model' folder.
- **test-abs-eicic.cc:** This is a test file to check if you have configured everything as it should.

Appendix C - Source code

The implementation of ABS mechanism is in the eicic controller files. However, the code implementation, as described in the Simulation Results section, needs an improvement so that the result will be satisfactory. The illustration of the source code and module organization is as follows.

Module Organization

- **model/:** contains source code for main part of module. Source - code files included are:

    abs-ff-mac-scheduler.cc

    abs-ff-mac-scheduler.h

    eicic-controller.cc

    eicic-controller.h

    pf-abs-ff-mac-scheduler.cc

    pf-abs-ff-mac-scheduler.h

- **helper/:**contains the code for helper classes

    eicic-helper.cc

    eicic-helper.h

- **examples/:**

- **tests/:**

- **bindings/:** files related to python

- **doc/:**

- **wscript:** the "Makefile" equivalent - make sure to specify the files to be included in the build process and the other modules that this module depends on.

Existing NS - 3 lena modules had to also be slightly modified.

- **lte-model/:** contains the list of files that were modifies from the 'lena/src/lte/model' lte-enb-phy.cc

lte-enb-phy.h

lte-sinr-chunk-processor.cc

lte-sinr-chunk-processor.h

lte-spectrum-phy.cc

lte-spectrum-phy.h

lte-ue-phy.cc

lte-ue-phy.h

lte-ue-rrc.cc

lte-ue-rrc.h

- **spectrum-model/:** contains the list of files that were slightly modified from the 'lena/src/spectrum/model':

  multi-model-spectrum-channel.cc

  multi-model-spectrum-channel.h

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