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Load Balancing in Heterogeneous LTE-A Networks

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Abstract

LTE-A is the latest cellular network technology. One feature of LTE-A is the use of heterogeneous networks (HetNets) which consist of macro-cells and low power nodes (LPNs). One of the objectives of heterogeneous networks is to increase capacity especially in hotspot areas where there is high density of users. Due to their low transmit power, very few users associate with LPNs and this will result in load imbalance between LPNs and macro-cells. Load balancing is therefore key issue in HetNets so as to maximize cell splitting gains and ensure even user experiences. Cell range extension (CRE) is a technique that can be used to achieve load balancing in HetNets. Under CRE, an offset is added to LPNs during cell selection so as to expand the range of LPNs and offload more users from macro-cells to LPNs. CRE usually involves the use of uniform offsets. The use of uniform offsets results in some degree of load balancing in a HetNet which is not optimal. This arises because different LPNs require different offsets due to varying conditions such as user distribution and propagation environment in different hotspots. The use of cell-specific offsets is necessary for improving the level of load balancing in HetNets. In this thesis a heuristic load balancing algorithm that is used to assign cell-specific offsets to LPNs is designed. The algorithm makes use of a range optimization framework which applies the concept of cell load coupling. Our results show that the use of the cell-specific offsets results in not only a high degree of load balancing as measured by Jain's fairness index but also more even user experiences in terms of throughput.

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Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
CDMA	Code Division Multiple Access
CoMP	Coordinated Multipoint
DL	Downlink
EDGE	Enhanced Data for Global Evolution
ETSI	European Telecommunications Standard Institute
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication
GW	Gateway
HetNet	Heterogeneous Network
HII	High Interference Indicator
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
ICIC	Inter-cell Interference Coordination
IMT	International Mobile Telecommunications
IP	Internet Protocol
LPNs	Low Power Nodes
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MME	Multimedia Entity
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
OI	Overload Indicator
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
RAN	Radio Access Network
RNTP	Relative Narrowband Transmit Power
RRM	Radio Resource Management
RSRP	Reference Signal Received Power.

S-GW	Serving Gateway
SINR	Signal-to-Interference Noise Ratio
TDMA	Time Division Multiple Access
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System
WCDMA	Wideband Code Division Multiple Access
WIMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

Chapter 1

Introduction

LTE (Long Term Evolution) and LTE-A (LTE-Advanced) are the latest cellular network technologies. LTE and LTE-A have a flat, all-IP architecture and all services in the system are IP-based. The aim of LTE and LTE-A is to provide a cellular network with high capacity, good coverage and high spectral efficiency. One important feature in LTE-A which is useful in achieving this is the use of heterogeneous networks (HetNets). HetNets have a topology of mixed macro-cells and low power nodes (LPNs). Compared to the usual eNodeBs, LPNs are smaller size and have lower transmission power. HetNets are useful for improving capacity and coverage in areas with unequal user distribution. LPNs are mainly used to provide high capacity in areas with dense user demand while macro-cells are used to provide coverage in the remaining areas.

Due to higher transmit power of macro-cells, it is not possible to offload sufficient amount of users in areas with high number of users to LPNs because a UE will usually select a cell with the highest received signal power. Many UEs will be associated with macro-cells even if they are placed in the vicinity of the LPNs and the coverage area of LPNs will be small. LPNs will have low cell load while macro-cells will have high cell loads.

Cell range extension (CRE) or cell biasing (CB) is a technique that can be used to offload more users from macro-cells to LPNs without increasing the transmit power of the LPNs. CRE allows UEs to be associated with weaker received signal by biasing the received signal of LPNs. Under CRE or CB, an offset is added to the received signal power of LPNs so that their coverage area (range) can be increased.

High cell biasing might lead to unsatisfactory performance of HetNets by overloading some LPNs. On the other hand, low cell biasing might not achieve the desired offloading effect and macro-cells will be overloaded. It is necessary to select optimum offsets so as to achieve load balancing in a HetNet by offloading UEs from macro-cells in such a manner that it will not lead to overloading LPN cells. Hence load balancing is a key aspect in radio resource management for HetNets. One uniform optimum offset value for all LPNs has usually been used to achieve load balancing in HetNets. Although this achieves the desired offloading effect and to an extent load balancing, it is necessary to have cell-specific offsets to achieve an even higher degree of load balancing. Cell-specific offsets are necessary due to varying conditions in different hotpots served by different LPNs. For example, LPN which is near a macro eNodeB will require a higher offset than one which is found in cell edges. This is because in areas near macro eNodeBs, the macro-cell signal power is higher. Cell-specific offsets are useful for LPN range optimization.

1.1 Thesis goals

The goals of this thesis are:

a) To investigate the use of cell-specific offsets to adjust the range of LPNs so as to achieve load balancing in LTE-A heterogeneous networks (HetNets). A HetNet in which macro-cells and LPNs are in a co-channel scenario will be considered.
b) To design an algorithm for LPN range optimization. That is to design an algorithm that can be use cell-specific offset assignment.

1.2 Method

The thesis is split into three main parts:

a) Design of an algorithm that can be used for cell-specific offset assignment. A range optimization framework which uses the concept of cell load coupling will be made use of when designing the algorithm.
b) Simulation of the problem using Vienna LTE System Level Simulator 1.4_r570. This will involve creation of a system model for simulation. A HetNet will be developed consisting of macro-sites and LPN sites. An appropriate propagation model and user distribution will be chosen from 3GPP 36.913 [1].
c) Performance evaluation of the load balancing algorithm using performance metrics. Minimum uniform offset of 0 dB and optimal uniform offset for LPN cells will be used as the baseline for performance evaluation. Jain’s fairness index will be used evaluate the degree of load balancing. Other performance metrics are throughput, SINR and number of UEs attached to LPNs and macro-cells.

1.3 Thesis Overview

In chapter two, an overview of LTE, LTE-A and HetNets has been given. In this chapter the background, system requirements, key features and system architecture of LTE and LTE-A have been described. The last part of this chapter focuses on heterogeneous networks. In this part, shortcomings of traditional macro base stations only network, benefits of HetNets and types of LPNs have been explained.

Chapter three focuses on LTE radio resource management and why load balancing is an important RRM issue. The chapter also includes a section which explains how radio resources are scheduled to UEs. The last part of the chapter looks at interference management techniques in HetNets. These techniques include static resource partitioning and adaptive resource partitioning.

In chapter 4 load balancing in LTE-A HetNets, which is the main subject of the thesis, has been discussed in detail. In the first part of the chapter CRE has been described. This part explains why using uniform offsets are not sufficient for load balancing in LTE and why cell-specific offsets are necessary for range optimization. In the second part of the chapter, range optimization framework has been described. In this section LTE cell load estimation using the concept of cell load coupling has been discussed. In the last part of the chapter, an algorithm which can be used for load balancing which we designed has been presented.

In chapter 5, the simulation environment has been discussed and implementation done has been presented. In this chapter reasons for choosing Vienna LTE System Level Simulator are provided and the structure and some details of the simulator are also discussed. The last two parts of the chapter describe the network configuration used for simulation and implementation done.

Simulation results and load balancing algorithm performance evaluation are found in chapter 6. The metrics used for performance evaluation are Jain’s fairness index, number of UEs attached to LPNs and macro-cells, throughput and SINR.

In Chapter 7 conclusions drawn from the results have been presented and suggestions on how to improve the performance the load balancing algorithm have been pointed out.

Chapter 2

LTE-A and Heterogeneous Networks

LTE is an evolution of Universal Mobile Telecommunications System (UMTS) and it provides the path towards fourth generation (4G) cellular networks. The term Long Term Evolution (LTE) is a name that was given to efforts to create a new air interface for cellular networks by the 3rd Generation Partnership Project (3GPP). LTE is based on LTE Release 8 3GPP standard. LTE-Advanced (LTE-A, Release 10 LTE) is a significant improvement of LTE. LTE-A is a name that was given for International Telecommunication Union Radio communication (ITU-R) efforts to create a standard that can meet IMT-Advanced system requirements [1]. LTE-A is a true 4G cellular network system.

2.1 Background of LTE-A

Up to the latest developments, mobile telecommunication has undergone four generations. Cellular networks came into being in the early 1980s. During the early 1980's the first generation (1G) of cellular networks, which was analog in nature, was deployed [2]. The 1G system was referred to as AMPS (Advanced Mobile Phone System). Due to increase in demand for mobile phone services, 1G system capacity became insufficient. Second generation (2G) systems which use a variety of multiple access schemes to increase network capacity were introduced in the 1990's to meet the then increasing demand for mobile phone services [2]. The multiple access schemes used in 2G are Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). The 2G system that became most popular worldwide was GSM (Global System for Mobile communications). GSM is a standard that was developed by 3GPP (formerly European Telecommunications Standard Institute, ETSI).

Due to the need for even more capacity and higher data rates which can support video transmission, third generation (3G) systems were developed. 3G provides high speed packet switching capability in addition to circuit switched voice transmission. UMTS Wideband Code Division Multiple Access (WCDMA) provides a high capacity air interface including transport of packet traffic. The target for 3G is to meet the system requirements for IMT-2000 [2].

Due to demand for even higher data rates which can support high quality multimedia data, UMTS has continued to become insufficient. LTE was then introduced. LTE provides even much higher data rates as well as good coverage which result in better user experience. LTE architecture is entirely different from UMTS. LTE has a flat, all-IP architecture and all services in the system are IP-based. All data that goes through LTE network are packet switched and thus there is no circuit switching in LTE. In order to achieve even higher data rates that can meet IMT-Advanced requirements, LTE-A was introduced [3].

2.2 System Requirements and Key Features

The key objectives of LTE and LTE-A are higher user data rates, reduced latency, improved system capacity and coverage, low complexity, reduced cost of operation and seamless integration with existing systems such as WLAN and WiMax [3]. The key features of LTE and LTE-A are summarized in Table 2.1 [4]. Key to achieving these objectives is the use of multiple-input multiple-output (MIMO) multi-antenna transmission techniques and Orthogonal Frequency Division Multiplexing (OFDM) multiple access scheme. The system requirements and key features of LTE and LTE-A are:

- LTE and LTE-A should both have high spectral efficiency and system capacity.
- LTE supports flexible transmission bandwidth from 1.4 MHz, 3 MHz, 5 MHz, 10 MHz up to 20 MHz. Due to very high data rates targeted in LTE-A, an even larger bandwidth is required. Carrier aggregation is used in LTE-A to increase bandwidth up to 100 MHz.
- LTE-A has to be fully backward compatible with not only LTE but also GSM and UMTS while LTE has to be fully compatible with UMTS and GSM.
- LTE-A support heterogeneous network deployment, advanced uplink and downlink spatial multiplexing and downlink coordinated multipoint (CoMP) [3]. Heterogeneous networks consisting of picocells, femtocells, relays and remote radio heads were introduced so as to meet capacity needs and achieve better coverage.

Feature	**DL/UL**	**Antenna Configuration**	**LTE**	**LTE-A**	**IMT Advanced**
Peak data rate	DL	-	300 Mbps	1Gbps	1Gbps
	UL	-	75Mbps	500Mbps	
Modulation	DL/UL	-	QPSK, 16QAM, 64QAM		-
Access Scheme	DL	-	OFDMA	OFDMA	-
	UL	-	SC-OFDM	DFT-S OFDM	-
Sub-carrier spacing	-	-	15 kHz		-
Peak spectrum efficiency [bps/Hz]	DL	-	15	30	15
	UL	-	3.75	15	6.75
Bandwidth [MHz]		-	1.4, 3, 5, 10, 20	100	-
Cell-edge user throughput [bps/Hz/cell/user]	DL	2-by-2	0.05	0.07	-
		4-by-2	0.06	0.09	0.06
		4-by-4	0.08	0.12	-
	UL	1-by-2	0.024	0.04	-
		2-by-4	-	0.07	0.03
Capacity [bps/Hz/cell]	DL	2-by-2	1.69	2.4	-
		4-by-2	1.87	2.6	2.2
		4-by-4	2.67	3.7	-
	UL	1-by-2	0.74	1.2	-
		2-by-4	-	2.0	1.4

Table 2.1: Comparison of system requirements for LTE and LTE-A

2.3 System Architecture

The system architecture for LTE is called Evolved Packet System (EPS) and it is an evolution of UMTS network architecture. Fig. 2.1 [5] shows the EPS architecture. EPS is wholly packet based (no circuit switching) and operates in the IP domain. The core network for LTE is called Evolved Packet Core (EPC) and the radio access network is called Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). The E-UTRAN and the EPC together form the EPS.

The EPC is different from the core network of GSM and WCDMA. The components of EPC are Mobility Management Entity (MME), Home Subscriber Server (HSS), Packet Data Network (PDN) Gateway (P-GW) and Serving Gateway (S-GW) [5]. MME is responsible for idle mobility, paging, P-GW and S-GW selection, authentication and bearer set up procedures [5]. Among the most important functions of the Serving Gateway (S-GW) are to provide packet routing and forwarding function and to act as a local anchor as UE for inter-eNodeB handover [6]. P-GW handles connectivity of EPC to the internet and assignment of IP address to the UEs. HSS stores subscriber and roaming information such as Temporary Mobile Subscriber Identity (TMSI) and IP address.

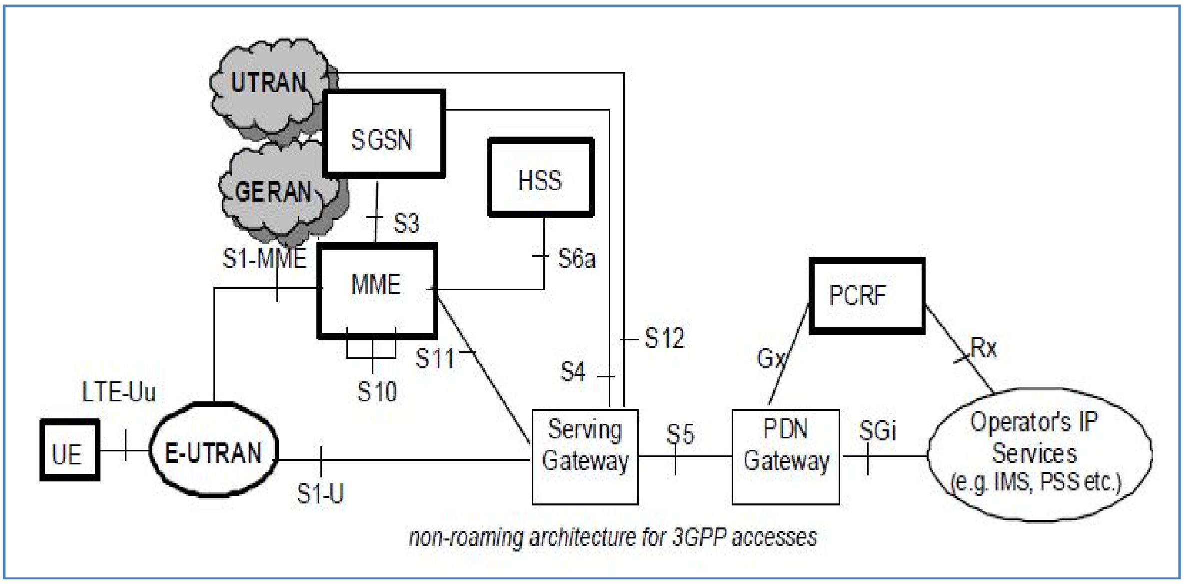


Figure 2.1: EPS architecture

E-UTRAN architecture is of a simpler architecture as compared to previous systems because eNodeB (evolved NodeB) is the only radio access network node or element in the E-UTRAN architecture. Unlike the previous systems which had a hierarchical structure, LTE E-UTRAN has a flat architecture. In LTE and LTE-A there is no centralized node such as Radio Network Controller (RNC) in WCDMA/HSPA or Base Station Controller (BSC) in GSM that exercises control over other nodes. UE (User Equipment) gets IP connectivity to the core network through E-UTRAN. E-UTRAN architecture of LTE or LTE-A is shown in Fig 2.2 [5]. The major function of eNodeB is Radio Resource Management. Other functions of eNodeB are radio bearer control, radio admission control, connection mobility control and dynamic allocation of resources to UEs in both uplink and downlink (scheduling) [5]. The purpose of the X2 interface is to interconnect eNodeBs so as to provide support for active mode mobility and Inter-Cell Interference Coordination (ICIC) [6].

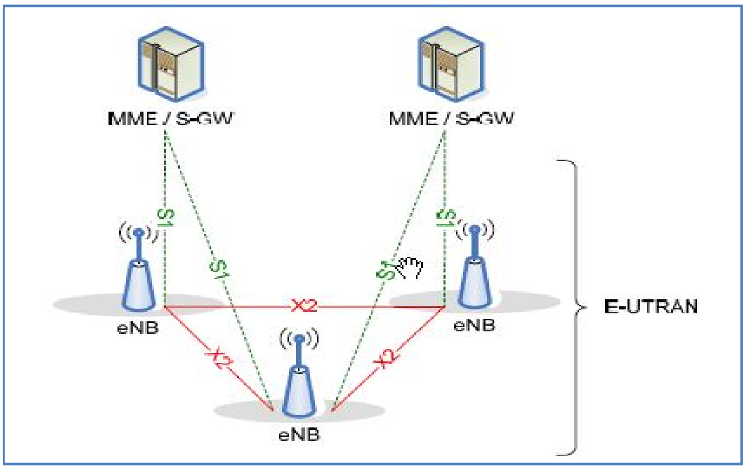


Figure 2.2: E-UTRAN architecture

2.4 LTE Time-frequency Grid

The basic time and frequency unit in the downlink and uplink is one OFDM symbol and one subcarrier, respectively. In LTE and LTE-A, the subcarrier spacing is 15 kHz and one OFDM symbol has a duration of 66.67 us. Each OFDM symbol is pre-appended with a cyclic prefix. Cyclic prefix can either be normal with a duration of 4.7 μs or extended with a duration of 16 μs.

LTE time-frequency grid consists of resource elements (RE). One resource element corresponds to one subcarrier in one OFDM symbol. OFDM symbols are grouped in subframes of 1ms duration. Each subframe is composed of two 0.5 ms slots. Each time slot is further subdivided in the frequency domain into Resource Blocks (RBs). The minimum scheduling unit for downlink and uplink is one resource block. One resource block pair consists of 12 subcarriers (15 kHz each) in the frequency domain and one subframe in the time domain. One RB is therefore 180 kHz wide. LTE time-frequency grid is shown in Fig. 2.3 and2.4.

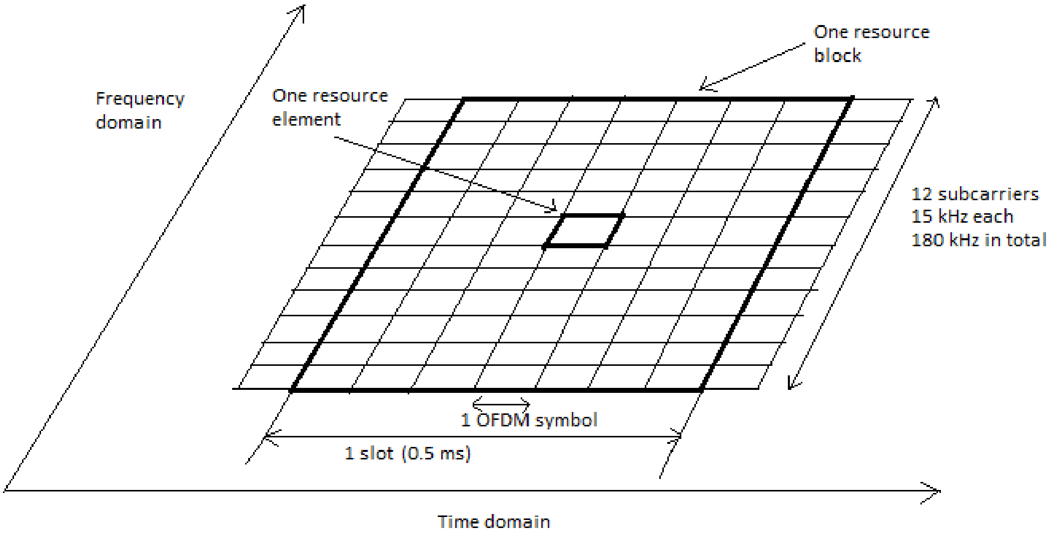


Figure 2.3: LTE resource block

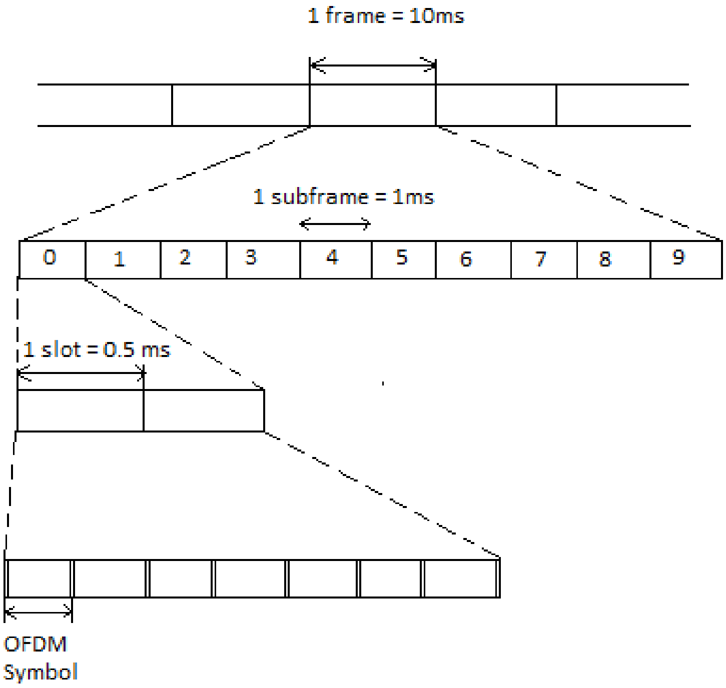


Figure 2.4: LTE subframe, slot and OFDM symbol

2.5 Multiple Access Schemes

In LTE-A, orthogonal frequency-division multiplexing (OFDM) is used in the downlink while single-carrier frequency-division multiple access (SC-FDMA) is used in the uplink.

2.5.1 OFDMA and OFDM

OFDM is the chosen downlink transmission scheme in LTE and LTE-A because of its robustness against multipath interference (MPI) and its flexibility for use in different transmission bandwidth arrangements including carrier aggregation. Due to high data rates being offered by LTE and LTE-A, a wider transmission bandwidth is required. When single wide transmission bandwidths (carriers) are used, there is a high chance of signal corruption due to radio channel frequency selectivity. Equalization can be used to solve this problem but it may amplify noise greatly in frequencies where the channel response is poor. One way to be able to use wider transmission bandwidth and avoid the problem of frequency selectivity is multi-carrier transmission [6]. This is where OFDM comes in. With OFDM many narrowband signals (subcarriers) are multiplexed so as to achieve a wider bandwidth. The power and rate of transmission in each subcarrier band depend on the response of the channel in that band.

Although an OFDM signal consists of many closely spaced carriers whose sidebands overlap, these carriers can be received without interference because they are orthogonal to each other. The amplitudes and phase of the subcarriers correspond to symbols to be transmitted. After the symbols are mapped to sub-carriers, they are then separately inverse-fourier transformed to the time domain. An OFDM modulator consists of N complex modulators where each modulator corresponds to one OFDM subcarrier. Transmission is in blocks. During each OFDM symbol interval N modulation symbols are transmitted in parallel. OFDMA modulation is shown in Fig. 2.5.

OFDMA involves assigning different subcarrier groups of an OFDM symbol to different users. If M modulators are being used by a single terminal, then it will be assigned M subcarriers. This is in contrast to OFDM/TDMA which assigns the entire OFDM symbol to one user (M=N).

In LTE and LTE-A the basic subcarrier spacing is 15 kHz. The number of subcarriers will vary depending on the selected transmission bandwidth. For example there will be 50 subcarriers if a bandwidth of 10 MHz is used. The number of subcarriers is directly proportional to the size of selected transmission bandwidth. The larger the transmission bandwidth, the higher the number of subcarriers.

Corruption of orthogonality of OFDM subcarriers necessitates the use of cyclic-prefix. This corruption usually arises due to frequency selectivity in radio channels and can lead to interference between subcarriers [6]. Cyclic-prefix insertion makes OFDM signals more robust under frequency-selective radio channel conditions.

In OFDMA intra-cell interference is totally avoided as all the subcarriers are orthogonal to each other. There are different resources that need to be shared properly among users. These resources are summarized as follows.

- Frequency of sub-carrier
- Time slot/frame
- Modulation and coding scheme (MCS)
- Transmission power
- Adaptive antenna and MIMO

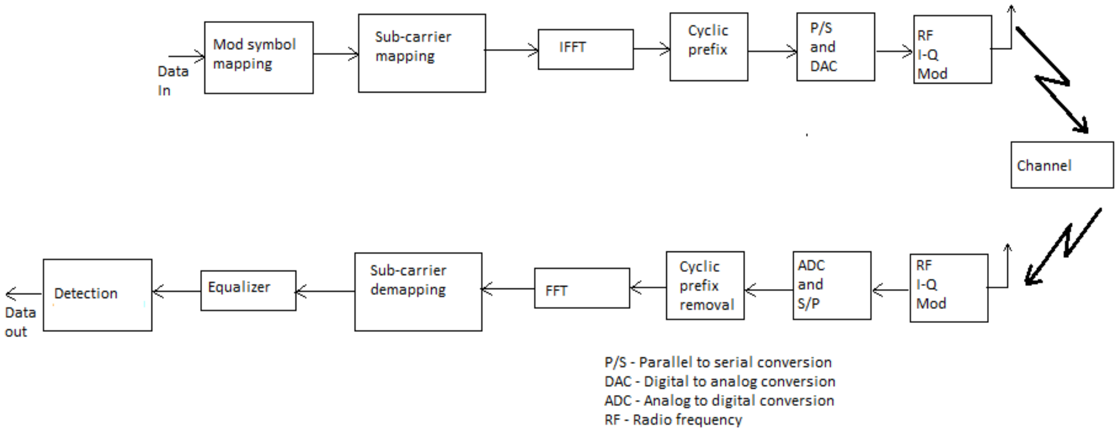


Figure 2.5: OFDM modulation and demodulation

The OFDMA standard provides time, frequency and spatial grid as illustrated in Fig. 2.6 [7]. This standard provides an option to adapt the modulation and coding scheme based on time, frequency or spatial domains. The modulation and coding can take different adaptation within each diversity systems. A chunk is formed by n × m set of resources where n is number of OFDMA symbols and m is the number of adjacent sub-carriers per chunk. These chunks can be independently assigned to UEs to support channel dependent frequency domain assignments.

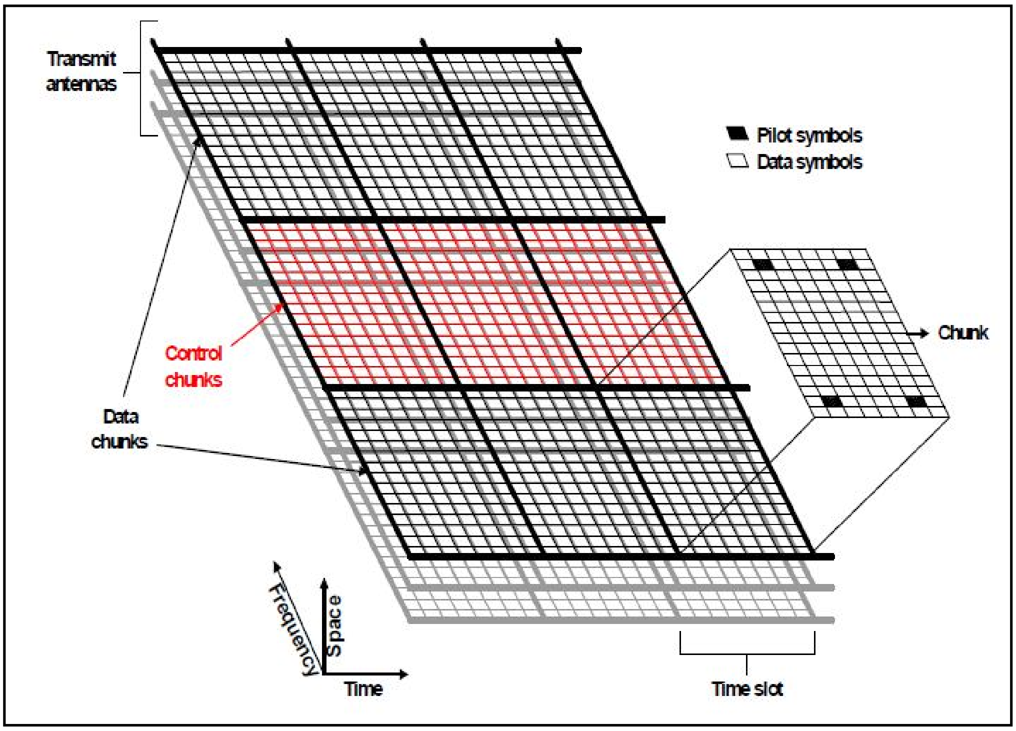


Figure 2.6: OFDMA transmission resources

Pilots in a chunk are used to estimate the channel conditions both for demodulation and link quality reports which are in turn used for link adaptation. Pilots are inserted in time/frequency grid by reserving a bunch of resources within each chunk as be depicted in Fig. 2.6. In addition to user chunks, there are also control chunks which are in charge of control signaling between cells and UEs. Control chunks carry scheduling and transmission format information, i.e. information indicating the intended receiver as well as the transmission format (modulation, coding and pilot pattern) used for each data chunk.

2.5.2 SC-FDMA

OFDM has certain shortcomings that make it unsuitable for use in the uplink. OFDM modulation, and also any multi-carrier transmission, will have large variations in the instantaneous power of the transmitted signal. The large variation in power will lead to high peak to average power ratio (PAPR). Low PAPR will reduce power amplifier efficiency and the consequence of this is higher power-amplifier cost [6]. This is undesirable because the mobile terminal should consume low power. SC-FDMA combines the high PAPR of single carrier systems with multi-path resistance and flexible sub-carrier frequency allocation offered by OFDM. SC-FDMA is a modified version of OFDM which tries to take the advantages of both single carrier transmission and OFDM. In SC-FDMA single carrier transmission scheme is implemented using DFT-spread OFDM.

Time division multiple access (TDMA) and frequency division multiple access (FDMA) can be used to achieve mutually orthogonal uplink transmissions within a cell. In order to achieve high data rates, wide transmission bandwidth is required. A user terminal can be assigned the entire bandwidth so as to achieve high data rates. Data from a UE is bursty in nature because UEs do not transmit data all the time and this makes TDMA necessary in the uplink. However using TDMA alone is bandwidth inefficient because the uplink is usually power limited [6]. When there is power limitation, wide bandwidth will not be made full use of. This is more so in LTE and LTE-A where the bandwidth is very wide. Hence FDMA is also necessary in the uplink so that many users can share the same channel. However if channel conditions allow (if the data rates are not bandwidth limited), the user terminal should be assigned the entire bandwidth. FDMA with flexible bandwidth allocation is therefore necessary. Different user terminals can be assigned different number of subcarriers depending on their current uplink channel conditions and this is what happens in SC-FDMA. Hence OFDM can be used in the uplink but in a different manner from the downlink.

In SC-FDMA data symbols are transformed to frequency domain by discrete fourier transform (DFT) before going through standard OFDM modulation. This is illustrated in Fig. 2.7. SC-FDMA is sometimes referred to as DFT-spread OFDM and can be thought of as the usual precoded OFDMA but in SC-FDMA precoding is done through DFT [8].

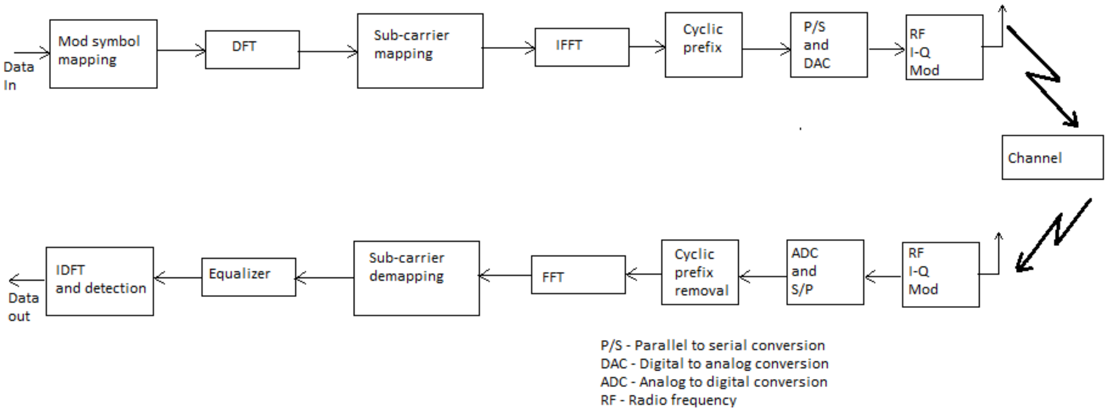


Figure 2.7: SC-FDMA modulation and demodulation

2.6 Multi –antenna Techniques

In LTE and LTE-A, several antennas can be used at the transmitter and/or at the receiver. The use of multiple antennas is very important in achieving the system requirements of LTE and LTE-A. This is because the use of multiple antennas results in an improved system capacity and coverage. Such improvement arises because of the following reasons:

- Multiple antennas at the transmitter and/or receiver provide additional diversity against fading. Diversity schemes use stochastic properties of a channel in order to reduce the effects of signal fading. This requires that the different transmission channels used by different antennas should have low mutual correlation. This can be achieved by having large inter-antenna distance (spatial diversity) or through the use of different antenna polarization directions (polarization diversity) [6].
- Multiple antennas can be used for beam-forming. With beam-forming multiple antennas can be used to shape the transmitted signal beam in a certain way so as to maximize gain in a specific direction or to suppress certain strong interfering signals.
- Multiple signals (one for each antenna) can be sent by the transmitter. At the receiver side, the signals are received by one or multiple antennas and then combined. This is referred to as spatial multiplexing or Multiple-Input Multiple-Output (MIMO) antenna processing. MIMO can also be used as a multiple access scheme. Spatial multiplexing is a form of multiplexing in which the space dimension is re-used. Separately encoded data can be transmitted from one of the multiple antennas in the

transmitter to one or many antennas in the receiver. This will contribute to high throughput.

Multiple antenna takes advantage of multipath and it even leverages it by combining signals which take different paths and time of arrival from the transmitter. MIMO was chosen for use in LTE and LTE-A because of its robustness to multipath. This robustness against multipath will contribute to an increase in range for the signals (better coverage). Other benefits of MIMO include high spectral efficiency, better cell-edge user throughput and link reliability.

In the downlink (as shown in Table 2.1) 100Mbps data rate can be achieved by 2-by-2 MIMO multiplexing while a peak data rate of 300 Mbps can be achieved by 4-by-4 MIMO multiplexing. In the uplink SIMO (Single Input Multiple Output) or 1-by-2 is adopted so as to simplify the circuit implementation in the UE and to also reduce its power consumption. LTE-A uses SU-MIMO (Single User MIMO) and MU-MIMO (Multi-User MIMO) in the downlink but only SU-MIMO in the uplink [4]. In SU-MIMO up to four antennas (4-by-4) can be used while in MU-MIMO up to eight antennas can be used in the downlink.

2.7 LTE-A Heterogeneous Networks

The traditional deployment of LTE networks is based on homogeneous networks consisting of macro base stations only. However it has been difficult to support the demand for higher data rates and capacity with the use of these traditional homogeneous networks. In order to cope with increased traffic demand, the concept of heterogeneous networks (HetNets) was defined in 3GPP standards. HetNets are useful in optimizing coverage and capacity especially in unequal user traffic distribution areas and in hotspot areas. In HetNets high power macro-cells are overlaid with layers of low power nodes (LPNs) like femto, pico and relay base stations.

2.7.1 Traditional Network and its Shortcomings

In traditional homogeneous network, all base stations have similar parameters and configuration and network deployment is planned. All base stations have nearly same transmit power, antenna patterns, similar backhaul connectivity to the packet data network and serve almost the same number of users [9]. During network deployment base station locations are carefully planned and chosen to maximize network performance and to control interference between the base stations.

Data traffic demand has been increasing and this trend is set to continue. In traditional homogeneous network, network capacity can be expanded by either increasing the bandwidth or improving link efficiency through the use of MIMO, OFDM and other advanced signal processing techniques. The macro layer bandwidth can be increased by using wider bandwidth and through carrier aggregation. Increasing bandwidth significantly improves downlink data rates. However uplink data rates do not improve much with the use of these techniques due to power limitation. Data rates are limited by low received power by the eNodeB from the user terminal due to large attenuation and challenging radio propagation conditions.

In traditional homogeneous networks link efficiency has been improved until it has reached theoretical limits and further improvement of system spectral efficiency can only be done through densification of macro layer [10]. Densification of the macro layer by adding more eNodeBs also improves network capacity. Both uplink and downlink data rates improve. Network capacity expands because of cell splitting gains. However this technique works well only in sparse deployments because there will be limited interference among the eNodeBs. In dense deployments cell splitting gains achieved by adding more nodes will be limited due to high inter-cell interference [11]. Other shortcomings of this technique are that it is repetitive, complex and site acquisition is difficult [9].

Heterogeneous networks are necessary so as to address the shortcomings of traditional homogeneous networks.

2.7.2 Benefits of Heterogeneous Networks

Heterogeneous networks consist of macro eNodeBs and LPNs. The LPNs are smaller in size, cost less and have lower transmission power. Due to the three features of LPNs, they are easier and more flexible to deploy. Having lower transmission power makes them easier to deploy because they causes less interference. Site acquisition is also less of an issue because of their small size.

Deploying additional low power network nodes will increase system capacity (traffic per m^2). As a result users-to-cell distance will be shorter implying the link-budget of users will be improved which in turn improves user data rate. HetNets also significantly improve network capacity and average spectral efficiency. Heterogeneous networks are especially useful in improving capacity in areas with uneven user distribution and in hotspots. LPNs eliminate coverage holes present in macro cells and are useful in providing high data rates at cell edges.

The benefits of LPNs do not, however, come without a cost. Firstly deployment of LPNs results in a higher number of the nodes to be managed and increase in effort for system configuration. Secondly user terminals served by LPNs will experience higher interference especially when LPNs are in a co-channel scenario with macro eNodeBs.

2.7.3 HetNets Network Architecture and Deployment

An example of a HetNet is shown in Fig. 2.8. The network consists of planned placement of eNodeBs that typically transmit with high power (~ 5W - 40W) overlaid with some LPNs. LPNs transmit at substantially low power levels (~0.2 - 2W) and have omni-directional antennas. LPN transmit power depends on the placement (outdoor/indoor) or the nature of LPNs (femto, pico, micro, relay) [11].

Deployment of low power nodes can be viewed as the second phase of LTE network deployment. Deployment of LPNs is not well planned and is often uncoordinated. The location of LPNs is just based on coverage problems and on rough knowledge of user distribution like hotspot areas.

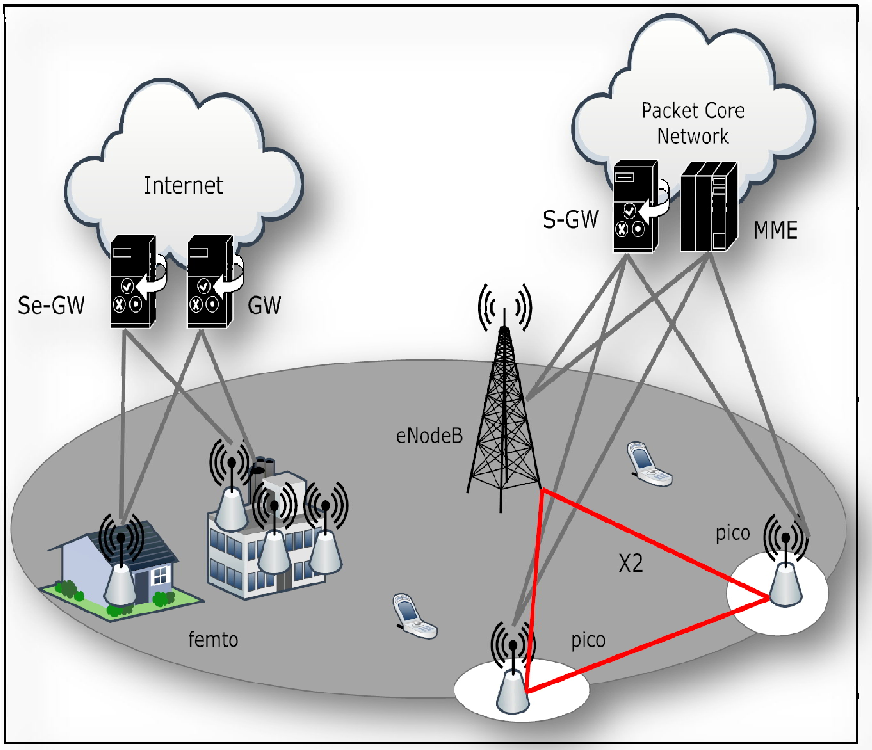


Figure 2.8: Heterogeneous network architecture

2.7.4 Types of LPNs

LPNs (femto, pico and relay) are base stations that transmit with very low power compared to macro-cells.

Pico

Pico cells are regular macro cells except that they have lower transmitting power. Pico cells are equipped with omni-directional antenna and hence they are not sectorized. The backhaul uses X2 interface for data communication and interference management. Their transmit power ranges from 250 mW to 2W for outdoor deployments and around 100 mW for indoor deployments [11].

Femto

Femto cells are typically consumer/operator deployed and their deployment are unplanned. The backhaul uses the existing internet connection such as Digital Subscriber Line (DSL) or cable modem [11]. They are also equipped with omni-directional antennas and have transmit power of less than 100 mW. Femto cells can be classified as closed or open depending on the access set to them. Closed femto cells only allow access by users that are in the Closed Subscriber Group (CSG) while open femtos are more like pico cells except for the different backhaul connection.

Relay

Relay node is another type of LPN node which can be used in HetNets to enhance the coverage. Relay nodes have no wired backhaul. Relay nodes provide wireless backhaul by relaying the signal from mobile station to the macro base station. A relay uses the air interface resources of the macro-cell. If the communication in the backhaul uses the same frequency as in the uplink and downlink of the UE, then the relay node is denoted as in-band. If the backhaul uses different frequency from that of the UE in UL and DL, then the relay is denoted as out -of-band. A typical relay node used as backhaul communication and access is shown in Fig. 2.9.

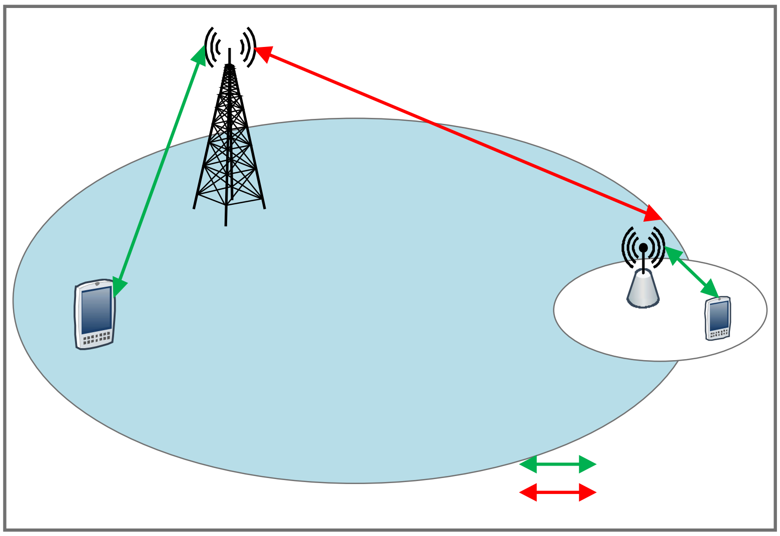


Figure 2.9: Relay used as access and backhaul

Chapter 3

Radio Resource Management in LTE-A

Radio Resource Management (RRM) is used in wireless cellular networks to effectively share and assign radio resources among users (e.g mobile terminals, radio bearers, and user sessions) of the cellular network. In LTE, resource assignment is done by a scheduler [7]. Efficient RRM ensures high QoS for different class of services, optimization of radio coverage, maximization of link spectral efficiency and provision of acceptable fairness in sharing of radio resources. The radio link quality varies rapidly due to fast fading fluctuations on the link. Link quality also varies due to mobility and interference fluctuations. Hence in any radio system the most challenging part is to contest the randomly changing channel conditions. This can be done by adjusting the modulation scheme, scheduling and coding rate. Due to fast fading fluctuations, LTE RRM functions have to operate on time scale matching with that of radio channel fluctuations. This is basically achieved if RRM control is located in the vicinity of the radio interface where each link quality measurement report is available in time. In LTE and LTE-A RRM schemes can be centralized, distributed and hierarchical [7]:

a) **Centralized:** In centralized RRM, a centralized entity is used which is connected to all cells. The Channel Quality Indicator (CQI) is reported from all cells in the cluster and from all sub-carriers available in the system. This centralized entity is responsible for resource allocation according to the feedback from mobile stations. Although the centralized scheme can be used as a bench mark for performance evaluation, it has high computational overhead due to the need to send assignment information to users and to receive channel information.

b) **Distributed:** Centralized RRM provides an optimal solution at the expense of extensive signaling overhead. Distributed RRM is an alternative solution with minimized signaling overhead. In this scheme there is no central entity responsible for resource assignment and receiving link quality measurements. In case of ICIC, each cell except femto-cell can exchange information through X2 interface to coordinate resource assignment. The measurements in this RRM scheme have not been standardized but rather they are implemented independently whereas in centralized RRM the interface need to standardized [7].

c) **Hierarchical**: In this type of RRM technique the allocation of resources is sub-divided among different nodes according to the hierarchical levels in the system. For example RRM server or super powerful eNodeB. This scheme provides a trade-off between the merits and demerits of centralized and distributed RRM schemes.

RRM functions in LTE-A includes scheduling and link adaptation, handovers, load balancing, cell selection and reselection, admission control and interference management. Scheduling, load balancing, interference management in HetNets and handover will be discussed in this chapter.

3.1 Scheduling

The purpose of scheduling is to share resources among different users (different terminals). Assignment of available resources in uplink and downlink communication is controlled by a scheduler located in eNodeBs. The scheduler assigns resources in units of resource blocks. A resource block (RB) consists of 12 subcarriers in frequency domain and one slot (0.5ms) in time domain. The scheduler selects the UEs to be scheduled and the RBs to be assigned based on Channel Quality Indicator (CQI).Fig.3.1 [12] illustrates the operation of DL and UL scheduler.

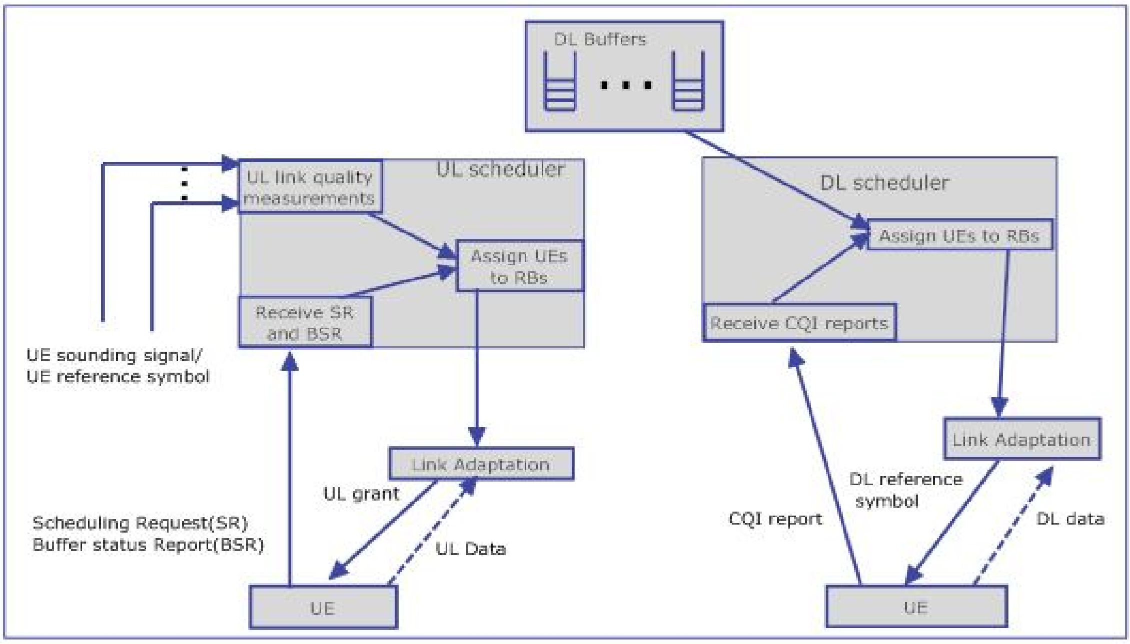


Figure 3.1: UL and DL scheduler

3.1.1 Channel Quality Information

Channel dependent scheduling in the downlink is based on the channel quality measurements from UE. CQI reports are used by UEs to send information about DL channel quality to the eNodeB. To perform measurements on RB basis, reference signals are transmitted in each RB. CQI reports can be sent either on the physical uplink control channel (PUCCH) if the UE has no uplink channel assignment or on the physical uplink shared channel (PUSCH) if UE has already been granted an UL channel [12]. UL channel quality measurement is easier than DL channel quality measurement because the cell itself can perform measurements on the UL transmission of the UE. Reference symbols similar to those in the DL are inserted in each RB in the UL. Channel quality is estimated only on RBs on which the UE is actually transmitting as the UE may not be transmitting at the full bandwidth.

The cell gets relative channel quality information only on RBs that it has assigned to UEs. RB assignment should be done according to best RB quality selected from the full bandwidth. To be able to allow a cell to estimate the channel quality on all RBs from the same UE, it should possible to transmit the so-called channel sounding reference signals from the UE. However RB assignment in the DL is constrained by single carrier frequency. Hence full flexible channel dependent scheduling in the UL is difficult even though full bandwidth channel quality report is available.

3.1.2 Link Adaptation and Power Allocation

If a bunch of RBs are assigned by the scheduler to the UE, appropriate modulation and coding scheme (MCS) and power allocation have to be determined. This can be done in link adaptation function [7]. The power allocation can be homogeneous or non-homogeneous. In this thesis only homogeneous power allocation to all available RBs will be considered. As depicted in Fig. 3.1, link adaptation function is not part of the scheduler function but it is closely related to resource assignment as a particular resource is defined by MCS and time-frequency allocation. MCS selection is done by the cell in the UL and DL. The selection of MCS is based on CQI information from UE in DL and based on measured link quality at the cell in UL. The buffer status in the serving cell and the UE is also considered during MCS selection. The selected MCS will be signaled to the UE through PDCCH. The UE then decodes the received data on PDCCH according to MCS indicated in the corresponding PDCCH information. In UL the serving cell decodes the data information from the UE based on MCS granted to the UE.

3.1.3 Buffer Status Information

Downlink buffer status information is available in the eNodeB. However, the eNodeB should receive buffer information from the UE in the UL transmission since UL buffer is located in the UE. The eNodeB scheduler in the UL will have knowledge of UL buffer if and only if the UE reports the buffer information to the eNodeB in time. In UL buffer reporting, it is important to consider the case in which the UE has been granted a valid UL grant and the case in which the UE does not have UL grant. To request resources in the second case there are two alternatives in LTE [12]. The first one is using Random Access Channel (RACH). The second one is dedicated scheduling request resource on the PUCCH if there has been such a resource granted to the UE by the eNodeB.

3.2 Load Balancing

The purpose of load balancing is to deal with unequal distribution of traffic load over multiple cells in such a way that there is an even resource utilization in all the cells. By having an even resource utilization, there will be a high QoS in all cells and for all users. Load balancing is a major issue in LTE-A HetNets because a few UEs associate with LPNs due to their low transmit power compared to macro eNodeBs. This will result in low load in LPNs and high load in macro-cells. Load balancing in HetNets can be achieved through the technique of Cell Range Extension (CRE). Under CRE, an offset or bias is added to LPN cells during cell selection so that more UEs can select LPN cells. This thesis deals with load balancing in HetNets and it is discussed in detail in chapter 4.

3.3 RRM techniques for Interference Management in LTE-A HetNets

In LTE-A HetNet, there are two layers of cells. One layer is composed macro-cells and the other is composed of LPN cells. The presence of high inter-layer interference in heterogeneous networks calls for the use of more robust interference management techniques.

The concept of HetNets deployment in mobile communication systems has been used for relatively long time. HetNets have been made use of in GSM networks. Different sets of carrier frequencies have typically been used in the different cell layers so as to avoid strong interference between the layers [6].

In homogeneous networks, a frequency re-use of one is used and thus all cells share one channel. All cells are in a co-channel scenario. If all cells in a HetNet are put in a co-channel scenario like homogeneous networks, there will be high inter-cell interference. Big differences in transmit power between LPNs and macro base stations in a co-channel scenario puts LPN cells at a disadvantage because LPN cells will experience high interference from macro-cells. This thesis will consider a HetNet in which macro-cells are in a co-channel scenario with LPNs.

Interference is even a bigger problem when cell range extension is used in HetNets to achieve load balancing. When CRE is used, some UEs served by LPNs will experience high interference from macro-cells because the strong signals from macro-cells which would have been selected to serve the UE act as strong interferers. Interference management is very important in HetNets so as to improve performance of HetNets. High QoS and data rates can be realized if interference is mitigated or avoided.

At the network level inter-cell interference management can be achieved through static resource partitioning or adaptive resource partitioning techniques.

3.3.1 Static Resource Partitioning

Static resource partitioning can be done in time, frequency or spatial domain. In LTE, frequency domain partitioning is frequently used. When it comes to the frequency distribution, a set of resource blocks or subcarriers will be assigned to a particular node in such a way that neighbor cells which may interfere with each other do not use the same set of frequencies. In this resource partitioning cell-edge users' SINR improves greatly while the spectrum efficiency will be reduced by the reuse factor. There are two static resource partitioning schemes.

The first technique is called hard frequency reuse. When hard frequency reuse is used, different carrier frequencies are assigned to LPN cells and macro-cells [13]. The use of this scheme will ensure that there is no interference between the two layers in the heterogeneous network. However this scheme will lead lower data rates due to smaller bandwidth that arises from bandwidth segmentation.

The second is fractional frequency re-use. Fractional frequency re-use combines the benefits of the above two schemes. With fractional frequency reuse, LPNs are allowed to use the entire system bandwidth while macro-cells use a fraction of the system bandwidth [13]. The non-shared portion of bandwidth of LPNs is guaranteed to be free from macro-cell interference. This allows for larger coverage by LPNs. However the performance of fractional frequency reuse highly depends on how users are assigned to the two layers [13]. It depends on whether users are assigned to LPN-only frequency or co-channel carrier frequency.

3.3.2 Adaptive Resource Partitioning

In LTE, there is no higher level controlling node like GSM's base station controller and scheduling is carried out at each individual node. Introducing the standard messages that convey information using X2 interface between different nodes provide the best solution to coordinate the scheduling policy. The cells can then use the information provided by neighboring cell to perform own scheduling activity in a way that will reduce interference to neighboring cells. This is called inter-cell interference co-ordination (ICIC).

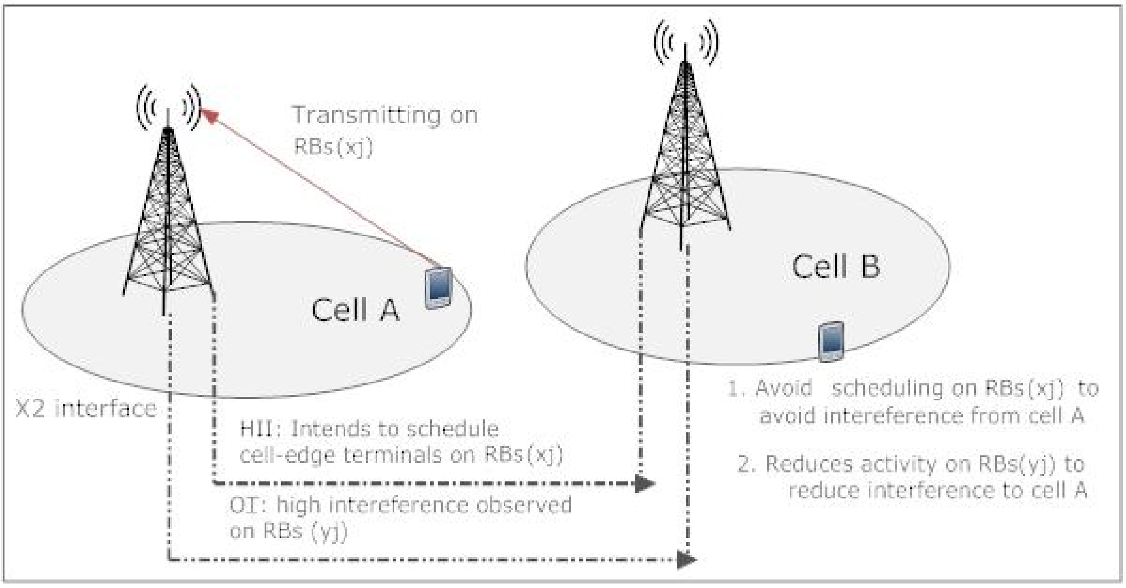


Figure 3.2: Uplink ICIC based on HII and OI X2 interface

To support uplink dynamic scheduling of resources among cells in HetNets, two X2 ICIC signals have been defined [14]. These include High Interference Indicator (HII) and Overload Indicator (OI). A cell uses HII to provide information to the neighbors about the set of resources it is going to schedule for cell-edge UEs. From the HII information the neighbor cells can expect high interference from the resource blocks assigned to edge UEs and thus they will avoid scheduling their own cell-edge users with the same resource blocks in order avoid interference. This is illustrated in Fig. 3.2. As a result uplink cell-edge transmission interference will be reduced in neighboring cells and this will improve average SIR of cell-edge UEs.

Overload Indicator is a reactive interference mitigation technique in which a cell can indicate interference situation in its own different resource blocks using three power levels (Low/Medium/High). A neighbor cell which receives OI message will try to change its scheduling behavior on the resource blocks which are transmitting with high power in the cell issuing the OI message. This is illustrated in Fig. 3.2.

Relative Narrowband Transmit Power (RNTP) is defined to support ICIC operation in DL [15]. Similar to HII, a cell uses RNTP X2 signaling to notify the neighbor cell whether or not downlink resource block cell-edge transmission power exceeds a certain threshold level. Using the same principle as in the uplink, in the downlink transmission the neighbor cell will perform its resource scheduling based on the RNTP message issued. Recently centrally located resource scheduling has been proposed also to effectively coordinate the scheduling between HetNet nodes. This can be achieved by introducing inter-node coordination within a central location or by deploying a powerful eNodeB that be able to handle all the connected nodes in the system. Fig.3.3 illustrates RNTP X2 signaling in DL.

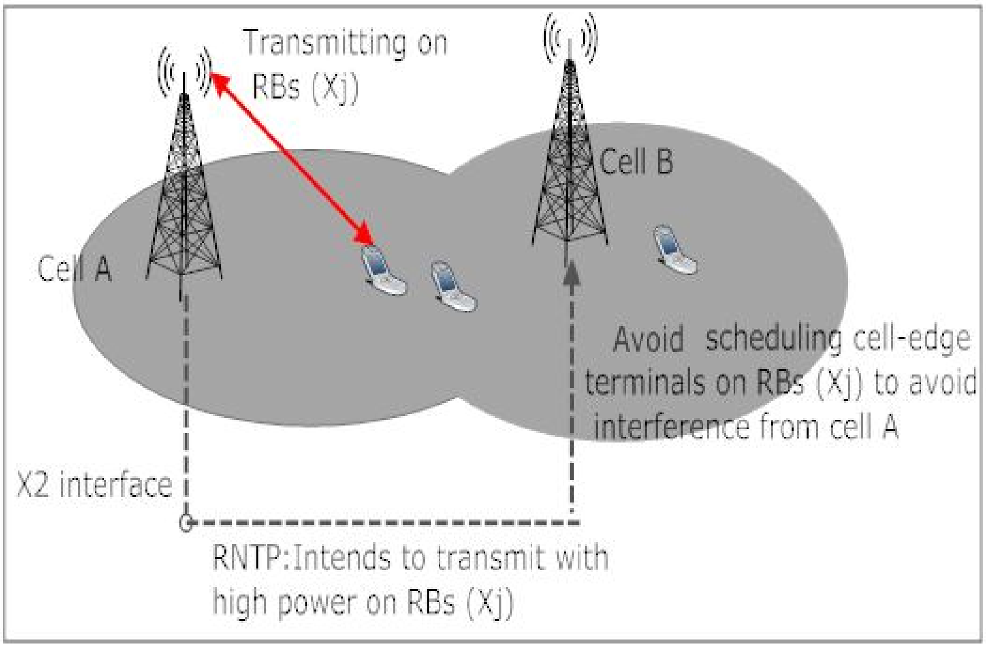


Figure 3.3: Downlink ICIC based on RNTP X2 signaling

3.4 Handover Control

Handover control is in charge of maintaining the radio link of user in active mode as the user moves from one cell coverage area to another. In LTE only hard handover is supported like in GSM systems. LTE handover is controlled by the network and assisted by the user [26]. The handover from one cell to another occurs in a break-before-make fashion. Users will have connectivity only to one cell at a time. This is dissimilar to WCDMA which uses soft handover where UE can be associated with more than one cell at any one time.

The network controlled and UE assisted handover characteristic implies that the decision to move the radio link connection of UE from one cell to another cell is made by the network (by the serving cell) assisted by the measurement reports sent by the UE. The serving eNodeB can use other information to make the handover decision. These include its own measurements, the availability of radio resources in the target cell and load distribution. The most important criterion used to make a handover decision is the UE path gain measure. In this case handover control should make sure that the UE is associated with the cell with the best average path gain. This is extremely important in reuse 1 system like LTE where a UE can be connected to a cell which is not the best cell which may cause a substantial nterference to a neighbor cell. The disadvantage of reuse 1 system is that the link quality (SINR) may change rapidly due to inter-cell interference as the UE moves towards to the cell edge. As described in section 3.3, the use of ICIC technique may mitigate the high cell-edge interference. To tackle the problem of rapid change of link quality, a fast handover execution is important from the UE performance point of view. In order to achieve good handover performance from radio efficiency and user QoS point of view, it is required to have limited interruption time and no user data packet losses during the handover.

Chapter 4

Load balancing in LTE-A Heterogeneous Networks

4.1 Introduction

The purpose of load balancing in cellular network is to deal with unequal distribution of traffic load over multiple cells. Load balancing is a major issue in LTE-A HetNets because a few UEs associate with LPNs due to their low transmit power compared to macro eNodeBs. During cell selection or reselection, a UE will usually select the cell with the strongest downlink Reference Signal Received Power (RSRP). This is the conventional cell selection scheme in LTE Rel. 8. In a heterogeneous network, LPN power is 250 mW - 2W while that of macro-cells is 5W - 40W [11]. Hence the power disparity can be as large as 20 dB. This will bring some challenges.

Firstly, cell splitting gains will not be fully realized as the cell area or range of LPNs will be small and the number of UEs associated with LPNs will be limited. Since LPNs are usually placed in hotspots and their main aim is to offload traffic from macro-cells, the desired offloading and cell splitting gains will vanish. The LPN may not cover the entire area of the hotspot and the usefulness of LPNs is greatly diminished.

Secondly, there will be load imbalance between the macro-cells and LPN cells as a result of few UEs being associated with LPNs. This will make macro-cells have a much higher cell load compared to LPN cells. As a consequence, macro-cells may end up not having enough radio resources to serve the many associated UEs while LPNs may be serving limited users or no users at all which make limited or no use of available radio resources. This difference in load distribution between LPNs and macro-cells can result in congestion in some cells and unfair distribution of data rates among users. This will result in uneven user experiences in the network. The Quality of Service (QoS) in macro-cells will be much lower than that in LPN cells.

There is therefore need to balance load between LPN cells and macro-cells. Load balancing is a key aspect in radio resource management. The aim of load balancing is influence load distribution in such a manner that there is almost uniform radio resource utilization across all cells in a network. Load balancing between macro-cells and LPN cells can be achieved by expanding the coverage area of LPNs so that more UEs are served by LPN cells. This technique is called cell range extension (CRE) [9], [16].

In this chapter, CRE is discussed in detail. A range optimization framework that uses the concept of cell load coupling is also discussed in this chapter. A load balancing algorithm that can be used to for cell-specific offset assignment is presented in the last part of the chapter.

4.2 Cell Range Extension

CRE can be achieved by either increasing the transmit power of LPNs or virtually by using an offset or bias during cell selection. The former does not provide a good solution. This is because increasing the transmission power of an LPN will imply increasing the cost and size of the node. Increasing cost and size will diminish the advantage of LPNs being low cost and small size which make them easy and less costly to deploy. This will limit availability of LPNs. The latter provides a better solution and is the subject of consideration of this thesis to achieve load balancing.

Virtual CRE is a technique that can be used to compensate for the difference in transmit power between LPNs and macro eNodeBs so that the coverage area of LPNs can be increased. In CRE, an offset or bias is added to the LPN RSRP during cell selection. Cell selection is a process that allows a UE to select a suitable cell to camp on in order to access available services. With CRE, UEs do not connect to a cell with highest RSRP but with the cell with highest (RSRP + Offset). This will allow more UEs to be associated with LPNs. Virtual CRE improves load balancing in a heterogeneous network without the need for increasing LPN transmit power. Biasing in LTE-A HetNets is an appealing feature because it does not have backward compatibility problems with LTE [17]. Fig 4.1 illustrates cell range extension.

Another benefit of CRE relates to the uplink. CRE solves the problem of uplink imbalance [17]. If the cell with the highest downlink RSRP is selected, it will imply that UEs will often select macro-cells even if they have a higher path-loss than the LPN cells. The UEs which select LPNs will experience a lower path-loss. This is not optimal especially from the uplink coverage point of view. If there is power control in the uplink, the UEs which have selected macro-cells will have to transmit at a higher power to compensate for the higher pathloss. This will increase interference levels in the uplink. If there is no power control, the received signal at the macro eNodeB will be lower than that at LPN. Under CRE, the cell with the lowest path loss will be selected and this would improve the uplink received power or SINR and uplink data rates will improve as a consequence.

The benefits of CRE, however, come at the cost of higher downlink interference for users on the edge of LPN especially when LPNs are in a co-channel scenario with macro-cells. Such users will experience lower than usual signal to interference ratio (SINR). This calls for interference management techniques. Interference mitigation or avoidance can be done at the user terminals or through resource co-ordination (statically or dynamically) among base stations.

4.2.1 Cell Range Extension Using a Uniform Offset

Usually a uniform offset value for all LPNs is used in a heterogeneous network and has recently been used to solve the problem of load imbalance. This offset value will determine the number of UEs associated with LPNs. The higher the offset value, the higher the number of UEs associated with LPNs. The lower the offset value, the lower the number of UEs associated with LPNs. Selecting a too high offset value can lead to overload of LPNs and if it is too low macro-cells may be overloaded. A high offset value may also lead to the serving cell being too weak in relation to interference. It is necessary to select an optimal uniform offset value that will lead to a balanced load between macro-cells and LPN cells. Selecting optimal uniform offset means selecting optimal range for LPNs.

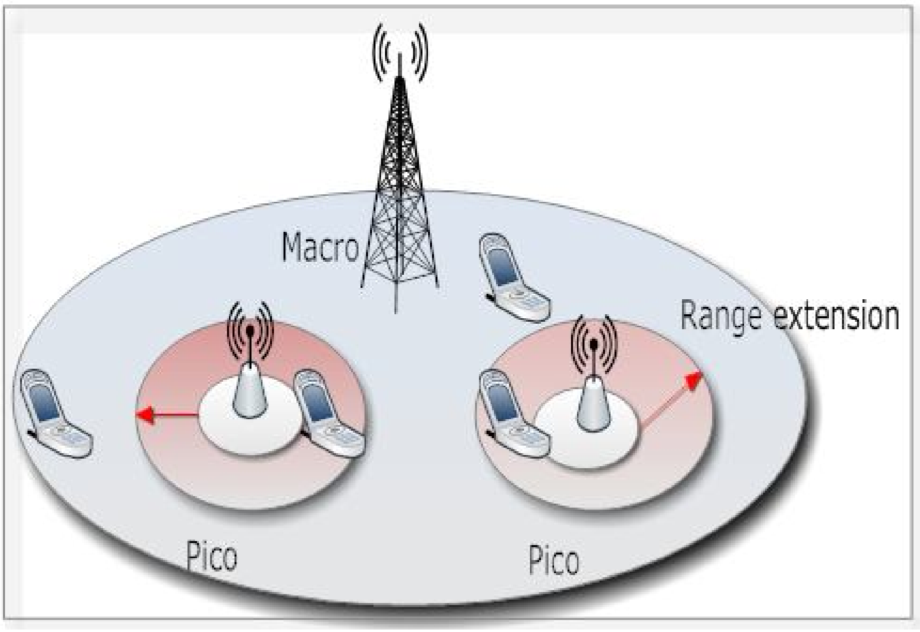


Figure 4.1: Cell range extension

4.2.2 Cell Range Extension Using Cell-specific Offsets

The use of optimal uniform offset is one way to achieve load balancing in HetNets. The degree of load balancing can be further improved by using cell-specific offsets. Cell-specific offsets means using different offset values for different LPNs. Cell-specific offsets are necessary because the conditions around different LPNs are usually different. Firstly, user distribution is different in various hotspots areas served by different LPNs. Secondly, LPNs may be experiencing different propagation conditions. Thirdly, the strength of macro-cell power received depends on the location of the LPN in the cell. The closer the LPN to the macro eNodeB, the higher the offset value required because the macro-cell signal is stronger and vice versa.

4.3 Range Optimization Framework

Cellular network planning is very important from the perspective of both the user and the network operator. After a network has been planned and deployed, radio network optimization is necessary to fine-tune the network so as to improve network key performance indicators. Range optimization falls under radio network optimization. Range optimization aims to find optimal LPN cell-specific offsets that can achieve the highest possible degree of load balancing.

4.3.1 LTE Rate Control versus UMTS Power Control

In UMTS, power control is used to compensate for variations in channel conditions. This compensation is done by adjusting power. The aim of such adjustment is to maintain a near constant E_b/ N_o (similar to SINR) at the receiver so that the receiver can send data with a tolerable bit error rate (BER) [6]. Transmit power will be high under poor radio channel conditions but it will be lower under good channel conditions. Hence transmit power is proportional to channel quality. Power control results in constant data rate irrespective of channel conditions and provides a form of link adaptation. Due to the use power control in UMTS to meet SINR requirements, the power in one cell is a linear function of those in other cells. Consequently power control can be represented by a system of linear equations which can be referred to as UMTS interference coupling [18].

LTE and LTE-A are designed to be able to handle high packet data traffic. Most of their traffic consists of packet data traffic. This makes it necessary to provide a certain constant data rate over a radio link. In order to meet the expectations of users, the data rate provided has to be as high as possible. Services such as voice and video are not affected by short term variations in data. However average data rate in the short term has to remain constant. Hence rate control can be used as an alternative for power control for link adaptation [6]. With rate control, the data rate is dynamically adjusted to compensate for varying channel conditions while power is kept constant. Radio link data rate can be adjusted through the use of adaptive modulation and coding whereby modulation scheme and/or channel data rate is varied so that the radio link data rate can be controlled [6]. Link adaptation and scheduling is as a joint function in LTE and LTE-A as discussed in section 3.1. Rate control scheme will result in non-linear relations between cell-coupling elements [19]. Cell load coupling is discussed in detail in section 4.3.3.

4.3.2 Cell Load in LTE networks

In LTE networks cell load can be measured by the total amount of resource blocks that are scheduled to UEs in a cell compared to the amount of resource blocks available in a cell. Different UEs will demand different number of resource blocks depending on their data demand. LTE scheduler will dynamically determine which terminals will transmit data and on which set of resource blocks. In each 1ms Transmit Time Interval (TTI), each eNodeB will transmit scheduling information to the terminals. The total number of resource blocks in a cell in LTE networks is fixed. Cell load can be determined as follows:

$$Cell\ load = \frac{Total\ number\ of\ scheduled\ resource\ blocks}{Total\ number\ of\ resource\ blocks\ available\ in\ a\ cell} \tag{4.1}$$

Cell load is a positive value which can be less than 1 or can be greater than 1. A cell load of less than 1 means that cell radio resources can meet the demand. A cell load value close to 1 (e.g. 0.95) will indicate congestion and a high probability of service outage to some terminals. A cell load value of greater than 1 means that the cell is overloaded and the cell resources cannot meet the demands of all the users. In a well planned and optimized network there will not be many overloaded cells.

4.3.3 Cell Load Coupling in LTE Networks

Let $C = \{1,\ldots..,n\}$ denote the set of cells (both macro and LPN) under consideration and let each cell have one antenna. The set of UEs is represented by U. The cell area can be considered as consisting of pixels with each pixel having similar propagation conditions. The set of pixels is denoted by J. The total power gain between antenna i and pixel j is denoted by g_{ij}. LTE can be modeled using a rate control scheme. Similar data rate demand of d_j by all UEs in all cells will be considered. UEs are located in different pixels but the data demand is the same. In a real network scenario, this will not be the case. This model targets a certain guaranteed bit rate for any type of service.

Let the load of a cell be represented by ρ_c. The load of the entire network can then be represented by a load vector given by $\rho = (\rho 1, \rho 2, \rho 3 \ldots \rho n)$. The performance of a network can be assessed by looking at the load vector. A well planned and designed network should have neither overloaded cells nor cells with big differences in their cell loads. Cell load depends on the user demands, channel conditions and the level of interference from other cells

[19]. The last factor couples the elements in the load vector. The load of a cell is determined by SINR and data rates within that cell and these two factors depend on the load values in other cells. Therefore loads of cells in a network are coupled. For user j being served by cell c, SINR can be computed as:

$$\gamma_j(\rho) = \frac{P_c \cdot g_{cj}}{\sum_{k \in C \setminus \{c\}} P_k g_{kj} \rho_k + \sigma^2} \tag{4.2}$$

P_c is the power spectral density per resource block and σ^2 is noise power. The total transmit power in a cell depend on the load of that particular cell. When the load of a cell is high, it means that more resource blocks will be scheduled and as a consequence more power in the resource blocks of that cell. It can therefore be deduced from (4.2) that the interference from a particular cell to another cell will depend on the load of that interfering cell. The higher the load of the interfering cell, the higher the interference from that cell. Hence ρ_k can be considered as the probability of receiving interference from all the subcarriers of all resource blocks of interfering cell k [19], [20].

Many techniques such as MIMO and OFDM have been used in LTE and LTE-A to try to achieve Shannon capacity bounds. It is necessary to have a model that can be used during radio network planning and optimization so that link bandwidths can try to achieve Shannon capacity bounds [21]. From Shannon channel capacity formula, the achievable data rate for one resource block can be represented by $Blog_2(1 + \gamma_j(\rho))$. B here is the bandwidth of one resource block (180 kHz). Let R represent the number of resource blocks in the frequency-time domain in question and ρ_{cj} represent the level of resource consumption in a cell due to serving users in a pixel within that cell. R (number resource blocks per cell) will be 50 if a bandwidth of 10 MHz is used. If a bandwidth of 20MHz is used, R will be 100. The number of resource units required to serve demand d_j in pixel j can be written as follows:

$$R\rho_{cj} = \frac{d_j}{Blog_2(1+\gamma_j(\rho))} \tag{4.3}$$

From (4.2) it can be seen that the load of one cell is a function of the load levels in other cells. The total load of cell c can be computed by summing (4.3) over all pixels in a cell.

$$\rho_c = \sum_{j \in J_c} \rho_{cj} = \sum_{j \in J_c} \frac{d_j}{RBlog_2(1+\gamma_j(\rho))} = \sum_{j \in J_c} \frac{d_j}{KBlog_2(1+\frac{P_c g_{cj}}{\sum_{k \in N \setminus \{c\}} P_k g_{kj} \rho_k + \sigma^2})} \tag{4.4}$$

Equation (4.4) can be written in another different compact form based on UEs if it is considered that one UE is located in a pixel. From (4.4), let $r_u = \frac{d_u}{RB}$, $b_{cku} = \frac{P_k g_{ku}}{P_c g_{iu}}$ and $m_{cj} = \frac{\sigma^2}{P_c g_{cj}}$. The first parameter represents the ratio of amount of resources demanded by UE u to the amount of resources in cell c, the second parameter represents inter-cell coupling through interference received by UE u from other cells and the third parameter represents noise power received by UE u. Since the load of a cell depends on the load of other cells, the second parameter has to be multiplied by the factor ρ_k in order to make interference received from each interfering cell proportional to its cell load. (4.4) can then be expressed as:

$$\rho_c = \sum_{u \in U_c} \frac{r_u}{log_2(1+\frac{1}{\sum_{k \in C\setminus\{c\}} b_{cku}\rho_k+m_{cj}})} \tag{4.5}$$

Equation (4.5) implies that cell load can be computed by summing the resource demand to meet the constant data demand by all UEs before being compared to the amount of resources available in a cell. Equations (4.3), (4.4) and 4.5) demonstrate cell load coupling. (4.5) can also expressed as $\rho = f(\rho, g, d, K, B)$. If there are a total of n cells in a network then there will n such equations forming a set of n non-linear equations. The set of non-linear equations can be represented by this shortened form as:

$$\rho = f(\rho) \tag{4.6}$$

For one cell $\rho_c = f_c(\rho_1, \rho_2, \rho_3, \ldots \rho_n)$. For example for a network with four cells, the set equations will be of the following form:

$$\rho_1 = f(\rho_2, \rho_3, \rho_4) \tag{4.7a}$$

$$\rho_2 = f(\rho_1, \rho_3, \rho_4) \tag{4.7b}$$

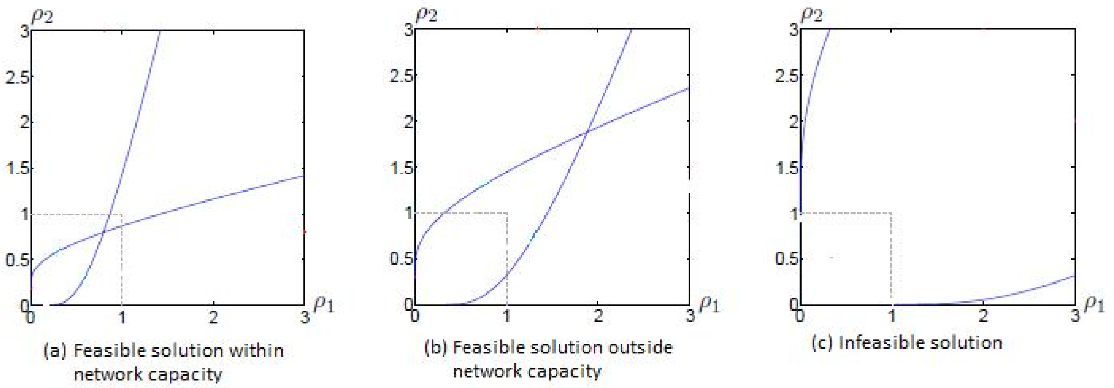
$$\rho_3 = f(\rho_1, \rho_2, \rho_4) \tag{4.7c}$$

$$\rho_4 = f(\rho_1, \rho_2, \rho_3) \tag{4.7d}$$

The function represented by equation (4.4) is continuous, it is at least twice differentiable and it is strictly positive for non-zero σ^2 even if the load values of other cells are zero[19]. When the load of other cells is zero, it means that there is no interference from those cells and therefore only noise will be in the denominator of equation (4.5).

In order to determine the load distribution in all the cells, the set of non-linear equations represented by (4.6) has to be solved. Let ρ^* denote the solution to (4.6). For a well designed and planned network the load values should range from 0 to 1 and there should not be a high load imbalance. Load values may be greater than one but this will mean that there are not enough resources to meet the demand by all users in that cell. In order for the solution to be feasible, it has to be non-negative.

Fig. 4.2 [19] illustrates cell load coupling for a network of two cells with similar parameters. The two equations will be $\rho_1 = f(\rho_2)$ and $\rho_2 = f(\rho_1)$. The solid lines show the solutions to the two non-linear equation of the network represented by equation (4.6). In Fig. 4.2(a) the two solid lines intersect within a region that represents cell loads of less than 1. In Fig. 4.2(b) the two solid lines intersect in a region that represents cell loads of more than 1. In Fig. 4.2(c) the solid lines never intersect and this represents an infeasible solution.



(a) Feasible solution within network capacity

(b) Feasible solution outside network capacity

(c) Infeasible solution

Figure 4.2: Cell load coupling for two cells

4.3.4 Optimization

Optimization involves making an optimal decision when dealing with a decision problem. Optimization begins with formulation or modeling. The variables are defined and the relationships needed to describe the relevant system behavior are quantified. After modeling the problem, then analysis can be done. Mathematical analysis can then be used to draw conclusions from the model. The next step in optimization will be making inference whereby it is determined whether the conclusions drawn are meaningful enough for decision making. The last step in optimization is assessment whereby the inferred decisions are assessed to determine whether they are adequate or practical for implementation. If the decisions are inadequate or not practical then the model will have to be revised and the whole process is repeated and the loop continues. Optimization problem is illustrated in Fig. 4.3.

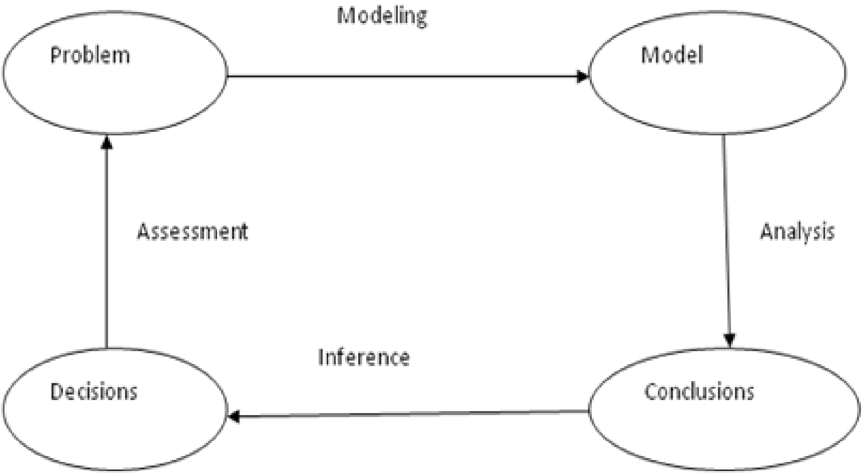


Figure 4.3: Optimization problem

A system model in optimization consists of the following elements:

- Assumptions
- Decision variables.
- Objectives – Measures the performance of various decisions. It is used to determine which decision is better compared to another.
- Constraints – These are the limiting decisions.

An optimization model represents problem choices as decision variables and seeks values that maximize or minimize objective functions of the decision variables subject to constraints on variable values expressing the limits on possible decision choices. An optimization model is written as follows:

$$\frac{Max}{Min} \quad f(x) \qquad (4.8)$$
$$s.t\; x \in X$$

A solution to an optimization model is represented by values of the optimization decision variables. A feasible solution is a choice of values for the decision variables that satisfy all constraints. The aim of optimization is the get the optimal solution. Optimal solutions are feasible solutions that achieve objective function value(s) that is (are) better than any other feasible solution.

There are two main types of optimization methods. An optimization method can either be exact or heuristic. An exact method searches for the optimal solution and can verify that the optimal solution has indeed been found. Examples of exact algorithms are Dijkstras algorithm for shortest path and simplex algorithm for linear programming. A heuristic method searches for solutions that are of good quality and which are close to the optimal solution. It is not possible to verify whether the solution is optimal when a heuristic method is used. A heuristic method can be based on simple rules of the thumb or on advanced optimization theory. Rules of the thumb are methods designed for a particular class of optimization problems and each heuristic is adapted to fit a specific decision problem structure. In this thesis a heuristic optimization method will be used for range optimization.

4.3.5 Jain's Fairness Index

Load balancing aims to achieve fair distribution of users among cells in a network. In any telecommunication network it is desirable to have a method or an index that can be used to compare the degree of fairness of a particular resource allocation strategy. This is more so in wireless networks where wireless channel resources have to be shared by many users. Jain's fairness is general purpose fairness index that has commonly been used to measure the fairness of different resource allocation schemes [22]. Jain's fairness index is given by the following expression:

$$I = \frac{|\sum_{c=1}^{n} \rho_c|^2}{n \sum_{c=1}^{n} {\rho_c}^2} \qquad (4.9)$$

Jain's fairness index can be used as a metric to assess the level of load balancing in a network. This index will be used in this thesis as the only optimization objective. The higher the index value, the higher the level of load balancing. Jain's fairness index will be 1 if all cells have identical load. In order to achieve load balancing, this index has to be maximized. This value can be maximized by adjusting an offset vector y. Hence range optimization using cell-specific offsets involves finding the offset setting for all LPN cells that maximizes Jain's fairness index.

4.3.6 Range Optimization Model

A heterogeneous network is composed of macro-cells and LPN cells. Let the cells in a HetNet be represented by $C = C_1 \cup C_2$ where C_1 is the set of macro-cells and C_2 is the set of LPN cells. In order to achieve load balancing, only LPN cells $c \in C_2$ will have offsets. The model is given by [20]:

$$\max \quad I(\rho^{a(x)}) = \frac{(\sum_{c \in C} \rho_c^{a(x)})^2}{n \sum_{c \in C}(\rho_c^{a(x)})^2} \tag{4.10a}$$

$$\sum_{z \in Z} y_{cz} = 1 \qquad \forall_c \in C_2 \tag{4.10b}$$

$$\rho \in {}^{n}_{+}$$

- y - Vector that represents network-wide offset vector. All macro-cells will have an offset value of 0.
- y_{cz} – Denotes whether cell $c \in C_2$ uses an offset value $z \in Z$.
- $a(x)$ – Denotes allocation of UEs to cells.
- $a_{cu}(x) = 1$ if cell $c \in C_1 \cup C_2$ is serving cell of UE $u \in U$.
- $\rho^{y(x)}$ – Load distribution vector after applying offsets.

Equation (4.4) now has to be modified to reflect the use of offset values in LPN cells. For a particular offset setting the load of a cell is computed as follows:

$$\rho_c = \sum_{u \in U : a_{cu}(x) = 1} \frac{r_u}{log_2(1 + \frac{1}{\sum_{k \in C \setminus \{c\}} b_{cku} \rho_k + m_{cj}})} \tag{4.11}$$

Equation (4.11) implies that for each offset setting, the cell load value will be different. Due to cell load coupling, for each offset vector setting a set of n non-linear equations will result and a solution ρ^* to this set of equations has to be found. The major task in range optimization is to find the network-wide offset setting y that maximizes Jain's fairness index and as consequence achieves a high level of load balancing [20]. An algorithm to do this is necessary.

4.4 Other Range Optimization Techniques

The use of cell-specific offsets, which is the subject of this thesis, for load balancing in a HetNet is one method out of many that can be used for HetNet radio network optimization that can result in load balancing in a HetNet. Other optimization methods are:

- Macro eNodeB antenna height or azimuth adjustment: Antenna height or azimuth of the underlying macro-cell can be adjusted so that the signal power of the macro-cell can reduce around LPN cell area. This way the range of the LPN cell can be increased.
- Transmit power adjustment: Transmit power of the macro-cells can be reduced so as to increase the range of LPN cells.
- Relocation of LPNs. LPN range can be increased by changing the location of the LPN.

4.5 Load Balancing Algorithm

In this thesis, load balancing will be done in a heuristic manner. The load balancing algorithm will start by getting a single network-wide value of cell offset for all LPNs that maximizes Jain’s fairness index. This will be done in a stepwise manner in steps of 1 dB within a specified range. An optimal network-wide offset value, although having the optimal fairness index, will usually result in overloaded (in relative terms i.e. as compared to other cells) and underloaded cells. This is because of dissimilar traffic distribution and propagation environment in different hotspots served by different LPNs. In order to improve the level of load balancing the offsets of some cells will have to be adjusted. This means that cell-specific offsets are required to further improve the fairness index.

First attention will turn to cells which have high load values including the ones which are overloaded or which have the potential of getting overloaded. The first cell that will be considered for offset adjustment is the one with the highest load value. A cell will be considered overloaded if its load value exceeds a particular maximum threshold value. The threshold is set to be the lower of 0.9 or $1.2 \times average\ cell\ load$. The use of a threshold value that is a factor of average cell load is necessary because there could be a network where there are no cells with very high load values (exceeding the threshold of 0.9) but the distribution of cells loads is not fair. Overloaded cells will most likely be found near the cell edges of macro-cells and these LPN cells require a lower offset value. This is because at the cells edges, the macro-cell power is not as strong as in areas which are very near to the location of eNodeB. In order to reduce the load values of overloaded cells, the offset value will have to be reduced so that a fewer number of UEs get attached to this cell. The range of such cells will have to be made smaller than the range that results from the use of uniform offset values. This will be done in a stepwise manner in steps of 1dB while looking at the effect on Jain’s fairness index. If the fairness index increases, it shows that the there is an improvement in the level of load balancing in the network and the offset adjustment for that cell will be accepted. If the fairness index reduces, it shows that while the load value of this cell reduces, the underlying macro-cell will be overloaded. The offset adjustment for that LPN cell will then have to be discarded and the previous offset setting returned to. In order to avoid returning to the same cell in subsequent iterations, that specific cell will have to be flagged. The next overloaded cell will then be considered. This will continue for a fixed number of iterations.

After offset adjustment is done for overloaded cells, attention will now turn to underloaded cells. In order to improve the level of load balancing, the load value for such cells will have to be increased by offloading more UEs from the underlying macro-cell which could be having a high load value. This is done by increasing the offset of such cells so that their range can be increased and more UEs can get attached to them. Like overloaded cells, this will also be done in a stepwise manner while looking at the effect on fairness index. If the fairness index is increases with increase in offset value, the offset adjustment will be accepted. Offset adjustment will be rejected if the fairness index degrades and that specific cell will be flagged so that offset adjustment will not be done in subsequent iterations. This will continue for a fixed number of iterations. There could arise a situation whereby a specific cell remains having the lowest load despite having been assigned high offset value after a number of iterations. In order to limit the number of offset adjustments on such cells, a maximum offset value will have to be set. This will usually happen for LPN cells which are very near to macro eNodeBs. When the offset value of such cells reaches the maximum offset value, they will be flagged to prevent further offset adjustment. A very high offset value is undesirable because the UEs served by the LPN cell will experience a very high interference from the underlying macro-cell.

Flags will be used to indicate whether offsets can be used for specific cells or whether cell offset can be changed. A flag of 1 indicates that an offset can be assigned to a cell or offset adjustment can be done. A flag of 0 indicates that an offset cannot be assigned to a cell or offset cannot be changed. Flags for all macro-cells will be set to zero so that no offset will be assigned to macro cells. Every time offsets are changed, cell reselection will be done for all UEs and hard handovers will be done if the serving cell has to change. The following variables will be used in the algorithm:

- X – Potential network-wide uniform offsets vector
- F – Flags vector
- $numIterOc$ – Number of iterations required to optimize overloaded cells' offsets
- $numIterUc$ - Number of iterations required to optimize underloaded cells' offsets
- $maxOffset$ – Maximum offset that can be applied to a cell.
- $maxThreshold$ – Threshold value used to determine whether a cell is overloaded
- x^* - Optimal network-wide offset
- y^*, I^* - Optimal cell-specific offsets vector and fairness index respectively

The number of iterations (numIterOc numIterUc) will vary from network to network. A network with high variation in cell loads will require a higher number of iterations. The maximum offset that can be applied to a cell is set to 13 dB.

The load balancing algorithm should be distributed and centralized but should not be hierarchical. It can be located in a server or macro eNodeB with higher processing capacity. Load balancing should be done for a group of HetNet cells of appropriate size. For example it can be done city by city. Each cell will collect and send the necessary load balancing data to the central processing node for a group of cells through the X2 interface.

Load balancing algorithm

```
Input: X, numIterOc, numIterUc, maxOffset
Output: $y^*$, $I^*$, $\rho^{y^*}$
$I^* = 0, F_c = 0 \ \forall C_1, F_c = 1 \ \forall C_2$
for k=1: length(X) do
    Get optimal network-wide offset
    $I_{X(k)} = I(\rho^{X(k)})$
    If $I_{X(k)} > I^*$
        $I^* = I_{X(k)}$
        $x^* = X(k)$
    end if
end for
$y_c = 0 \ \forall C_1, y_c = x^* \ \forall C_2$
for k= 1: numIterOc do
    Deal with overloaded cells
    Find overloaded cell
    highestCellLoad = 0
    for k=1:length(cells) do
        If $\rho_k > maxThreshold \ and \ F_k > 0 \ and \ \rho_k >$ highestCellLoad
            highestCellLoad = $\rho_k$
            highestCellLoadId = $c$
        end if
    end for
    y(c) = y(c)-stepsize //Reduce offset
    $I_{y(c)} = I(\rho^y)$
    if $I_{y(c)} > I^*$
        $I^* = I_{y(c)}$
    else
        y(c) = y(c)+stepsize // Go back to previous offset setting
        $F_c = 0$ // Set flag to zero
    end if
end for
for k= 1: numIterOc do
    Deal with underloaded cells
    Find underloaded cell
    lowestCellLoad = 1
    for k=1:length(cells) do
        If $\rho_k <$ lowestCellLoad $and \ F_k > 0$
            lowestCellLoad = $\rho_k$
            lowestCellLoadId = $c$
        end if
    end for
    y(c) = y(c)+ stepsize //Increase offset
    $I_{y(c)} = I(\rho^y)$
    if $I_{y(c)} > I^*$
        $I^* = I_{y(c)}$
    else
        y(c) = y(c)-stepsize // Go back to previous offset setting
        $F_c = 0$ // Set flag to zero
    end if
end for
```

Chapter 5

Simulation Environment and Implementation

Implementing and simulating the load balancing algorithm would first of all require implementation and simulation of HetNet. This chapter looks at various simulators that are available that can be used to simulate the thesis problem. Vienna LTE System Level Simulator was settled on because of certain benefits over the rest of the simulators. The chosen simulator is briefly described in the chapter. In last two sections of the chapter the network configuration used for simulation and the implementation done have been described.

5.1 Choice of Simulator

There are various available simulators for LTE network analysis and simulation of LTE algorithms. The options available for implementing and simulating the load balancing algorithm are Network Simulator (NS), OPNET or Vienna LTE System Level Simulator.

OPNET is a commercial simulator which is used for modeling and analysis of a broad range of wireless networks. It can be used to simulate cellular networks (GSM, CDMA, UMTS and WiMAX), mobile ad-hoc networks, wireless LANs (IEEE 802.11), personal area networks (Bluetooth, ZigBee) and satellite networks. OPNET allows for analysis of end-to-end behavior of networks and fine tuning of network performance. The main shortcoming of OPNET is that the open source models are not free. Implementing the load balancing algorithm would require an open source simulator so as to be able to add the required load balancing algorithm.

NS is a discrete event simulator targeted primarily for research and educational use. NS is an open source and free simulator. NS-2 and NS-3 are the two currently available versions of NS. Both programs have been written in C++. However some components in NS-2 are written in OTcl. It is not possible to run a simulation in NS-2 purely from C++. Simulation programs in NS-2 are scripted using OTcl. NS-3 is written entirely in C++ with optional Python bindings and thus simulation programs can be written in C++ or Python. Currently there is a simulation module that has been developed for NS3 for simulation of LTE networks [23]. The module can support the following aspects of LTE systems: RRM QoS-aware packet scheduling, Inter-cell Interference Co-ordination and dynamic spectrum access. This simulator has the benefit of already having LTE simulation framework. However it has some shortcomings. Firstly, it does not support certain features such as MIMO and HARQ. Secondly, it has a long simulation time. For example simulating 12 eNodeBs with 10 UEs each would take almost an hour [23].

Vienna LTE System Level Simulator [24] is the most suitable simulator for implementing the load balancing algorithm because it is open source and it already has an LTE framework. By having LTE simulation framework it would mean less work to be done to implement the algorithm and therefore less implementation time. By being open source, it can easily be studied so as know what changes to make in order to implement the load balancing algorithm and test it. The simulator has been programmed using object oriented features of Matlab and has a modular structure. The two features make it understandable. Being a

Matlab-based simulator, it has an optimization toolbox which can be used to solve non-linear equations. This will be useful when solving equation (4.11) so that cell loads can be estimated.

5.2 Vienna LTE System Level Simulator

Vienna LTE simulator 1.4_r570 allows for both link level simulation and system level simulation. The simulator allows for simulation of not only LTE physical layer which makes it possible to analyze link-level related issues but also the entire LTE system whereby the physical layer is abstracted from link level results [24]. With this simulator, entire network performance analysis can be done.

5.2.1 Link Level Simulation

Link level simulation deals with development and analysis of transmitter structure, receiver structure and channel models. Fig. 5.1 [25] shows the structure of link level simulator as implemented in the simulator.

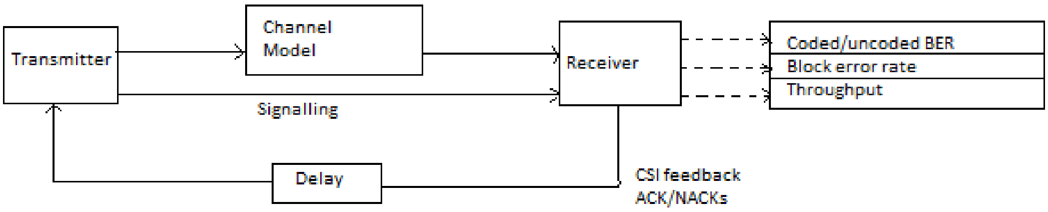


Figure 5.1: Structure of link level simulator

The transmitter sends data to the receiver through the channel model to the receiver. The feedback is implemented as a delayed error-free signaling channel. In the downlink, signaling information is sent by the transmitter to the receiver. The contents of the information are coding, Hybrid Automatic Repeat Request (HARQ), scheduling and precoding parameters. In the uplink, the contents of the signaling information are Channel Quality Indicator (CQI), Precoding Matrix Indicator and Ranking Indicator. This uplink information form Channel State Information (CSI) feedback.

The UE will give CSI feedback which will be used in scheduling. The scheduler assigns resource blocks to UEs, sets suitable modulation and coding scheme, MIMO transmission mode (Transmit Diversity (TxD), Open Loop Spatial Multiplexing, Closed Loop Spatial Multiplexing) and precoding/number of spatial layers for each and every user [25]. At the receiver, disassembling of resource blocks is done for each UE before MIMO and OFDM detection is carried out. CQI is used to select suitable MCS while RI and PMI are used for MIMO pre-processing. Transmitter structure and receiver structure diagrams can be found in the diagrams in appendix A and B.

The simulator supports block and fast-fading channels. Channel is constant during duration of one subframe (1 ms) for block-fading while for fast-fading time-correlated channel impulse response are generated for each sample of transmit signal [25]. The simulator supports the following channel models:

- Additive White Gaussian Noise
- Flat Rayleigh fading

- Power Delay Profile-based channel models such as ITU Pedestrian B or ITU Vehicular
- Winner Phase II+

5.2.2 System Level Simulation

The simulator consists of two major parts. It consists of link measurement model and link performance model. This is shown in the Fig. 5.2 [25]. The link measurement model determines the link quality for each UE from the measurement reports by the UE and thereafter performs link adaptation and resource allocation. Link quality measurement is done per subcarrier. The UE calculates the feedback (PMI, RI and CQI) from SINR. The feedback is then used for link adaptation. The link performance model determines BLER from the SINR computed by the link measurement model.

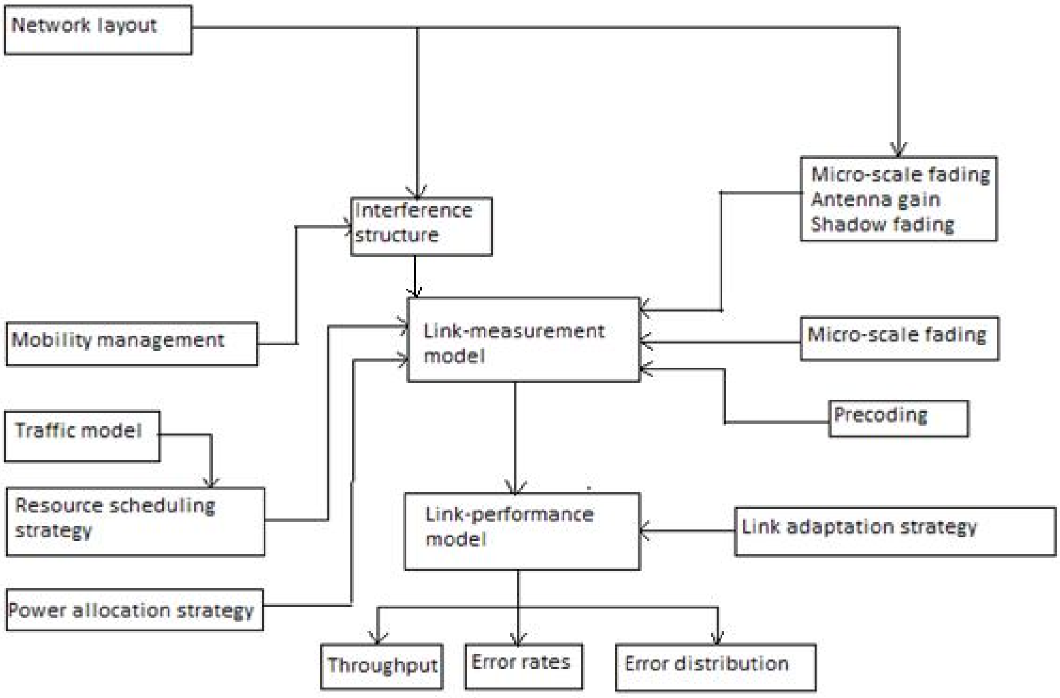


Figure 5.2: System level simulator structure

The scheduler assigns resources and appropriate MCS to each UE based on the scheduling algorithm and received UE feedback. This is shown in Fig. 5.3 [25]. The UE uses the link measurement model to calculate SINR. The SINR for a particular UE depends on serving signal, interference and noise power levels. These three factors in turn depend macroscopic pathloss, shadow fading and time-invariant small scale-fading. CQI feedback from each UE is calculated from subcarrier SINR and target BLER [25]. Mapping between CQI and SINR is pre-computed and made available to all UEs. After SINR has been calculated by the UE, it can determine CQI from SINR-to-CQI mapping. A diagram showing SINR-to-CQI mapping is found in appendix C. The UE sends CQI feedback to the eNodeB via uplink feedback channel. The eNodeB then selects an appropriate MCS based on the received CQI feedback.

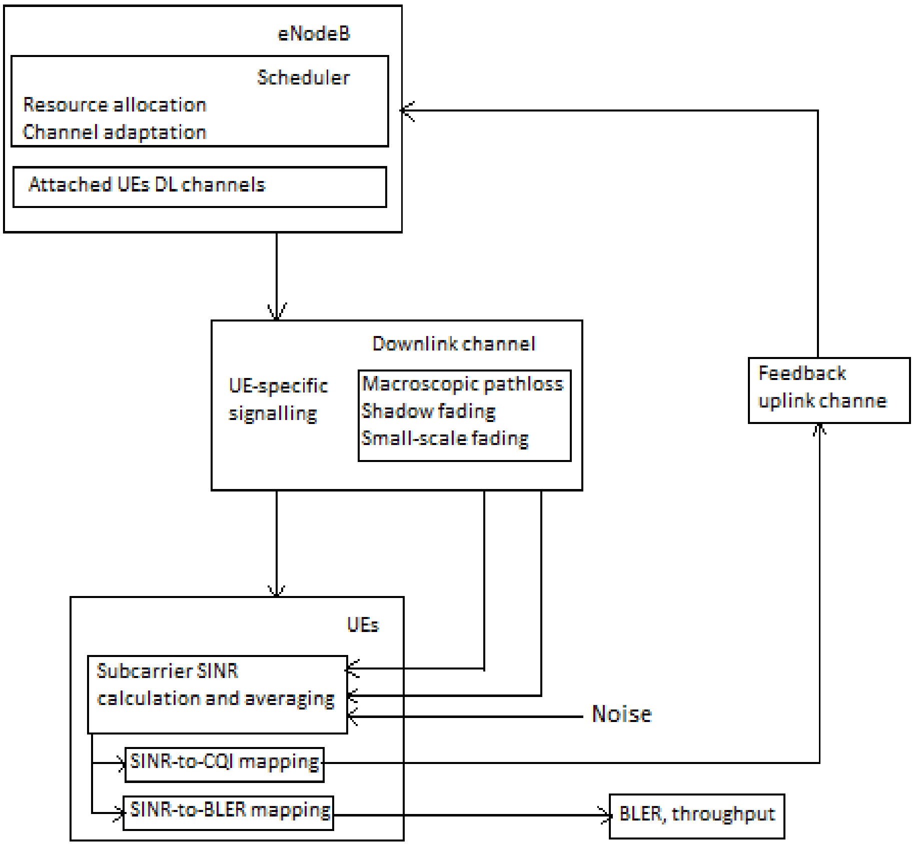


Figure 5.3: Link adaptation

5.2.3 Network Layout

Fig. 5.4 shows an example of a HetNet layout. UEs and eNodeBs are placed in within an area called the region of interest. Macro eNodeBs are represented big cyan dots with sectors while LPNs are represented by big cyan circles only.

5.2.4 Simulator Classes

As stated before, the simulator has a modular structure and has an object oriented design. Table 5.1 shows the major packages and the corresponding classes which are found in the simulator.

Table 5.1: Simulator classes

Package	Classes
Antennas	omniDirectional, katherein Antenna, bergerAntenna
ChannelGainWrappers	fastFading, macroscopicPathLoss, shadowFading
ChannelModels	downlinkChannelModel, uplinkChannelModel
NetworkElements	eNodeB, eNodeBSector, resourceBlockGrid, UE
Schedulers	propFairScheduler, roundRobinScheduler, bestCQIScheduler
TrafficModels	FullBuffer, Gaming, Voip, video, FTP

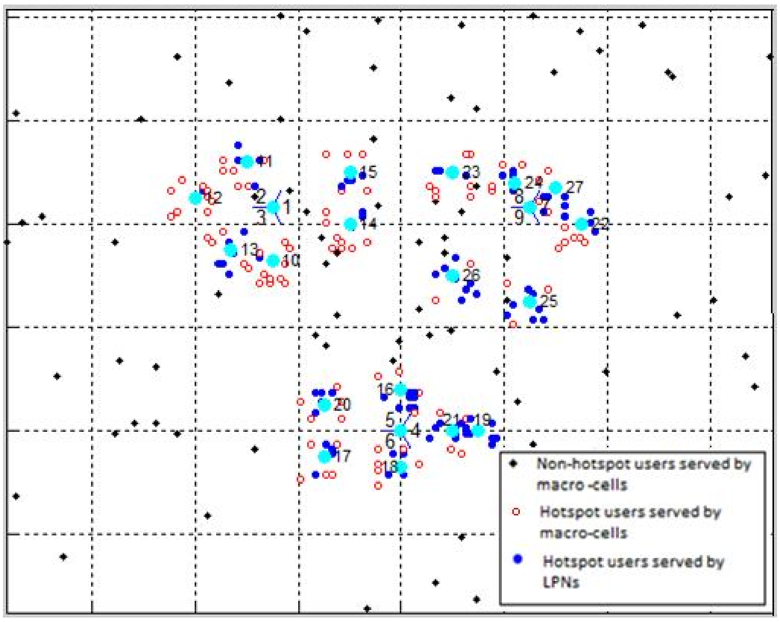


Figure 5.4: Network layout

5.2.5 Macroscopic Pathloss

In the simulator, UEs and eNodeBs are placed in a map which forms the region of interest (ROI). An example of a ROI is shown in Fig. 5.5. The ROI consists of pixels with x-y co-ordinate values. UEs are represented by circles while pixels are represented by '+'.

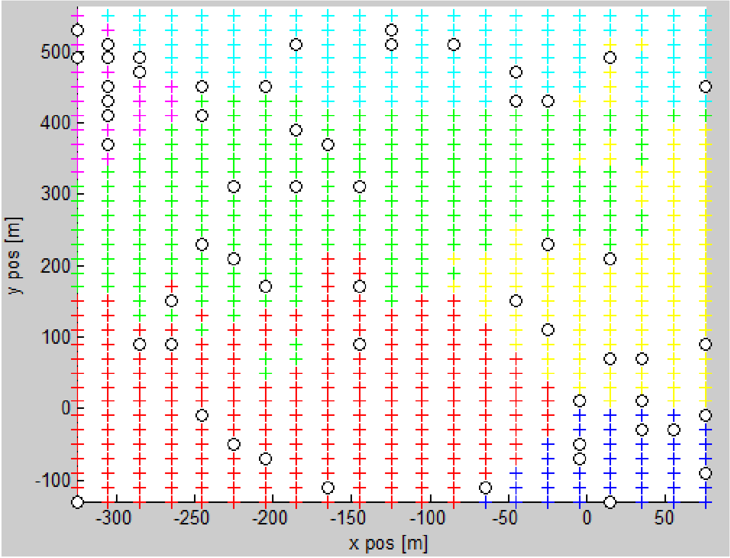
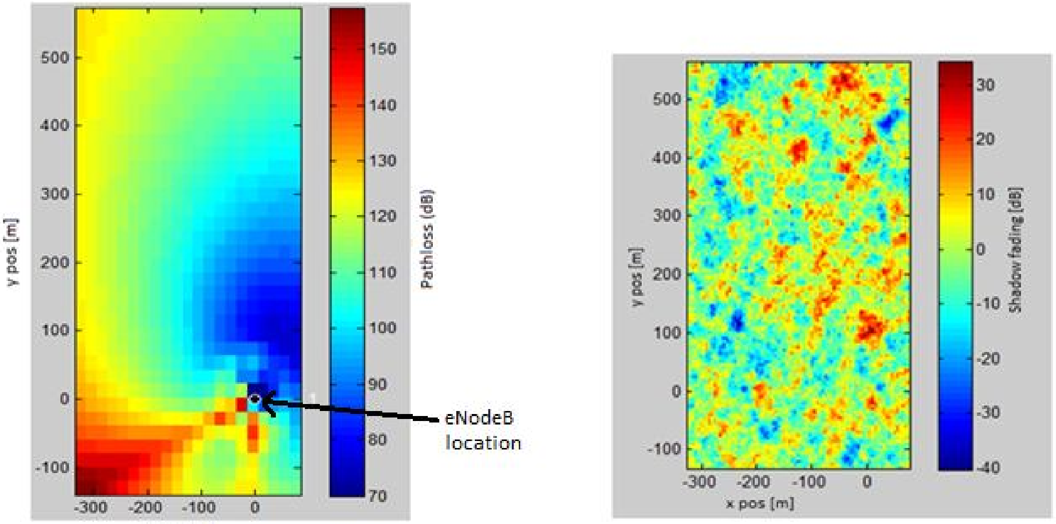


Figure 5.5: Region of interest with pixels and UEs

For each pixel position, macroscopic pathloss for each eNodeB sector transmitter is computed using known pathloss models and antenna gain pattern for each eNodeB sector antenna. This will form the pathloss map. Since each UE is located in a pixel, the pathloss and received signal for each eNodeB is known by each UE. The UE can then be assigned to the strongest available signal on the pixel in which it is located but after considering shadow fading and fast fading losses also. Offsets can also be incorporated the same way. They are added to LPNs only during cell selection and reselection. Fig.5.6 (a) shows macroscopic pathloss around an eNodeB. It can be seen from the diagram that pathloss increases with distance from the eNodeB.



(a) Macroscopic pathloss

(b) Shadow fading

Figure 5.6: Macroscopic pathloss and shadow fading around an eNodeB

5.2.6 Shadow Fading

Shadow fading arises due to obstacles that are present in the propagation path between the UE and eNodeB and is mainly caused by changing geographical terrain. Shadow fading is approximated in the simulator by log-normal distribution of with a specified mean (in dB) and standard deviation (in dB) [24]. Fig. 5.6(b) shows shadow fading for a small area in region of interest.

5.2.7 Small-scale Fading

Unlike macroscopic pathloss and shadow fading which are position-dependent, small-scale fading is time-dependent. Small-scale fading is calculated based on transmitter precoding, small-scale fading MIMO channel matrix and receiver filter [25].

5.3 Network Configuration

The HetNet layout used for analysis of load balancing algorithm is shown in Fig. 5.7. Macro eNodeBs are represented by cyan big dots with sectors. Cyan big dots with no sectors represent LPNs. UEs served by macro-cells are represented by square dots (black and red) while users served by LPNs are represented by blue circles. The layout consists of three macro eNodeBs with three sectors. Each macro eNodeB has a down-tilted directional antenna with 14dBi antenna gain. The transmit power of macro cells is configured to 40 W (46 dBm).The spacing between each macro eNodeB is set to 500m. LPNs are configured with omni-directional antenna with 0 dBi antenna gain. The transmit power for all LPNs is set to 1W (30 dBm). The numbers indicate the cell IDs (1, 2…, 27). The first 9 cells are macro-cells and the next 18 are LPN cells.

The user distribution follows 3GPP scenario 4b [1]. Each macro-cell area has two hotspots of 40 m radius with each hotspot being served by one LPN. There are two layers of users with a total of 30 users in each macro-cell. 10 users, which represent one-third of the users, are randomly distributed in the coverage area of each macro cell. The remaining two-thirds of users (20) are placed in hotspots. 10 users are randomly dropped within a radius of 40m of each two LPNs in each macro-cell to create the required two hotspots. All users generated have an omni-directional antenna with 0 dBi antenna gain.

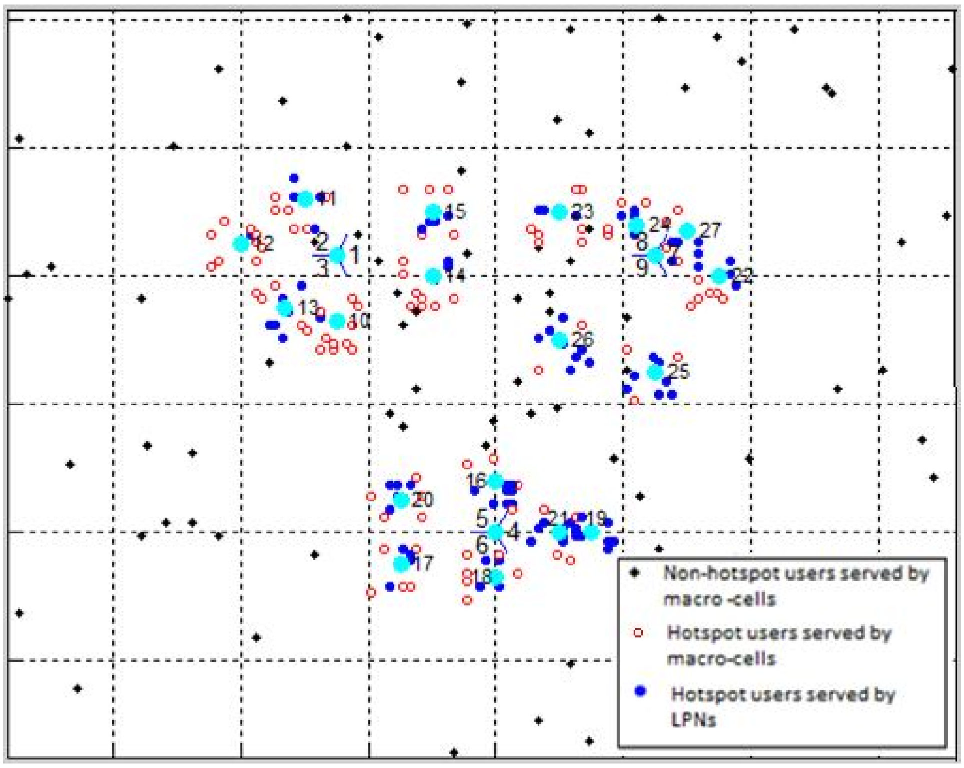


Figure 5.7: Network layout

The chosen propagation model used is Okomura-Hata for an urban environment. The model is given by expression (5.1). h_m is the height of the mobile station, h_b is the height of the base station, d is the distance between the mobile station and the base station and f is the frequency in use. For an urban environment pathloss is given by:

$$L_p = 69.55 + 26.16\,log_{10}(f) - 13.82log_{10}(h_b) - C_H + \left(44.9 - 6.55log_{10}(h_b)log_{10}(d)\right) \qquad (5.1)$$

C_H is antenna height correlation factor. A small or medium size city will be assumed. For such a city C_H is given by:

$$C_H = (1.1log_{10}(f) - 0.7)h_m - (1.56log_{10}(f) - 0.8) \qquad (5.2)$$

Shadow fading and fast fading are also taken into account. Shadow is modeled with log-normal distribution with urban 8 dB standard deviation and a mean of 0 dB. After distribution of the users, long term radio characteristics (pathloss and shadowing fading) and fast fading are calculated. Users are then associated to the cell with the strongest serving signal after considering macroscopic pathloss, shadow fading, antenna gain, coupling losses (70 dB) and offsets for LPNs. Fast fading is only considered when computing received signal strength at the receiver. The chosen traffic model for cell load analysis is gaming and this model has been configured in such a way that there is a CBR traffic demand of 1.5 Mbps by each user. Full buffer traffic model will be used for throughput analysis. Users will stay in a fixed position for ease of load estimation. Other configuration parameters are found in Table 5.2.

5.4 Implementation

Vienna LTE System Level Simulator 1.4_r570 supports simulation of a homogeneous network consisting of sectored cells only by default. The simulator had to be modified so that a HetNet can be simulated. This involved adding LPNs with omni-directional antennas and different power setting. The following functions were added to the simulator so as to implement the load balancing algorithm:

- A function which is used to get interference power from all interfering cells was added to the class UE.
- A function which gets the UEs attached to each and every cell and thereafter gets interference and noise data for those UEs. Interference data here refers to interference power from all cells that cause interference to the UE. The interference and noise data is stored in an array so that it can be used during cell load estimation. This function makes use of the function added to the UE.
- A function for cell load estimation. This function makes use of *fsolve* which is a function found in the optimization toolbox of Matlab. *fsolve* is used to solve a set of non-linear equations. This cell load estimation function also makes use of the array consisting of interference and noise data for each UE.
- Function to compute Jain's fairness index
- Function for adding offsets to LPN cells.
- Load balancing algorithm function.

Since there are 27 cells, there will be a set of 27 equations. The solution is computed by solving using *fsolve* to solve the set of equations represented by (4.6) directly. These set of equations come about by summation in equation (4.11). In the equation $r_u = \frac{d_u}{RB}$ where r_u is the demand by UE u, R is the number of resource blocks in the selected bandwidth and B is the bandwidth. From the configuration used $d_u = 1.5\,Mbps$, $R = 100$ and $B = 180\,kHz$ (when transmission bandwidth of 20 MHz is used). Therefore $r_u = \frac{1.5\,Mbps}{100 \times 180\,kHz} = 0.0833$. Constant data rate demand is configured using gaming traffic model. Other factors will vary from UE to UE.

In order to get the optimum value of uniform offset range the network is simulated from 0 to 12 dB offset in steps of 1 dB. The number of iterations for dealing with cells will low and high cell loads is limited to 15.

Table 5.2: Simulation parameters

Parameter	**Value**
System parameters	
Carrier frequency	2 GHz
Bandwidth	20MHz
Thermal noise PSD	-174dBm
Penetration loss	20dB on eNodeB UE
Inter-eNodeB distance	500m
Pixels resolution	10m/pixel
eNodeB parameters	
eNodeB cell Transmit Power	46dBm
eNodeB antenna gain	Directional,14dBi
eNodeB antenna configuration	TX-2,RX-2
eNodeB noise figure	9dB
LPN parameters	
LPN transmit power	30dBm
LPN antenna gain	Omni-directional ,0dBi
LPN noise figure	9dB
LPN antenna configuration	TX-2, RX-2
UE parameters	
Maximum transmit power	23dBm
Antenna configuration	0dBi
UE noise figure	9dB
Traffic model and scheduler	
Scheduler	Round robin
Traffic model	Full buffer/Gaming

Chapter 6

Simulation Results and Analysis

In this chapter simulation results are presented and analyzed. The last part of the chapter focuses on performance evaluation of the load balancing algorithm. The performance metrics used are Jain's fairness index, UE distribution, UE throughput and SINR.

The network generated using simulation parameters in table 5.2 is shown in Fig. 6.1. In the network layout shown in Fig. 6.1, big cyan dots with three sectors represent macro eNodeBs and each sector is considered as a cell. Big cyan dots with no sectors represent LPNs. Each cell has been assigned a cell Id.

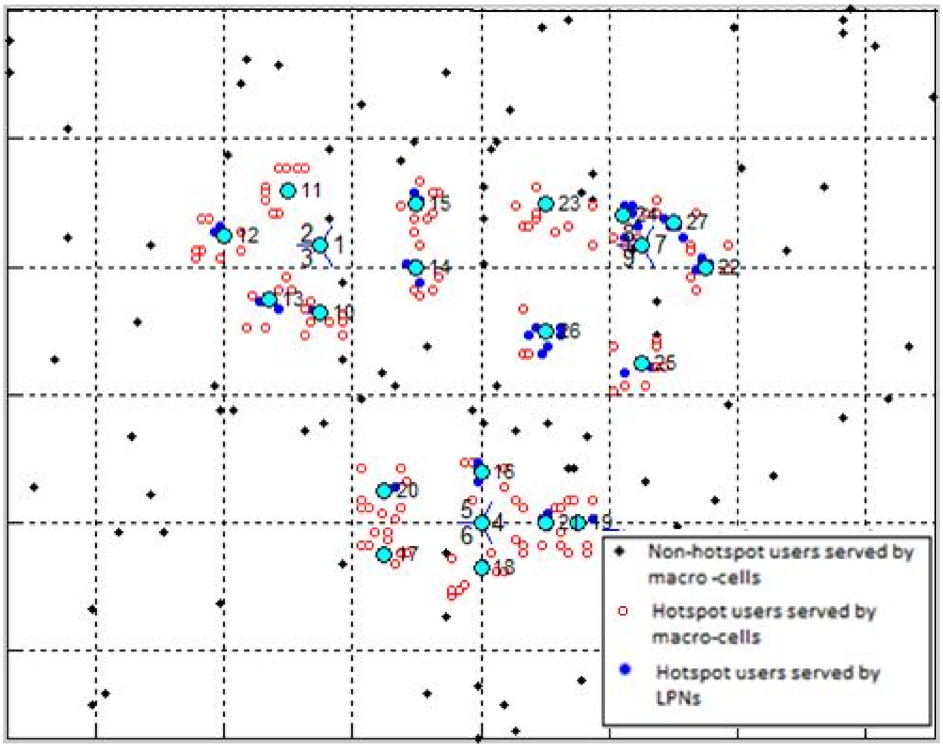


Figure 6.1: HetNet layout and UE distribution with 0 dB offsets

6.1 Load Estimation and Load Balancing Results

The computed cell loads with no offsets used is shown in Fig. 6.2. Distribution of UEs among macro-cells and LPN cells is shown in Fig. 6.1. More analysis of UE distribution is found in section 6.2. The cell loads are the solutions to a set of non-linear equations represented in compact form by equation (4.6). In Fig. 6.2, the first 9 cells are macro cells and the next 18 cells are LPN cells. With no offsets, most LPNs have very low load values and hence there is need to increase the range of LPNs so as to balance loads among the macro cells and LPN cells. It can be seen that cells 11, 17 and 23 have zero load at 0dB offset. It is necessary to use offsets so that some UEs in the hotspot area which should be served by LPNs can be offloaded from macro-cells to LPNs.

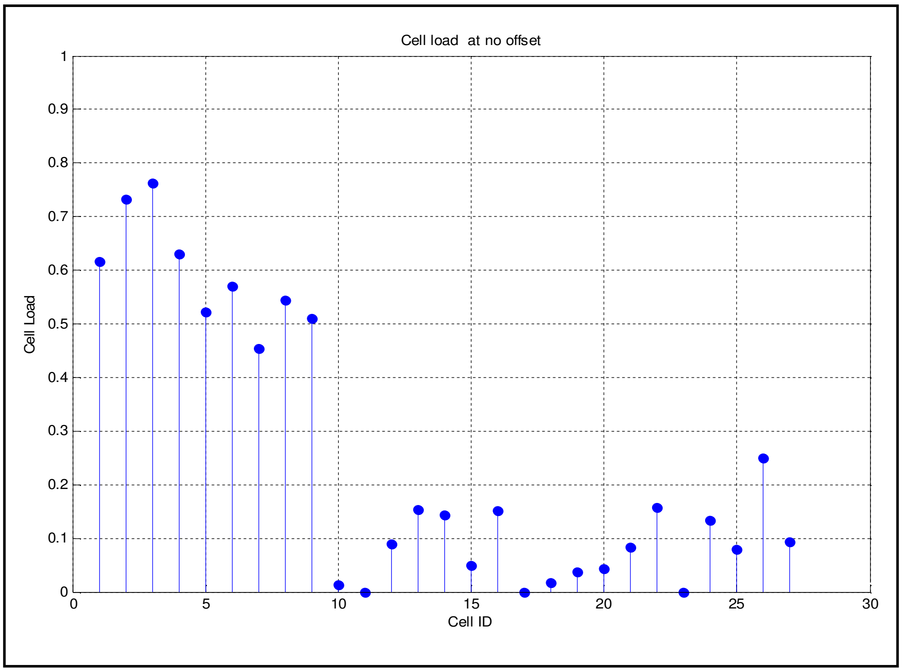


Figure 6.2: Cell loads at 0 dB offset

Offsets will be assigned to cells according to the load balancing algorithm found in section 4.4. The first step in the algorithm is to get an optimal network-wide uniform offset value for all LPN cells. The chosen candidate values are between 0 dB to 12 dB simulated in steps of 1 dB.

Jain's fairness index is used to determine the optimal uniform offset value. Different Jain's fairness index values result when different candidate uniform offset values are applied to LPN cells. This is shown in Fig. 6.3. As the offset is increased from 0 dB, the fairness index increases steadily up to 6 dB offset. After 6dB the fairness index started to fluctuate and the maximum index achieved is 0.82 at 10 dB where it starts to drop again. With low uniform offset value, the LPN cell loads are very low because very few UEs are associated to LPNs while the loads of macro-cells are high due to high number of UEs attached to them. This is undesirable because LPNs should serve majority of the users in hotspots so that cell splitting gains can be realized. This imbalance is reflected in the low values of fairness index. The load balancing index at 0dB offset is 0.50. It can be seen from Fig. 6.3 that the optimum uniform offset is 10 dB. When 10 dB offset is used the resulting load balancing index is 0.82. The fairness index at 10 dB is 64% higher than that at 0 dB. The fairness index reduce when offset values higher that 10 dB are used because LPNs start to get overloaded. This is illustrated in Fig. 6.4 when a uniform offset of 11 dB is used.

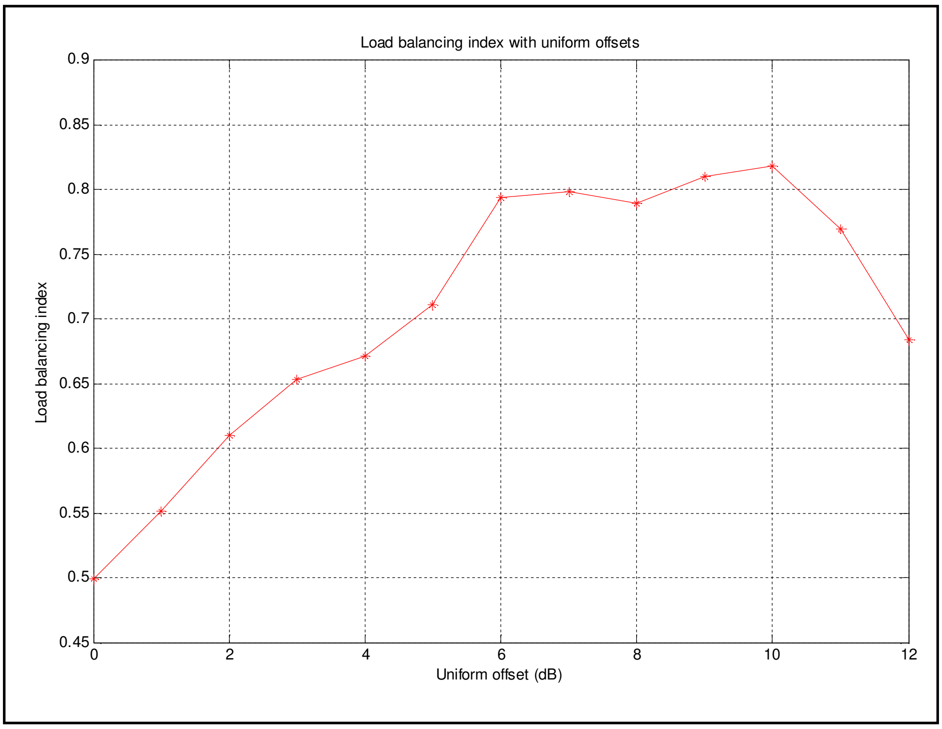


Figure 6.3: Load balancing index for different uniform offsets

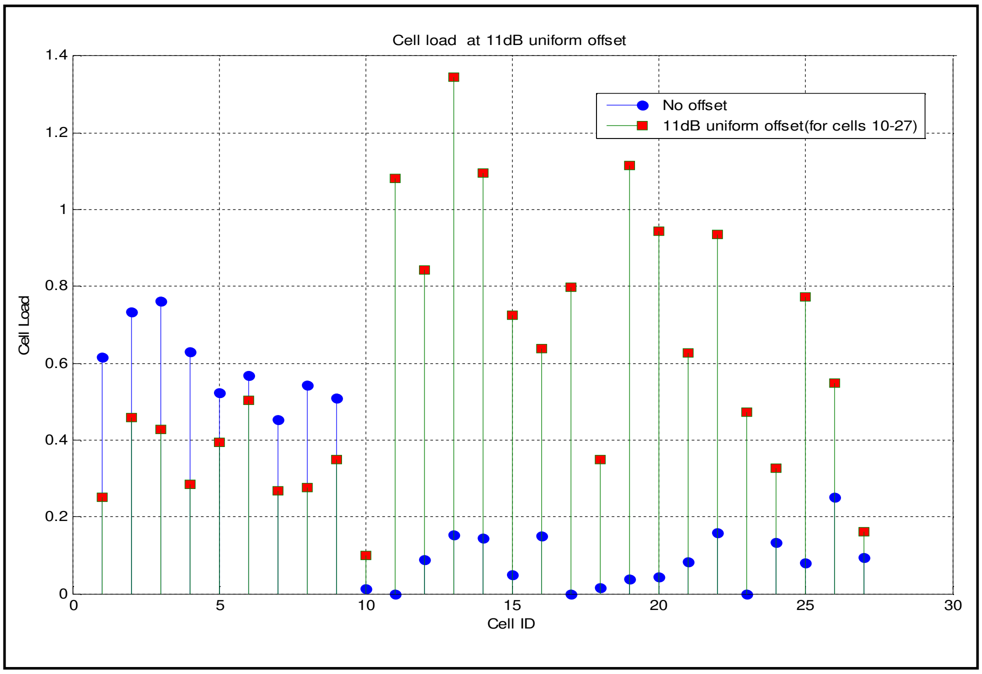


Figure 6.4: Cell loads at 0 dB and 11 dB offset

Comparison of cell loads with no offset used and with the use of the optimal uniform offset value of 10 dB is shown in Fig. 6.5. From the figure it can be seen that the load of each LPN has increased while the loads of macro-cells have reduced at 10 dB offset. With this uniform offset setting some LPNs (e.g. 13 and 19) have relatively high loads. From the

HetNet layout, it can be seen that these cells are the ones which are relatively far from the macro eNodeBs. These LPN cells do not require high offsets values because at their position, the macro-cell signal power is lower. In contrast LPN cells such as 10 and 27 which have low load values require higher offsets because they are either close to the macro eNodeB or have a challenging propagation environment due to shadow fading. When the LPN is close to macro eNodeB, higher offsets are required because the macro eNodeB signal power is stronger. This problem of low and high cell loads in some LPN cells can be overcome by the use of cell-specific offsets.

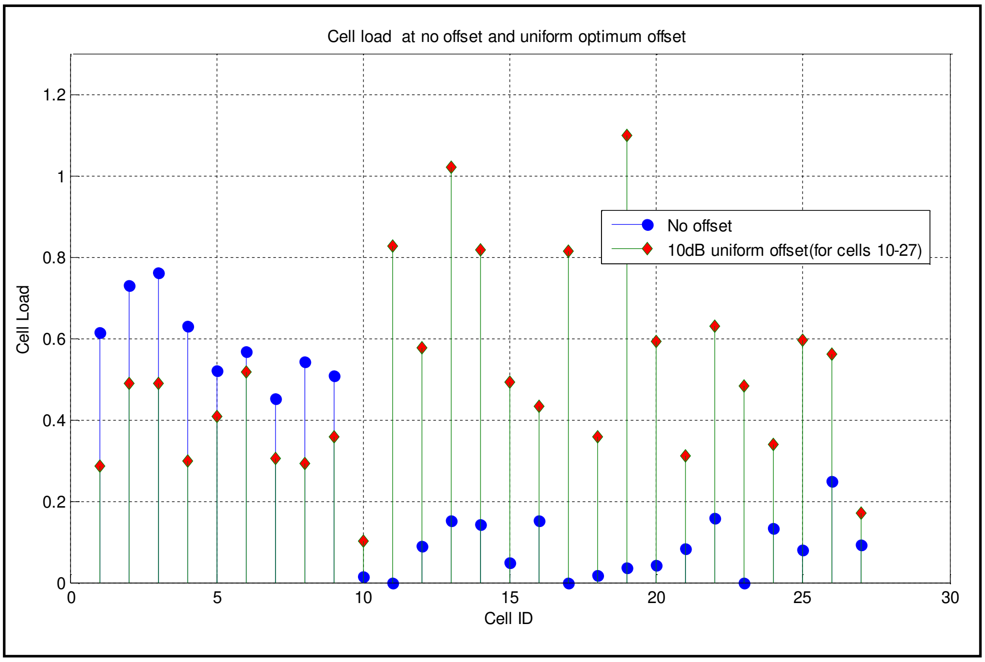


Figure 6.5: Cell load at 0 dB and 10 dB uniform offset

After obtaining the optimum uniform offset value, cell specific offsets can then be used to further improve the degree of load balancing. The maximum offset value is set to 13 dB so as to avoid a situation where there is high degradation of the SINR of UEs attached to LPN cells. Each LPN cell is assigned an offset value according to the algorithm described in section 4.4. The offset of each cell is shown on top of cell load plotting shown in Fig. 6.6. From the figure, it can be seen that the load values of cells 13 and 19 is now lower than that of 10 dB after applying cell-specific offset values of 6 dB and 8 dB respectively. The use of cell specific offset has also resulted in a higher load for LPN cells such 10 and 27 which had low load values before the use of cell-specific offsets. The offset value for cells 10 and 27 is now 13 dB. The use of cell-specific offsets results in an improvement of the load balancing index to 0.92 from 0.82 when 10 dB uniform offset is used. This is because with the use of cell-specific offsets, cells with relatively high low loads have their loads reduced while those with relatively low loads have their loads increased. This way there is a fairer distribution of loads among cells and this is reflected in the increase fairness index. Since the algorithm is heuristic, it neither results in nor guarantees the most optimal solution but gives the best solution possible.

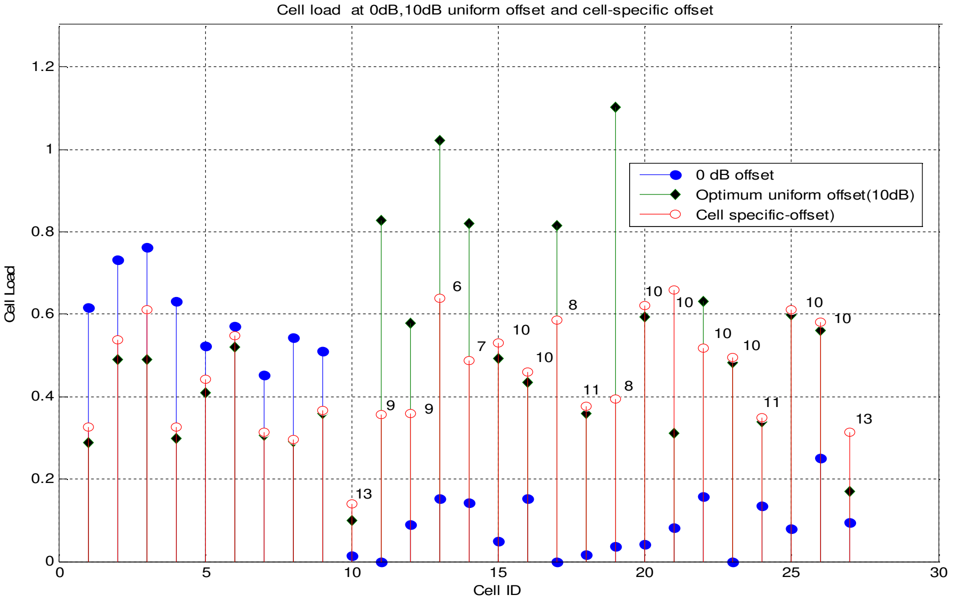


Figure 6.6: Load values at 0 dB, 10 dB uniform and cell-specific offsets

6.2 Distribution of UEs among LPNs and Macro-cells

Since the macro-cells transmit power is much higher than that of the LPN cells, only limited numbers of UEs are associated with LPNs when no offsets are used. From Fig. 6.7 and 6.1, it can be seen that with 0dB offset, the majority of UEs are associated with macro-cells even in hotspot areas. 85.6% of the UEs are attached to macro and 14.4% are attached to LPNs. LPN cells 11, 17 and 23 have no attached UEs. This is undesirable because LPNs should serve majority of the users in hotspots so that cell splitting gains can be realized.

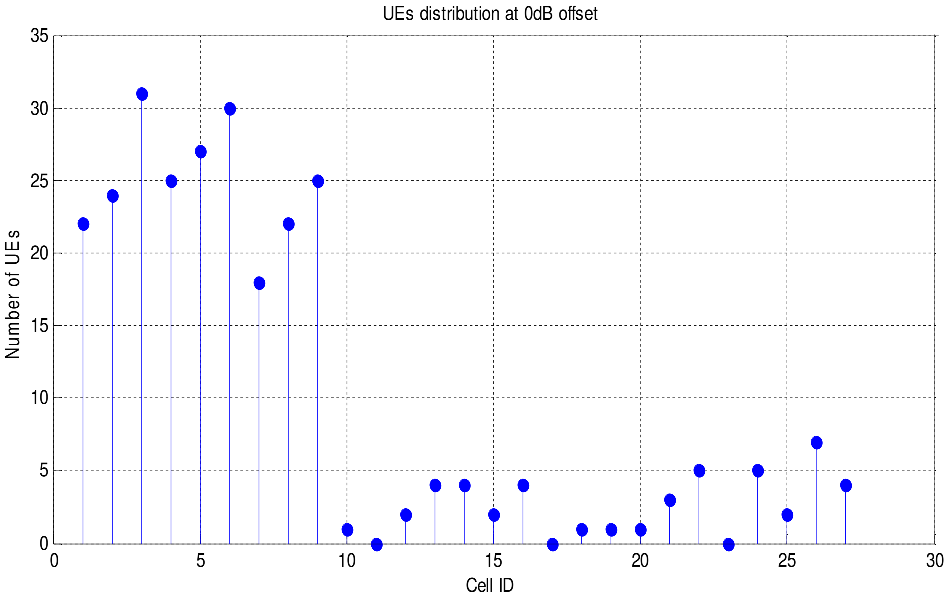


Figure 6.7: UE distribution at 0 dB offsets

When 10 dB uniform offset is used the number of UEs served by LPNs increases by 197% and the percentage of UEs associated to LPNs increases from 14.4% to 43%. The improvement in offloading of UEs from macro to LPN cells is shown in Fig. 6.8 and 6.9. It can be seen from Fig. 6.8 that now there are more users in the hotspot are served by LPNs as compared to the situation in Fig. 6.1 when no offsets are used.

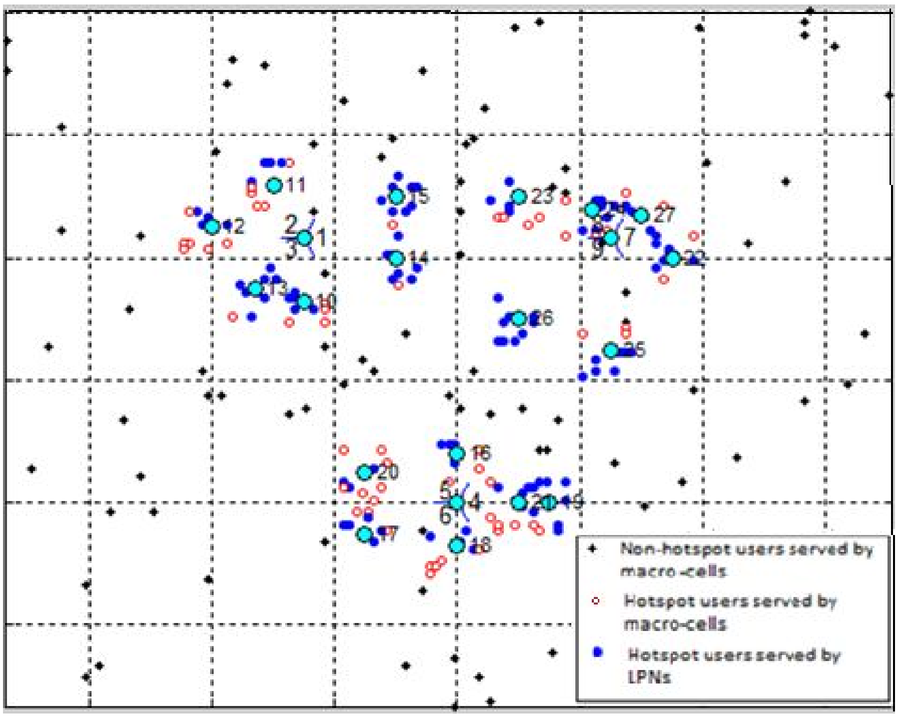


Figure 6.8: UE distribution with 10 dB uniform offset

Load balancing does not result in a fair distribution of UEs among macro-cells and LPN cells. This arises due to cell load coupling. Interference received from other cells in one cell will increase the load of that cell. This is illustrated in equation 4.4 and explained in section 4.3.3. When offsets are used, there will be one or more cells with stronger signal than that of the serving cell of some UEs that are attached to LPNs. The cells with stronger signals will only act as strong interferers when LPNs are in co-channel scenario with macro-cells. Such strong interferers will contribute to high cell loads in LPNs. As a consequence, LPNs will have high cell loads with low number of UEs attached to them. Addition of very few UEs to LPN cells with the aim of load balancing contributes to a high increase in LPN cell loads. A fairer distribution of UEs among macro-cells and LPN cells will be seen if interference management techniques such as those described in section 3.3 are used. Nevertheless, it can be seen that the use of optimal uniform offset and cell-specific offsets results in a substantial offloading of UEs from macro-cells to LPN cells which goes a long way towards achieving load balancing.

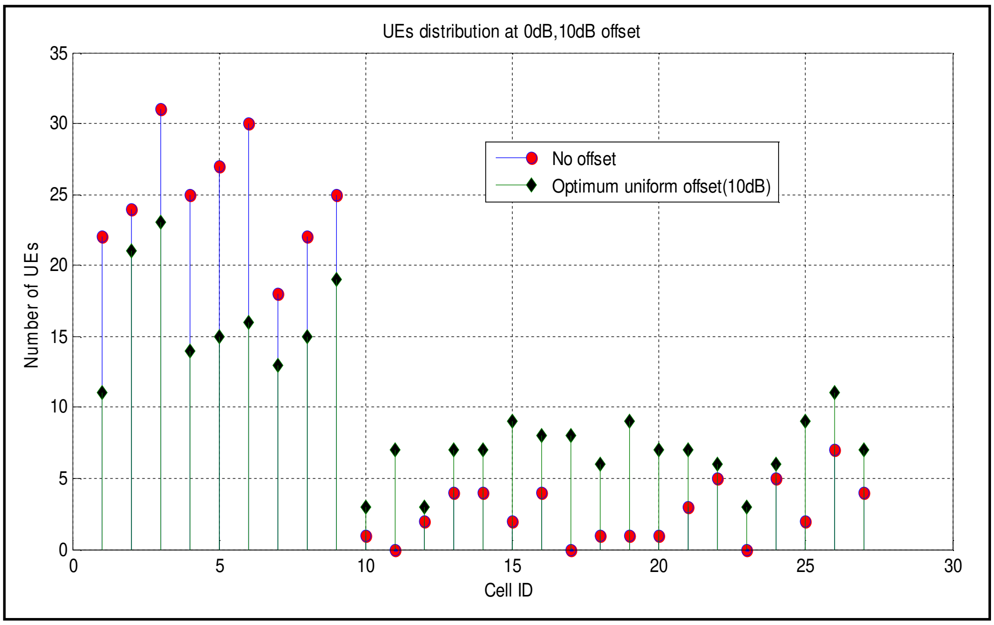


Figure 6.9: UEs distribution at 0 dB and 10 dB uniform offset

Distribution of UEs among macro-cells and LPN cells after applying cell-specific offsets is illustrated in Fig. 6.10. From Fig. 6.10 and Fig. 6.11, it can be seen that the number of UEs in some cells has decreased while in other cells has increased. The load balancing algorithm will change the number of UEs attached to some cells as it moves towards a higher degree of load balancing in the network. The number of UEs attached to LPNs is still lower because of the same problem of interference that contributes to high cell loads in LPNs.

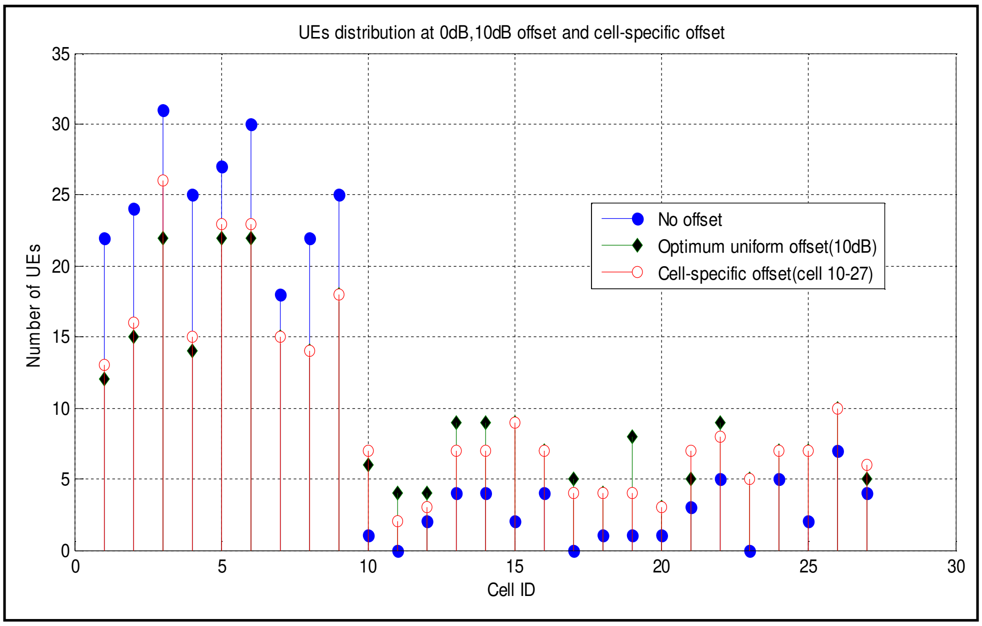


Figure 6.10: UEs distribution at 0 dB, 10 dB and cell-specific offsets

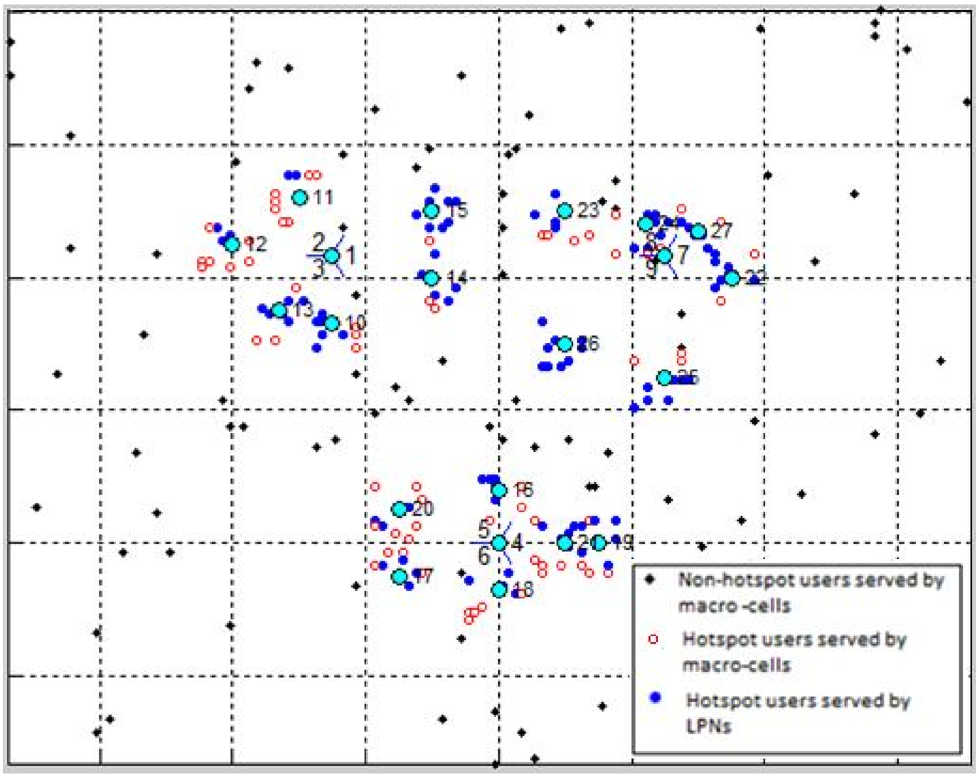


Figure 6.11: UE distribution with cell-specific offsets

6.3 Load Balancing Algorithm Performance Evaluation

6.4.1 UE Distribution

Table 6.1 summarizes the distribution of UEs among macro-cells and LPN cells at 0 dB uniform offset, at 10 dB uniform offset and with cell-specific offsets. As expected many UEs are offloaded from macro-cells to LPN cells when a uniform offset of 10 dB is used. The use of cell-specific offsets, however, does not guarantee additional UE offloading. This is because the load balancing algorithm may result in more UEs being handed over from LPN cells to macro-cells than those that are offloaded to LPN cells. This is what happened in Table 6.1.

Table 6.1: UE distribution among macro and LPN cells

Offset value	0dB		10dB		Cell-specific	
No of UEs	Macro	LPN	Macro	LPN	Macro	LPN
	231	39	154	116	178	92
Percentage (%)	85.6	14.4	57	43	66	34

6.4.2 Jain’s Fairness Index

Table 6.2: Load balancing index with no offset, optimum uniform offset and cell-specific offsets

Offset	0 dB	10 dB	Cell-specific
Jain’s fairness index	0.50	0.82	0.92

Table 6.2 shows Jain’s fairness index at different offset settings. With no offsets used, the index is 0.50. When 10 dB uniform offset is used the fairness index rises to 0.82. The use of cell specific offsets further improves Jain’s fairness index to 0.92. This shows that the use of cell-specific offsets assigned by the load balancing algorithm to LPNs results in a higher degree of load balancing in a HetNet.

6.4.3 Throughput

Fig. 6.12 shows comparison of throughput with different LPN offset settings. In order to analyze the effect of offsets on throughput, full buffer traffic model was used with no restriction on demand by UEs. It can be seen from the diagram that there is a high variation in throughput when no offsets are used than when offsets (uniform of 10 dB or cell-specific). With no offsets used, the user experiences are uneven because some UEs (top 10 %) are enjoying relatively high throughput of up to 96 Mbps of while some (35%) are having close to zero throughput. This happens because when no offsets are used, very few UEs are attached to LPNs due to their low power and they can make use of all the resources of LPNs allowing them to enjoy very high throughput. In contrast some macro-cells have many UEs attached and these many UEs have to share the macro eNodeB resources and this makes them have very low throughput. With no offsets used the standard deviation of the throughput of all UEs is 9.16 demonstrating high variation in throughput among users.

When offsets are used some more UEs are offloaded from macro-cells to LPNs and cell splitting gains can be realized. The cell loads become more even and as a consequence user experiences in terms of throughput also become more even. It is slightly more so when cell specific offsets are used as can be seen in Fig. 6.12. With offsets, the number UEs which have relatively high and low throughput reduce. The UEs having close to zero throughputs reduce to 17% for both 10 dB uniform offset and cell-specific offsets. The highest achieved throughput is 19 Mbps and 15 Mbps when 10 dB uniform offset and when cell-specific offsets are used respectively. When offsets are used, user experiences in terms of throughput become more even due to the balanced loads between LPN cells and macro-cells. The standard deviation of throughput of all UEs is 3.22 and 2.65 when 10 dB uniform offset and when cell-specific offsets are used respectively as compared to 9.16 when no offsets are used. This indicates less variation in throughput when offsets are used. The slight reduction in standard deviation when cell-specific offsets shows even slightly less variation in throughput due to a higher degree of load balancing.

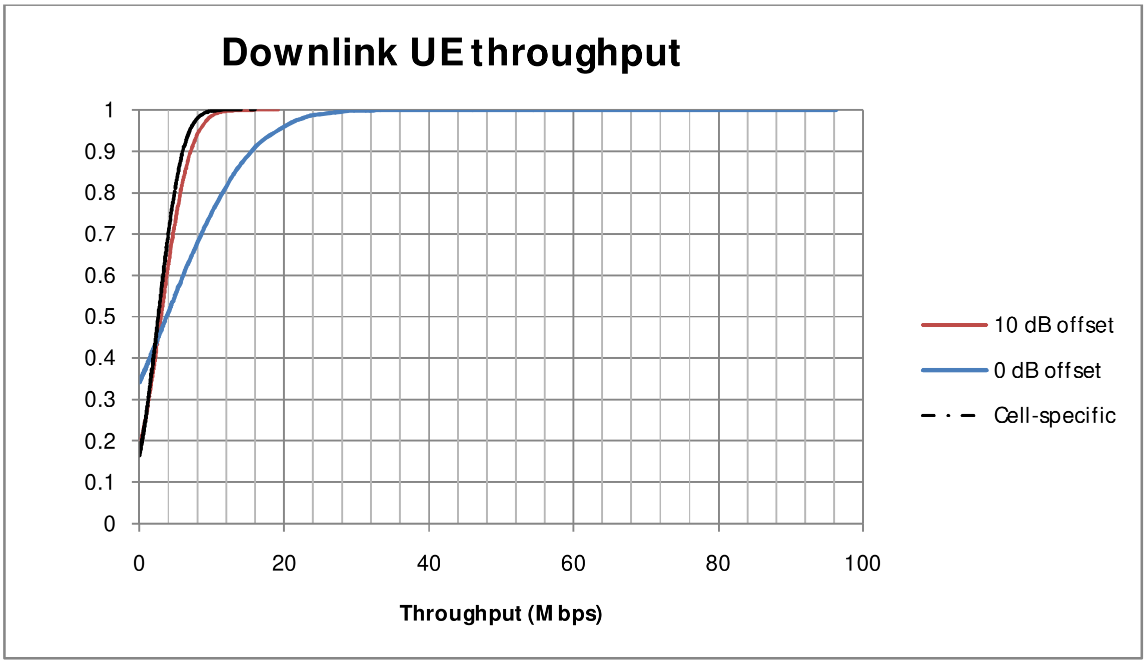


Figure 6.12: Downlink UE throughput comparison for different offset settings

6.4.4 SINR

Fig. 6.13 shows comparison of SINR for different offset settings. It can be seen from the diagram that UEs have higher SINR values when no offsets are used than when offsets are used. This is expected to arise when LPNs are in a co-channel scenario with macro eNodeBs. When offsets are used, some UEs will not be served by the strongest received signal served but instead weaker signal from LPNs. Such UEs will then experience high interference from such strong macro eNodeB signals. SINR degrades even more when cell-specific offsets are used because some LPNs will have even higher offsets implying some UEs will have even lower SINR values. The degradation of SINR will negatively impact throughput. The use of offsets therefore necessitates the use of interference management techniques such as those discussed in section 3.3 so that load balancing gains can be realized even more.

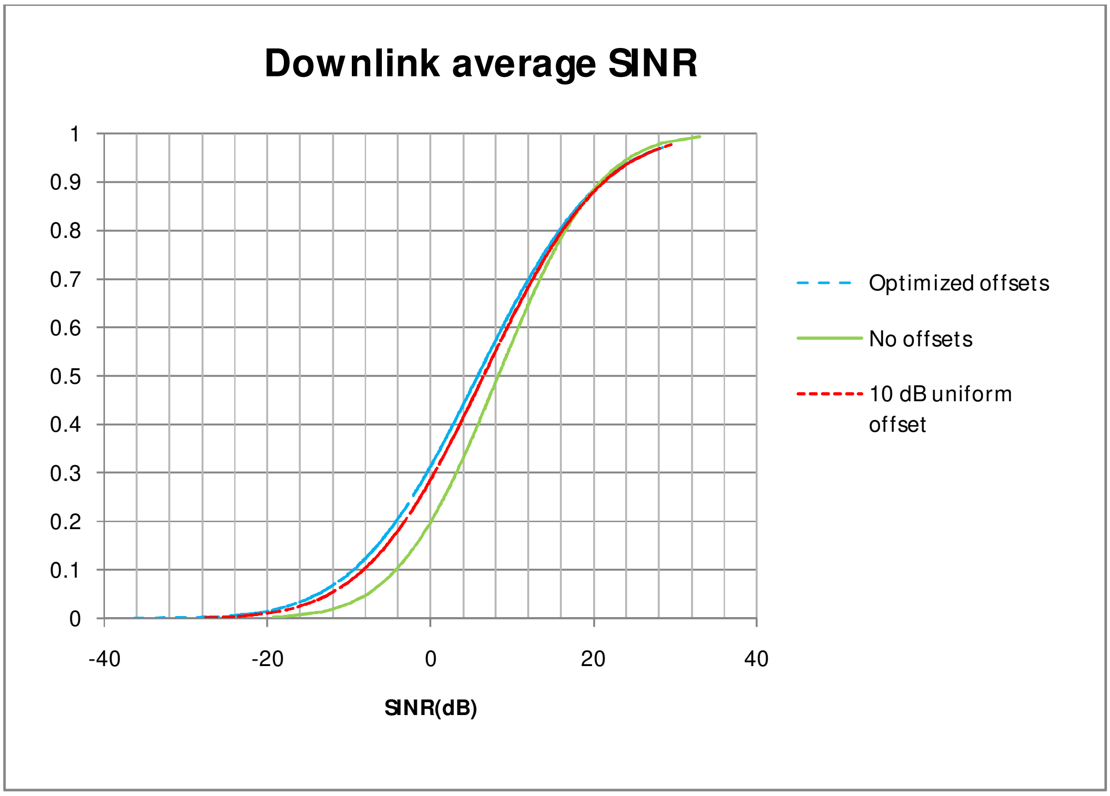


Figure 6.13: Downlink UE SINR comparison for different offset settings

Chapter 7

Conclusion and Future Work

In this chapter conclusions drawn from the results are presented and some suggestions on how to improve the performance the load balancing algorithm are pointed out.

7.1 Conclusion

In this thesis work a heuristic load balancing algorithm which can be used for range optimization in LTE-A HetNets has been designed. The algorithm is able to assign cell-specific offsets to LPN cells. This load balancing algorithm makes use of an optimization framework that applies the concept of cell load coupling.

As it has been seen from simulation results, there is need for not only just uniform network-wide offset but there is also need for cell-specific offsets to further improve load balancing in a HetNet. The fairness index is 0.50 when no offsets are used. With no offsets used, LPN cell loads are very low with some having zero loads while macro-cells have high loads. When an optimal offset of 10 dB is used, the fairness index rises to 0.82. This indicates an improvement in load balancing and it shows that offsets are necessary for range optimization in HetNets. The optimal network-wide offset result in overloaded (relatively) as well as underloaded cells. This is because of dissimilar traffic distribution, distance of LPN from macro eNodeB and propagation environment in different hotspots served by different LPNs. When the cell-specific offsets are used, the fairness index rises from 0.82 to 0.92. This shows that applying cell-specific offsets further improves the level of load balancing even after optimal uniform offset has been used.

The use of cell-specific offsets results in more even user experiences in a HetNet as compared to the use of uniform offsets. When no offsets are used, there is a higher variation in downlink throughput than when offsets are used. This is because when no offsets are used, LPNs will have low number of UEs attached and these few UEs will use all the cell resources resulting in high throughputs. This is in contrast to the many UEs which are attached to macro-cells that compete for cell resources which result in them having low throughput. When offsets are used, whether cell-specific or uniform offsets, there is a more balanced distribution of cell loads resulting in more even user experiences in terms of throughput. Cell-specific offsets results in even less variation in UE experiences in terms throughput as compared to uniform offsets even if it optimal.

The use of offsets will result in degradation of average downlink UE SINR. This is expected to happen when offsets are used and LPNs are in a co-channel scenario with macro-cells. When offsets are used, some UEs attached to LPNs will experience higher than normal interference because the serving cell signal is weaker relative to interfering signals. It is therefore necessary to use interference mitigation or avoidance techniques in a HetNet.

7.2 Future work

In order to see the full impact of load balancing in LTE-A HetNets, it is necessary to implement interference avoidance or mitigation techniques. Static or adaptive resource partitioning can be used. If this is done, load balancing in a HetNet using the proposed algorithm will also reflect in UE distribution among macro-cells and LPN cells and not only on computed cell loads. This will imply incorporating ICIC techniques in the simulator.

In case of a network with large number of cells, there will be a many non-linear equations to be solved in order to get cell loads and this will result in high computational overhead. This is compounded further by the need to have many iterations in the algorithm so as to achieve a high level of load balancing. The concept of upper bound and lower bound scheme can be used to estimate cell loads with lower computational overhead [19], [20]. This therefore means more work will need to be done if a large network is to be used for simulation or in a real network scenario where there are many cells so as to have a fast algorithm.

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Appendix A: Transmitter Structure

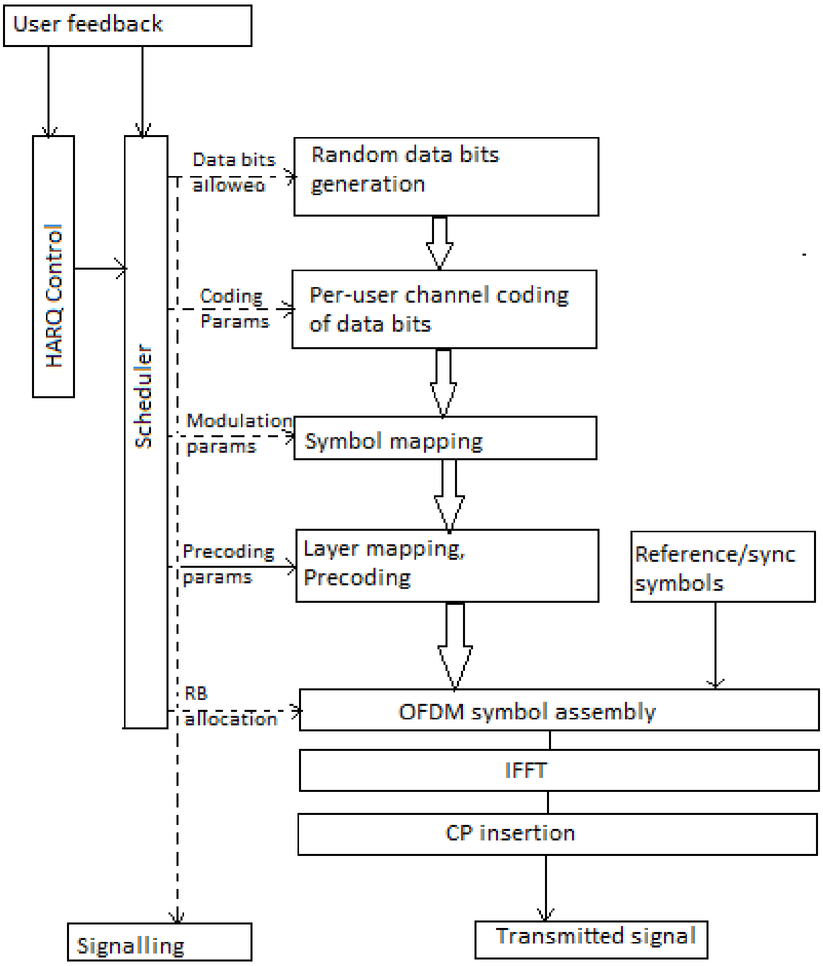

Figure A.1: Transmitter structure [24]

Appendix B: Receiver Structure

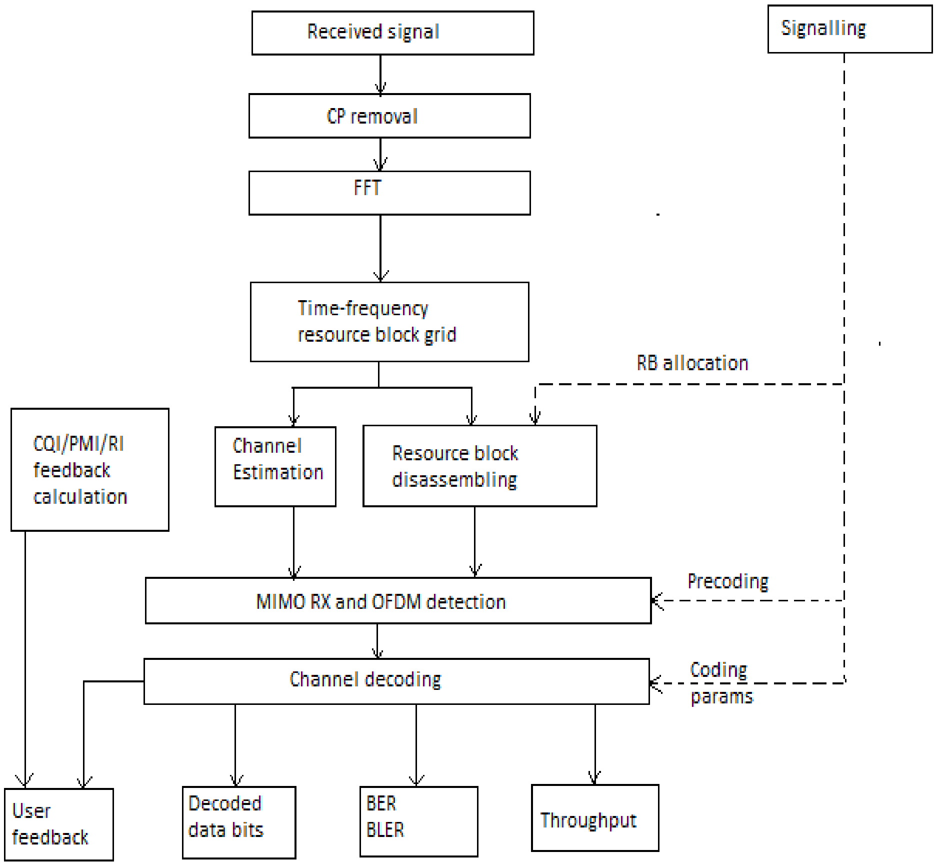

Figure B.1: Receiver structure [24]

Appendix C: SINR-CQI mapping

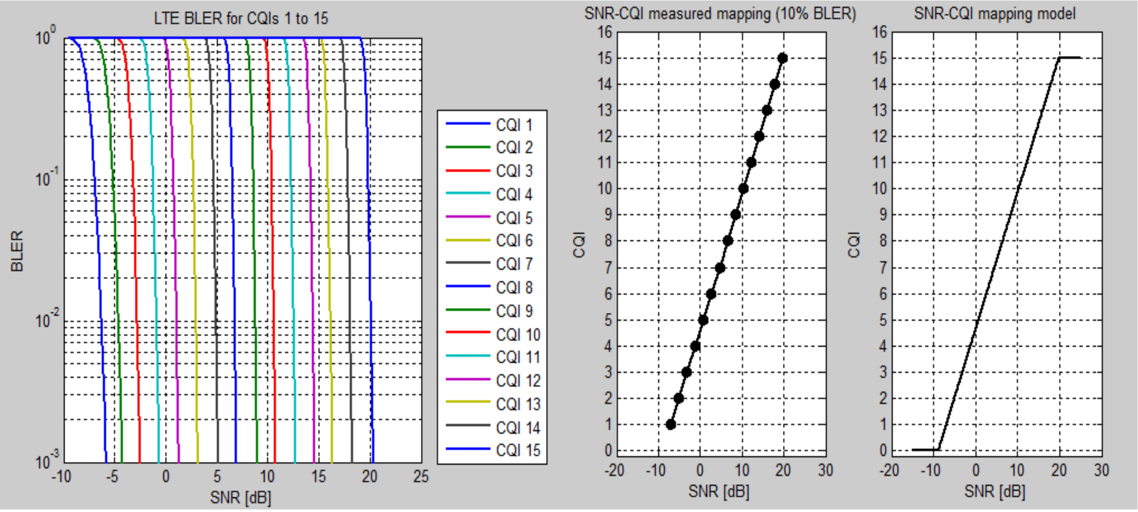

Figure C.1: SINR-CQI mapping