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Coordinated Multipoint Communications In Heterogeneous Networks

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AALTO UNIVERSITY ABSTRACT OF THE MASTER'S THESIS

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As users' demands on cellular service escalate rapidly, operators are required to deploy technologies with wider and more sophisticated techniques. In order to meet the future service needs, the standardization body 3rd Generation Partnership Project (3GPP) has standardized Long Term Evolution (LTE) and it has been working on enhancement of LTE and LTE-Advanced. The two key enabling technologies of LTE-Advanced are Heterogeneous Networks (HetNets) and Coordinated Multipoint (CoMP) communications. The former is aimed to improve inconsistent user experience and its basic feature is standardized in 3GPP release 11. The latter one where small cells are deployed within macro-cellular networks has been considered to enhance coverage and capacity.

This thesis presents a concise literature survey of cooperative communications and CoMP technologies. Furthermore, a detailed Matlab-based simulation study on CoMP between macro and small cells in HetNets is presented. Comparative analyses and evaluations are also made for different CoMP schemes under different deployed scenarios. At the same time, a new CoMP UE selection criterion is proposed to fit the modified round robin scheduling deployed in simulation and optimize the resource allocation among CoMP and non-CoMP UEs.

Keywords: *CoMP; HetNets; Small Cells; Cooperative Communication; Quantized Co-phasing; DPS/DPB.*

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ABBREVIATIONS

3D-BF	Three-Dimensional Beamforming
3GPP	The Third Generation Partnership Project
AAS	Array Antenna System
ABS	Almost Blank Subframe
AF	Amplify-and-forward
AWGN	Additive White Gaussian Noise
BS	Base Station
BW	Bandwidth
CBF	Coordinated Beamforming
CCI	Co-channel Interference
CF	Compress-and-Forward
CoMP	Coordinated Multipoint
CQI	Channel Quality Indicator
CRS	Common Reference Signal
CS/CB	Coordinated Scheduling/Beamforming
CSI	Channel State Information
DAS	Distributed Antennas Systems
DF	Decode-and-Forward
DL	Downlink
DPB	Dynamic Point Blanking
DPS	Dynamic Point Selection
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FFR	Fractional Frequency Reuse

HetNet	Heterogeneous Network
HII	High Interference Indicator
ICIC	Inter-Cell Interference Coordination
JP	Joint Processing
JR	Joint Reception
JT	Joint Transmission
LOS	Line-of-Sight
MIMO	Multiple-Input Multiple-Output
OI	Overload Indicator
QCP	Quantized Co-phasing
QoS	Quality of Service
RAU	Remote Antenna Unit
RB	Resource Block
RNTP	Relative Narrowband Transmit Power
RP	Reception point
RRH	Remote Radio Head
SE	Spectral Efficiency
SINR	Signal-to-Interference-Noise Ratio
TDMA	Time Division Multiple Access
UE	User Equipment
UL	Uplink

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1. INTRODUCTION

This thesis mainly studies about the coordinated multipoint (CoMP) techniques that can be applied between macro cells and small cells in heterogeneous networks.

1.1. Motivation and Background

Since March of 2009, 3GPP has standardized both LTE and LTE-Advanced since 3GPP Release 8. Many emerging and promising techniques like CoMP and HetNet are included in the standardization.

LTE Advanced-based Heterogeneous network use a mix of macro and small cells including pico, femto and relay base stations with lower transmit power to improve spectral efficiency per unit area, expand service range and provide a uniform user experience. Additionally, as it is flexible to insert cheap, self-configurable BSs in an unplanned manner into the existing macro cells based on concrete demands, Hetnet especially implement the scalability of today’s cellular network and cost-effectively enhance the capacity.

Coordinated multipoint (CoMP) is a promising and effective technique that can be developed and incorporated into LTE HetNet. CoMP essentially enables either transmission or reception points cooperating to serve a single UE. It basically helps to convert the inter-cell interference into useful single so that cell-edge performance and throughput of UEs are eventually promoted. The advantages become more outstanding in Hetnet, because more small cells exist and inter-cell interference from small cells is more likely to become the dominant interference degrading UE’s service. Therefore, CoMP can be regarded as an efficient and reliable solution to reduce interference and enhance cell-edge quality of service.

1.2. Problem Statement

Despite of the outstanding advantages of HetNet, inter-cell interference has become one major technical problem in LTE heterogeneous network. The conventional HetNet reuses the full frequency band in macro cell and small cell. Therefore, macro cells interfere neighbouring macro cells and small cells; and small cells interfere neighboring small cells and macro cells. More amount of interference will be received by the cell edge UE when we compare it to the case where we have only macro cells. CoMP in HetNet can be a candidate solution to alleviate the interference challenge and further enhance the performance of HetNet. However, earlier research work and proposed standardization associated with CoMP are all about CoMP between macro cells and RRHs so far.

1.3. Objective of the Thesis

In the thesis, in addition to revising different types of cooperative communication and coordinated multipoint technologies for LTE and LTE-Advanced, detailed and comprehensive study is made on specific CoMP techniques between macro cells and small cells. Literature survey and simulation are the key methodologies used for the thesis work. Different technical publications and reports have assessed to understand cooperative and coordinated communications and give a concise overview on the topics. Matlab-based simulation work has been performed on different CoMP algorithms and techniques applied between macro cell and small cell so that the technology performance gain can be analyzed.

1.4. Outline of the Thesis

Chapter 2 contains the literature review describing the general cooperative communication principles, system architectures and technical features.

Chapter 3 gives an overview about CoMP and with respect to different types of CoMP schemes employed both in uplink and downlink in release 11.

In chapter 4, many simulation works about CoMP between macro cell and small cell are done. The CoMP improvement of whole system is presented based on SINR gain of CoMP UEs and cell-edge UEs, percentage of CoMP UEs, cell edge throughput gain and average system throughput are comprehensively covered in that chapter. The outcomes for all cases are analyzed.

Chapter 5 makes some conclusions about CoMP between macro cell and small cell based on the simulation results from chapter 4. And some future work on CoMP is raised as well.

2. COOPERATIVE COMMUNICATIONS

2.1. Introduction

The idea of cooperative communication has been raised since the year 1970 by Van Der Meulen. In the recent decade, hundreds of researches have been done that show great potentials and a bright future especially in cellular network. Now, it has been one of the fastest growing technologies to improve the entire performance of network.

Cooperative communications enable efficient utilization of communication resources [1], which users share resources among multiple nodes in the cellular network. From the users' perspectives, cooperative communications help to save power, share hardware and obtain more stable mobility. The main goals of cooperative communication are to increase the network capacity and expand the coverage with higher SINR. Moreover, it enhances quality of service (QoS) by taking advantage of cooperative diversity and multiplexing [2].

2.2. Principles of Cooperative Communication

Most of cooperative techniques are user-based cooperation which essentially request to share resource of the whole system to maximize the efficiency of system and quality of service to users. Basically, there is no size limitation to implement cooperation which means network in any size or environment is able to achieve gain or benefits from this technology. The very basic purposes of any cooperative techniques are mainly to achieve cooperative diversity, reduce interference, save transmit power, maximize utilization of resource, increase capacity of cells, improve user throughputs at cell edge and so on. There is enormous number of methods to convert conventional network to cooperative one. The following sections briefly introduce some of them.

2.3. Different types of cooperative communication

The key concept of cooperative communication is to make the nodes or users in the network cooperating with each other to transmit, forward or receive the information. Mainly there are three kinds of technologies such as relay, distributed antennas systems (DAS), and multi-cell coordination.

2.3.1.**Relay**

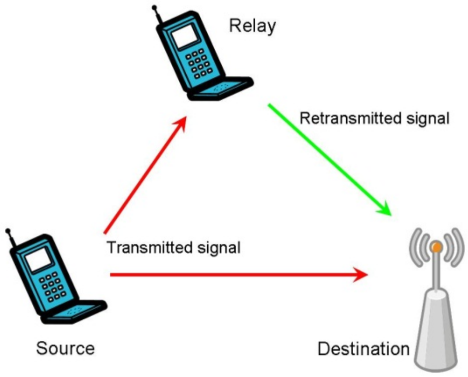

Figure 1: Relay Model

The cooperative relay system is a promising scheme that improves the overall throughput of network due to the gain of cooperative diversity and mainly profits users who are far away from the source node. The architecture of relay system is depicted in figure 1. A relay system consists of a source, a number of relay nodes and a destination. Relays can be some other users with source in the same cell while destination is normally a common base station (BS) that most of the users are motivated to send information towards the same BS. In a relay system, when source communicates to BS (destination), simultaneously the relay node will also choose to receive the data and then process and forward to next relay node or BS. Therefore, the information data will be transferred through two entirely different fading channels to combat the multipath fading and enhance the channel capacity. Finally, BS combines all these received signals transmitted from different nodes and having the same data. Consequently transferring through different channels leads to cooperative diversity which potentially mitigates the impact of multipath and improves the SINR of signals. Moreover, because of path loss, the received power in BS logarithmically decreases with propagation distance of signals. Then the deployment of relay in cellular network helps to save transmit power at user end and further prolong the usage time of mobile battery.

Paper [1] presents the node cooperative systems. Different from the original relay, in node cooperative systems, more than two relay nodes are able to simultaneously help source forward data to the destination. Cooperation between different nodes is realized by deploying joint processing (JP) or coordinating communication strategies. The source first shares its data information with relay nodes nearby. Then all these nodes transmit to destination at the same time with the corresponding relay protocols. This kind of communication is equivalent to a MIMO transmission that each cooperating node stands for a single antenna transmitting and receiving signals. Apparently, relay node cooperative system enables more significant spatial diversity than the normal relay systems. However, it is more complicated to implement. Because the exchange of channel state information (CSI), coordinating information and data among those cooperative nodes requires high quality backhaul link and the method of sharing these information is crucial for system efficiency. Otherwise, synchronization and delay problems will heavily degrade the performance of node cooperative system. Moreover, in the case that system allows terminals of user acting as the relay node, it's also a challenge. When users in network are moving randomly, the uneven distribution of relay nodes makes the performance unstable and more complicated to cooperate with each other.

The performances of above two systems are heavily affected by the employed relay protocols which comprise amplify-and-forward (AF), decode-and-forward(DF), and compress-and-forward(CF)[1].

- **Amplify-and-forward:** Before forward the received signal to destination, the relay node will scale the signal. Because the path of the forwarded signal is longer than that of direct signal from source, the two versions of the same signal transmitted through different channels are better to have the closer received power in destination so that the performance of spatial diversity might be more significant. Practically, this protocol AF is simplest to implement and has the best effect of spatial diversity. But its performance is sensitive to the fading of channel. Along with amplifying the information signal, the noise is also scaled in the same level.

- **Decode-and-forward:** In this protocol, the relay node will first decode the signal from source. Then the node encodes the obtained original signal again and forwards it to the destination. Compared to AF, DF eliminates the added noise received by relay. If the channel between source and relay is in a good condition, DF will heavily outperform AF. However, one of its weaknesses is that DF requires changes at both the source and destination [3]. Moreover, when the channel link between source and relay suffers from deep fading, the decoding errors will propagate to destination and can never be corrected. Consequently, DF performance in this case will be even worse than AF.

- **Compress-and-forward:** In CF, after relay node receives the signal from source, it decodes and compresses the received signal into another signal. Then node encodes and sends the compressed signal to the destination. CF does not necessarily require changes at the source but it does require some extra knowledge about the link capacity [3]. Compare to DF protocol, when the relay is close to destination, CF has a better performance that the data rate could reach maximum in an ideal case.

Generally speaking, for systems with good backhaul links, DF based cooperation schemes are more favorable, while for systems with relative poor backhaul links, AF or CF based cooperation schemes are more advantageous [1].

2.3.2. Distributed Antennas Systems (DAS)

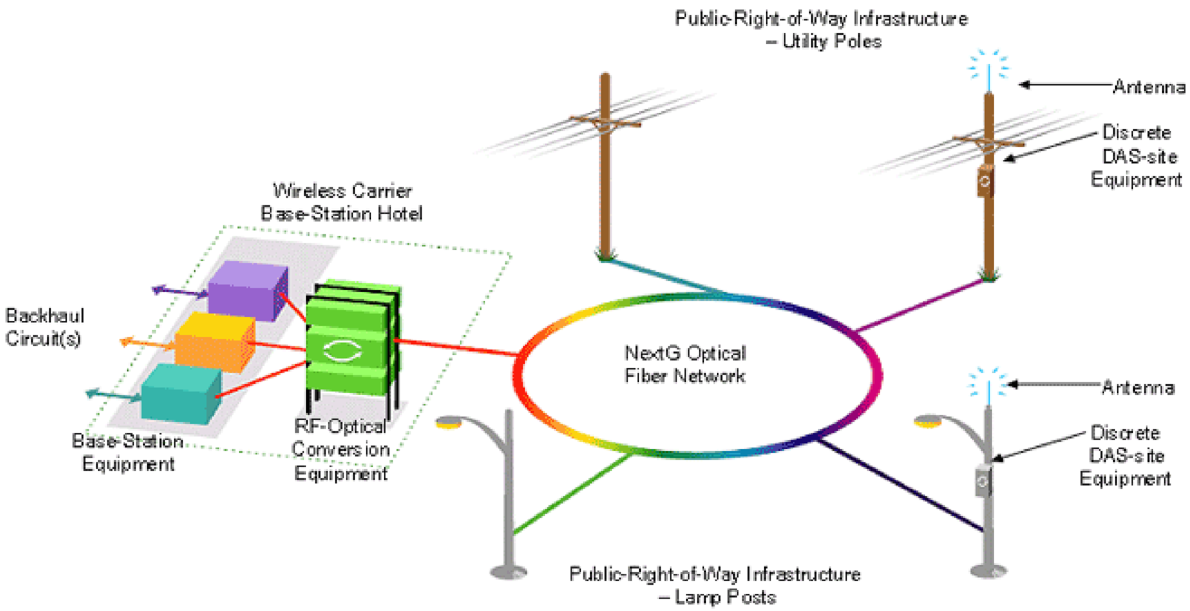

Figure 2: Distributed Antenna System

The layout of distributed antennas system is depicted in figure 2. It is a macro cell which has a single BS inside of it. Unlike the multiple-input multiple-output (MIMO) cell which is made up by collocated antenna arrays, antennas which are called as remote antenna units

(RAUs) in DAS are geographically distributed in the coverage of macro cell. All the RAUs are connected to the BS through optical fiber. Since the antennas are uniformly located in the network, essentially the average distance between a random user and its serving RAU is more or less reduced so that fewer users suffer from the bad quality of service even roaming at the cell edge. Additionally in some particular cases, for the users who are located at cell edge and unfortunately there is no RAU offering good channel condition, then multiple RAUs will simultaneously transmit the same signals to the victim user in a cooperative way to exploit the advantage of spatial diversity. However, when some user has a local RAU that implies this user is geographically close to the serving RAU, then probably only one RAU serves this kind of user. Paper [7] proves that DAS provides a promising performance enhancement in capacity. Since in DAS the distance of radio link between RAU and user is reduced, the spectral and power efficiency is improved significantly. In literature [8], the authors propose to employ larger frequency reuse factor to improve the performance of DAS that the average and cell edge spectrum efficiencies will be enhanced.

As MIMO system is similar to DAS except distribution of multiple antennas, it is fair to compare with each other to display the advantages of DAS. In case of traditional MIMO, the multiple antennas of BS are closely placed together, and there are two limitations weakening the gain of MIMO. First of all, conventional MIMO locates all antennas in the same position so that some users far away from BS might have low received power and face to high interference and low data rate at edge between two cells. However, the DAS places antennas in different locations. User who has a larger distance to one specific antenna on the flip side must be close to one of others. It has at least one antenna serving UE with lowest slow fading and best channel quality. Secondly, if antennas are geometrically collocated, signals transmitted or received by individual antennas probably go through the analogous transmission path resulting in the similar fading of channels. Thus, MIMO does not obtain a really high level of spatial diversity. In cooperative DAS, multiple signals transmitted from different location send towards destination via completely different transmission environment. In terms of co-channel interference which is caused by inner-cell RAUs or adjacent macro cell, DAS effectively mitigates it. Because the distance between transmitter and receiver is shortened, then transmit power can be reduced and occurred interference to other UE in the cell is consequently mitigated both in uplink and downlink.

Nowadays, distributed MIMO is practically evolved inspired by DAS. That is each RAU is geographically equipped with multiple antennas instead of a single antenna. This kind of system integrates advantages of both DAS and MIMO. In order to employ distributed MIMO more effectively and reliable, cooperation among adjacent cells is taken into consideration. For a particular user, it is possible that the nearest RAU is located in another cell. Furthermore, the interference towards the specific user from inner cell or adjacent cell can be avoided by muting the interferer.

Although DAS shows great advantageous potentials, it also has some problems to tackle. The fixed frequency spectrum limits the capacity of each RAU and high density of users degrades the performance of DAS. Moreover, the limitation of backhaul link brings about additional latency. From the economic aspect, implementing a cooperative DAS with high quality requires a relatively high cost as much additional infrastructures and hardware are required.

2.3.3. **Multi-cell Coordination**

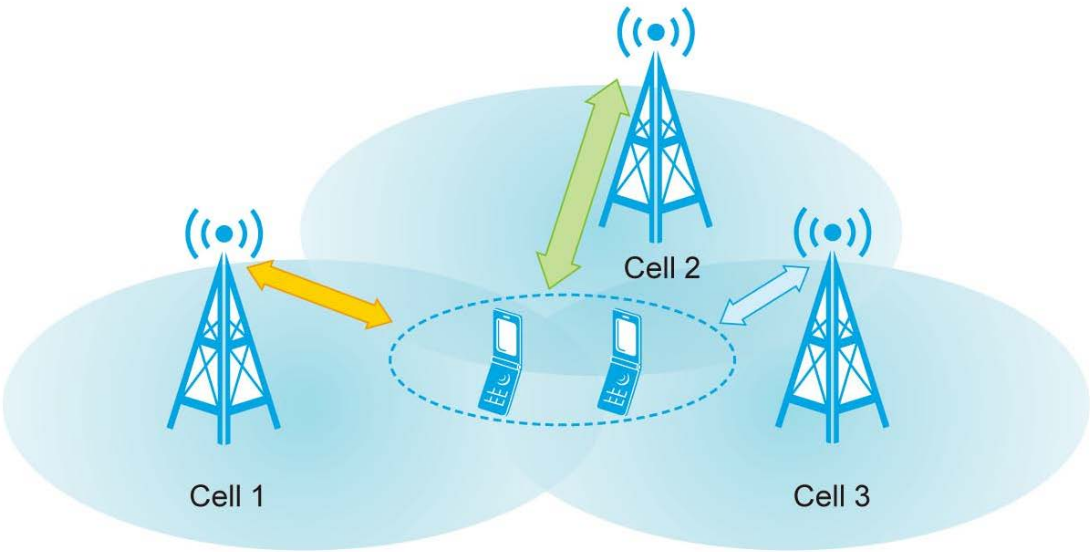

Figure 3: Multi-cell Coordination

Like the previous two techniques mentioned above, multi-cell coordination is designed to improve the throughput and coverage of system, meet the traffic demands, optimize utilization of radio resources and enhance spectral efficiency per unit area. It mainly increases the system capacity by mitigating inter-cell interference. Different from the previous two systems, multi-cell coordination occurs among the multiple adjacent cells that means the cooperative cells share resources of scheduling or data information with each other to diminish the inter-cell interference or strengthen the power of received signals at user end.

Inter-cell Interference Coordination (ICIC)

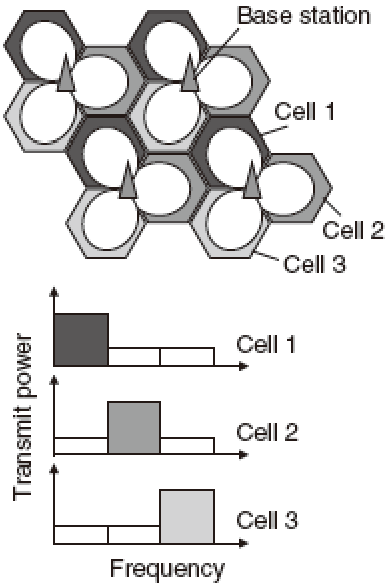

Figure 4: ICIC based on FFR [10]

As users at the edge of a cell suffer from strong co-channel interference from carrier used with same frequency band from adjacent cells, the coverage area is shrunk or at least hardly approaches its maximum range determined by transmission power.

Inter-cell interference coordination (ICIC) is introduced for LTE in 3GPP Release 8 as one of the multi-cell coordination techniques (eICIC in LTE-A) to reduce inter-cell interference and improve quality of service for users at cell edge. The technique ICIC can be implemented based on fractional frequency reuse (FFR) shown in figure 4. The whole bandwidth is divided into three components. However, the reuse factor for each cell is still 1 which means any cell apply the whole bandwidth. The entire frequency band is available for the central users and the fraction which has a relatively stronger transmit power is only available for the cell-edge users. Therefore, the fraction of frequency band with lower transmit power are preferable to be scheduled by users who are close to BS. Meanwhile, to coordinate inter-cell interference, the adjacent cells must pick distinctive strong band. In order to effectively apply ICIC, different coordination signals should be defined separately for downlink and uplink. In downlink, the signal called relative narrowband transmit power (RNTP) is used for interference coordination [10]. The RNTP signal describes the ratio of transmit power of every resource block (RB) and is then sent to all its adjacent eNBs. Subsequently, other eNBs are able to know the situation of frequency band with strong power that is employed by their adjacent cells and avoid allocating that kind of RBs to a user at cell edge. In uplink, there are two types of signals for interference coordination: high interference indicator (HII) and interference overload indicator (OI). The function of HII is similar to that of RNTP in downlink. HII tells its adjacent cells the uplink RB with strong transmit power. The OI signal is used to inform other cells about the realistic interference power for every RB.

In LTE-Advanced based heterogeneous network, the source of interference turns to be wider and more complex. Because macro cell employs the same carriers as small cells aiming to achieve the maximum spectral efficiency, macro cell's BS causes relatively strong interference to users comprised in the small cell. Due to the tremendous coverage of macro cell compared to smalls cell like pico cell, femto cell and so on, the macro cell's transmit power is fairly stronger than small cell's so that the co-channel interference cannot be mitigated merely by using ICIC. Consequently, the inter-cell interference coordination technique in HetNet of LTE-A called eICIC is designed and its principle is shown in figure 5. Instead of lowering the power of fractions of frequency band in ICIC in LTE, eICIC is to blank specific parts of subframes in time domain with coordination for small cells. Hence, the macro cell's eNB is able to reduce interference to comprised small cells by using almost blank subframes (ABS). The subframes under ABS are only used to transmit common reference signals (CRS) and some mandatory information with a low power like PBCH, PSS and Paging signaling and so on. Those subframes without any co-channel interference are used by small cells and data throughputs of users will be significantly enhanced. In order to obtain enough gain from eICIC, the base station packet scheduler and link adaption functionality in principle needs to be aware of the ABS muting patterns at the different base station types [11]. Macro-cell configuration is decided with coordinated scheduling through interface X2. Small cell first sends ABS request to macro cell. Then macro cell mutes the requested subframes and replies small cell with ABS information. Later, macro cell will keep asking the small cell to report the usage and status of ABSs. Then macro cell is able to increase or decline the number of ABSs depends on the reports about ABSs status from small cells. Additionally, ABS information can also be exchanged among different macro cells to prevent interference of its small cells from other possible adjacent macro cells. An example of this process is given in figure 5. There are two users (2, 3) in a pico cell. Macro cell configures subframes 2, 42 and 45 as ABSs and user 2 and user 3 are separately scheduled in these subframes without having interference from macro-cell BS or from user 1 if in uplink. Furthermore, if the pico cell is located at the cell edge and is close to adjacent macro cell. That macro cell is also responsible to blank the corresponding subframes to cause inter-cell interference.

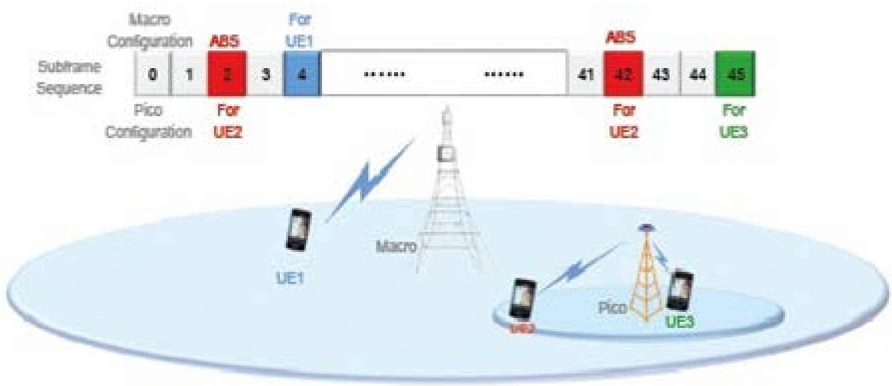

Figure 5: eICIC in HetNet

Overall, ICIC for 3GPP Release 8 (LTE) and eICIC for release 10 (LTE-Advanced) are introduced above. Although, they have much attractive features like most of other cooperative techniques, there still exist some disadvantages. Throughput of the whole cell is decreased, since full resources blocks are not being utilized. A major problem for applying ICIC is the difficulty to anticipate the interference level which is varying due to dynamic scheduling in adjacent cells. As coordination is sensitive to measured interference, a small margin may incur scheduling error of itself and interference to other cells. Last but not least, like any other cooperative technologies as well, the backhaul links between macro cells or macro cells and small cells limit the performance and lead to latency in communication.

Coordinated Beamforming (CBF)

Coordinated beamforming is another multi-cell coordination technique, that is, downlink channel information is shared among eNBs so that beams are cooperatively scheduled to communicate under low level of inter-cell interference and performance of entire system is improved.

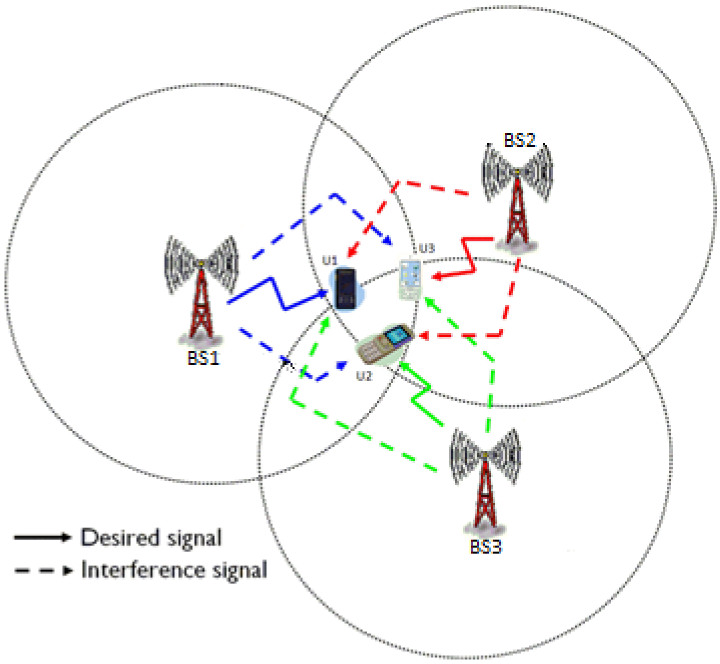

Figure 6: CBF Model

Unlike most of cooperative schemes, in CBF, there is only one serving BS for user wherever it locates in a cell at any time instance. The purpose of using beamforming technology is to prevent BS from interfering with other users near the target user and the average SINR of the whole system will be increased. Users scheduled with different angles of beams are able to use same resource blocks even if in a same cell. Thus not only interference is mitigated, but the capacity of network is enlarged. Apart from deploying single beamforming, to further improve the SINR of a single user, cooperation occurs that scheduling and beamforming decisions are made with coordination among all neighboring cells. Consequently the principle of coordinated scheduling is to avoid both unnecessary inter-cell and inner cell interferences. Additionally, neighboring cells share their scheduling information which contains the scheduled beams' angles for separate users and the deployments of their corresponding resource blocks. Hence, for each BS, it knows the angle information of the whole system, the underlying interference from adjacent cells to all beams and the potential interference a newly added beam will cause to users in other cells within specific RBs. Consequently, receivers in the same radiating area use distinct RBs even serving by different base stations.

An example about CBF is shown in figure 6. Three users locate in the overlapping area among three cells. Assume BS 1 serves U1, while BS 2 and BS 3 serve U2 and U3 separately. Then the beams deployed by these three BSs may interfere with each other if they are applying the same resource blocks. For instance, the locations of BS1, U1 and U3 are in a line, and signals sent from BS1 to U1 interfere with U3. Therefore, in order to reduce the unnecessary interferences, with exchanging their angle information of deployed beams under coordination, each BS must allocate different RBs their own serving UEs.

Apart from lower co-channel interference, another advantage of CBF is that it works well with limited quality of backhaul. Because, only scheduling information is exchanged between base stations rather than data information which has tremendous amounts of data and need to set up backhauls with extremely high throughput.

Similarly in heterogeneous network in LTE-Advanced, CBF is also an efficient scheme to be applied as macro and small cells simultaneously reuse the full frequency band. The specific user whose location has the same angle as small cell to macro cell cannot be served by beams using the same resource blocks which are already assigned to some other user in small cell. Generally speaking, CBF mitigates the interference without making a sacrifice of high spectral efficiency.

Despite of attractive and promising merits, the drawbacks of this technique cannot be neglected. The coordinated scheduling means to have a more complex system. Moreover, the procedure of learning context from other base station and making the own scheduling decision bring about a delay for communication.

Joint Processing

Joint processing has been proved being a prominent and effective coordination technique. Basically it provides higher throughput of system than coordinated beamforming (CBF).

There are large numbers of JP schemes for different types of cluster of UMTS. For simplicity, three most basic schemes for static clusters of BSs are introduced below.

- **Centralized joint processing:** In this scheme, the set of BSs jointly cooperate and send the same data to the assigned user without causing extra interference. Channel state information (CSI) is available at the transmitter side, and base stations within a cluster jointly perform the power allocation and the design of the linear precoder [12]. All the base stations included in cluster are connected by backhauls so any one of BSs can choose the serving BSs and make the decision of beamformer. Beside this, a central unit can be applied to dedicatedly responsible for implementing joint processing. Anyway, this scheme need to share the full transmit data among the serving base stations and a relatively high quality of backhauls are required.

- **Partial joint processing:** Partial joint processing is an advanced application of the previous scheme (CJP) as it generally reduces the overhead of feedback and load of backhaul. It is more agile and efficient since it defines several degrees or stages of joint processing. Each user has a separate active subset which is made up by one or several base stations in a cluster. Every time, only base stations belong to the subset send data to user. Therefore, abandon communication through a bad channel condition helps receiver easily receive and save energy and ease load in perspective of base stations. But for a subset, it does not learn all CSI in the cluster so that more or less co-channel interference rises up.

- **Distributed Joint Processing:** In a cluster, BSs only know their own CSIs, therefore all decisions and calculations are individually done by each BS. Based on feedback CSI, BSs who have high quality of channel condition serve the user. A multibase scheduling algorithm is required in order to assign users to BSs [13].

Joint Decoding

In order to effectively serving user varying from different channel condition, communication system normally applies various types of modulations like QPSK, 16QAM, 64QAM and so on. In terms of a user, when receiving signals, it needs to detect the transmitted symbol with a demodulator. But conventional way to demodulate will lead interference into the desired signals. If the modulation order of both the desired signal and interference signal are known to the receiver, the receiver can attempt to decode the desired symbols by jointly decoding the desired symbol and interference symbol. In reference [14], the joint ML detector is introduced to be such a proper demodulator. The joint ML detector jointly detects the desired and interference signals and then extracts the wanted signals with discarding the interference from other cells.

Joint decoding is an efficient technique to work in fast fading environment and is advantageous to cooperative CBF system. Like most cooperative, it also offers a high diversity gain. However, the complexity of computation and needed hardware are necessary to be taken into account when being applied.

Overall, multi-cell coordination is promising from many aspects like interference limitation, cooperative diversity, spectral efficiency and so on. Practically, individual disadvantages of above techniques have been separately introduced already, but there still exist some common and fundamental limits or shortcomings to all of them. First of all, the latency due to sharing date and quality of backhauls during communication cannot be avoided. Cells in a cluster have to share channel, data or coordination information with each other through backhauls. Otherwise, coordination could not work anymore. Secondly, coordination decision is normally made based on the feedback from receiver. But the reliability of feedback depends on channel condition. The wrong feedback information because of large fading in channel probably misleads a coordinated scheduling or any other decisions. What's more, when in large-scale multicell networks, the limitation to overcome seems to be more. For instance, it is difficult to get rid of saturated spectral efficiency as transmitters transmit with a relatively and necessarily high power. Literature [14] shows many limits in some extreme cases.

3. COOPERATIVE COMMUNICATIONS IN LTE AND BEYOND

Coordinated multipoint (CoMP) transmission and reception is such a cooperative technique to mitigate inter-cell interference, enhance cell-edge throughput and ensure consistent service quality. It can be categorized as one of multi-cell coordination technologies. It has been standardized by 3GPP (the 3rd Generation Partnership Project) for LTE-Advanced in Rel-11. This chapter contains the basic principle of CoMP, implementation challenges and future development.

3.1. Description of CoMP in LTE (Release 11)

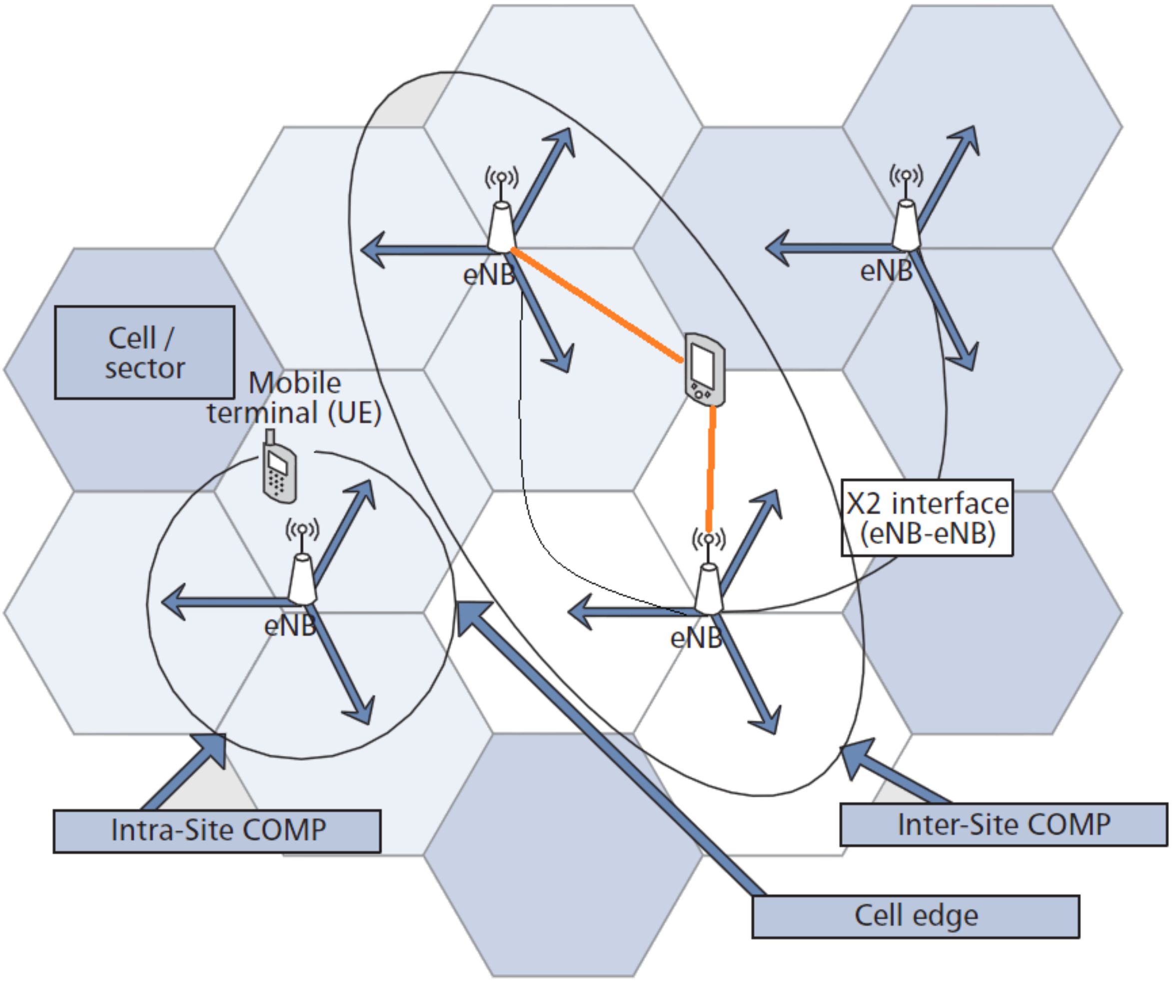

Figure 7: CoMP in LTE [19]

The main idea of CoMP is that multiple BSs in a cooperating set simultaneously serve a specific UE together either sending/receiving same data or scheduling UEs in coordination to avoid unnecessary interference. The coordinated transmission both enhance the power of desired signals and reduce the power of interference. Figure 7 displays both intra-site and inter-site CoMP. In figure, the leftmost eNB offers the intra-site CoMP to UE so that there is no load on backhaul link. Additionally, another two eNBs perform the inter-site CoMP and coordination information is exchanged through backhaul.

Actually, CoMP works in different ways in uplink and downlink. The details are introduced following based on the standardization proposed by 3GPP.

3.1.1.**Downlink CoMP**

In downlink, CoMP scheme basically consists of two categories: joint processing (JP) and coordinated scheduling/beamforming (CS/CB). The essential principle of them is similar to multi-cell coordination. Either data or scheduling information is shared among multiple sectors in intra-site CoMP or multiple eNBs in inter-site.

Joint Processing

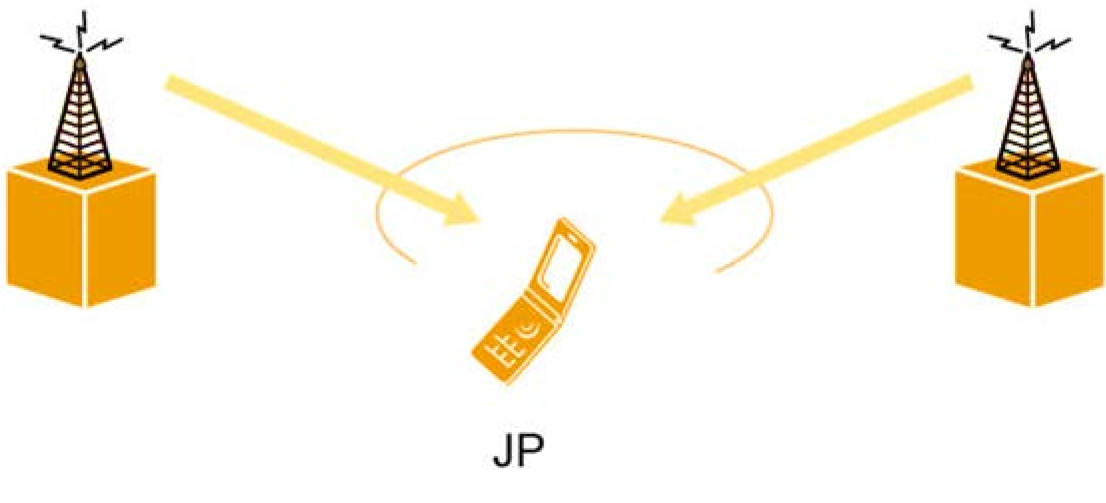

Figure 8: Principle of JP in downlink

The principle of JP is depicted in figure 8. In JP, multiple BSs send same data towards UE to achieve spatial diversity gain and diminish the dominant inter-cell interference. Actually in downlink CoMP, JP can be implemented with different schemes, for instance: joint transmission (JT) and dynamic point selection (DPS). The essential difference between these two schemes is that JT makes serving points simultaneously send data to UE while DPS uses a fast point selection approach and only the one who has the best channel condition transmits data at one subframe. These two schemes are further introduced below.

I) Joint Transmission

Joint transmission (JT) is described as technique that data to a single UE is transmitted coherently or non-coherently from multiple transmission points in the same resource block. The interfering signals from adjacent cells are converted into useful signals so that not only the level of interference is reduced but also the power of desired signal is strengthened. Therefore, the cell edge user who is more likely to have weak signal and strong interference is able to achieve much higher SINR. The concrete application based on different fading environment may employ different coherency. There are two types of joint transmission: the non-coherent JT and coherent JT.

In non-coherent JT, precoder of each multiple point will individually precode to achieve the diversity gain. UE only reports channel quality indicator (CQI) to their serving points instead of CSI. The relationship of channels between different multiple transmission points is unknown, and consequently received signals cannot be coherently combined. The open-loop transmission, single-frequency network or cyclic delay diversity is the alternative solution to realize the non-coherent JT.

In coherent JT, oppositely the transmission signals from multiple transmission points are precoded jointly so that UE is able to coherently combine all received signals. Precoder of each multiple point adjusts phase and amplitude of transmit signal based on the corresponding spatial CSI feedback. However, in order to approach the perfect coherent combination of received signals in UE, good synchronization, precise CSI feedback and small timing error differences between transmission points are needed to be taken into account when implement the coherent joint transmission. Nonetheless, the CSI feedback send to transmission points is limited due to concrete uplink channel. One way to reduce feedback signal overhead is applying precoding with code book.

In addition, when implementing JT, using a fixed set or all of transmission points leads to a waste of resources of network. Consequently, dynamically determine the serving set of eNBs which is to form a CoMP cluster is fairly crucial. The setup for a CoMP cluster of transmission points might be semi-statically or statically. Later with collecting more information of PMI, CQI or CSI reported from UE, the serving points in the corresponding CoMP set is changeable based on quality of service and traffic load. Points offering worse quality of service are removed from the set and would improve their resource utilization by serving other UEs.

II) Dynamic Points Selection

Dynamic point selection is another joint processing scheme that the signal to a specific UE in a CoMP cluster is always transmitted from a single transmitted point at a time. UE frequently reports the corresponding CSI to all points involved in the serving set of eNBs. Consequently, a point is drawn based on the feedback CSI and practical resource utilization to serve the UE. If there is a potential point being able to offer better service, automatically that point will substitute the previous one to send signal to UE at next subframe. But the procedure of switching among multiple points in the CoMP cluster is transparent from the perspective of UE.

As there are more transmission points simultaneously sending signals to UE in JT in same resource block, normally JT provides more gain and has a better performance in a light load of network. DPS is an alternative scheme to have a good performance when the network is in a heavy load. However, both JT and DPS need to have a fast backhaul to accomplish sharing data, channel and scheduling information. The backhaul issue is the main problem affecting the performance of JP and is critical to be improved. In addition, DPS may be jointly used with JT when the serving set of eNBs is dynamically determined.

Coordinated Scheduling/Beamforming (CS/CB)

Unlike JP, in CS/CB, user data is only available in and transmitted from one transmission point. But the information about UE’s channel condition to every point should be shared between transmission points in the CoMP cluster. Consequently, the user scheduling or beamforming decisions are made independently but with coordination among the CoMP cooperating BSs. The transmission points are chosen semi-statically.

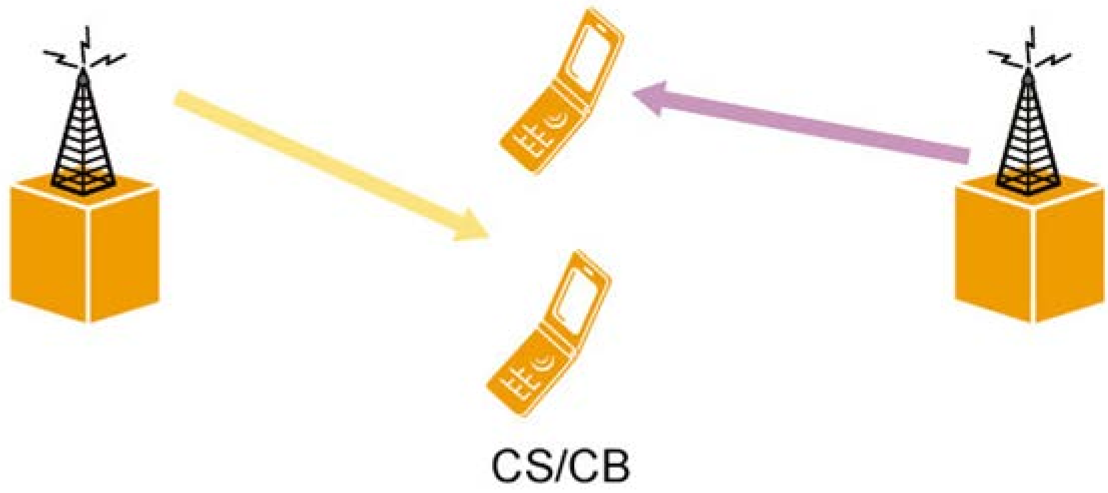

Figure 9: CS/CB in downlink

Figure 9 shows the principle of CS/CB. Different color of arrow means scheduling beams with different resource blocks. Both of these two UEs are located in each other's radiated area of their corresponding BSs' beamformers. Due to coordinated precoding at each eNB to achieve beamforming, almost no interference incurs. Technically, CS/CB maximizes the SINR by avoiding underlying interference from/to the opposite cell.

To implement a simple and basic approach of CS/CB, BSs involved in the CoMP cluster request the UE to feed back the channel information which includes the downlink channel condition of all possible serving BSs. Based on reports, each BS locally precodes and UE is scheduled in the subframe with the best resources and channel quality. After that, each cell needs to keep updating the status of coordination for every UEs. The principle is that each scheduling decision should account for not only the scheduled UE but also the utility of the victim UE scheduled by other cells. Any change of a scheduled beam at next subframe in a specific cell likely affects all other scheduling decisions.

Overall, coordinated beamforming is such an approach with a low feedback overhead aiming to reduce interference variation and enable accurate link adaption. As data information is only available in one point, the burden of backhaul link is much less than that in JP. Thus, this feature makes CS/CB more suitable for application in the case with non-ideal quality of backhaul. Based on outcomes of many simulations that have done so far, CS/CB with reliable feedback is able to achieve significant gain especially to users at cell edge.

But when compared to scheme non-coherent JT, the limitation of CS/CB is apparent. When in a more complicated scenario with heavy fading and multipath problems, the feedback information may be unreliable. That affects performance of CS/CB heavily. Moreover, It is also possible and realistic to implement a hybrid category of both JP and CS/CB. Paper [20] proposes the scheduling-assisted joint processing schemes.

CSI Feedback

Apparently, in both JP and CS/CB schemes, the CSI reported to transmission points from UE plays a critical role in CoMP. The following three feedback mechanisms have been adopted in CoMP:

- Explicit channel state/statistical information feedback.
- Implicit channel state/statistical information feedback
- UE transmission of SRS can be used for CSI estimation at eNB exploiting channel reciprocity.

Notably, the first two are the main schemes in the standardization of 3GPP LTE-A. In implicit CSI, the feedback contains an index of the precoder and the index points to the corresponding codebook at BSs. While in explicit CSI, instead of sending the precoder index, CSI directly includes the codebook itself which is more reliable and close to the concrete channel information.

Combinations of full or subset of above three are possible to apply based on different CoMP categories and requirements. In CS/CB or DPS inter-point phase information in feedback is not necessary while coherent JT may need both inter-point phase and amplitude information. Probably, enhancement or modifications on the existing CSI reporting procedures are needed. The feedback also contains the channel state information of all cooperative points in the CoMP cluster and the receiving point or points may exchange feedback reports among all points through X2 interface. As the calculation of the precoding matrix depends on the CSI feedback of other UE, once the channel state information is globally available, the calculation of the precoding matrix can take place.

The procedure of feedback exchange varies from different architecture of network. In the centralized network where there is an eNB or dedicated control unit connecting to every eNBs in the CoMP cluster, the controller gathers CSI of all UEs to all eNBs and is responsible for computing the precoding matrix corresponding to user data. After that, the precoding matrix is sent back to all the cooperating eNBs with user data. In distributed network, instead of sending all CSI feedback to a specific controlling unit, the CSI at each cooperating point needs to be shared among the CoMP cluster. As each eNB is acted as a controlling unit, they locally compute their own precoding vector with respect to user data.

It's definitely true that more overhead into feedback information leads to better performance of CoMP. However, due to the uplink constraint, the overhead is limited. What's more, the feedback overhead is proportional to the size of the CoMP cluster. In another word, increasing number of cooperative eNBs leads to growing overhead of feedback. Thus, reducing the CSI feedback overhead is a crucial issue. Works in [16] proposes a framework to mitigate the feedback overhead by setting a proper threshold for the feedback. The simulation results show the average feedback load is lower by setting the threshold.

Backhaul Support

As there is a large amount of data exchange between eNBs through backhaul, the minimum latency is an issue to be solved. Basically, high-capacity communication links and efficient protocol is considered as two methods to improve the performance of backhaul. By the way, note that the intra-site CoMP does not account for the requirement of backhaul. But in inter-site CoMP especially in JP scheme, the requirement of backhaul is more challenging due to a bunch of channel state information, scheduling decisions, precoding weights and user data to be exchanged. The following content in this section gives some possible technologies working as a high quality backhaul link for CoMP.

- **X2 Interface:** The logical X2 interface which is independent from the physical deployment of the E-UTRAN can be used as backhauling link. It can be either a direct physical link or a multi-hop link. The protocol stacks contain X2-U and X2-C which are separately used for user data transfer and control data transfer. The X2 delay comprises of interface propagation delay and eNB Tx/Rx processing delay. Compared to the optical technologies, the weakness of X2 is the loss in performance. Basically an X2 delay of 5 ms leads to a loss in spectral efficiency of 20%.

- **Point-to-point Fiber:** The cooperating points are connected with each other through a point-to-point fiber. Time division multiple access (TDMA) is a suitable multiplexing technique to realize the two-way communication among these points. Normally the date rate of over 2.5 Gbit/s can be guaranteed. Like other wire line technologies, the good error performance is an advantage. The possible latency is around 100 µs which depends on the bandwidth of the fiber link. Hence, in order to achieve a fixed delay, the required bandwidth of the link should be fixed as well. When in centralized network, the passive optical network (PON) which essentially is a point-to-multipoint network can be applied. It enables a single controlling unit serving multiple eNBs. In this case, the delay of the system may be much larger than that of point-to-point fiber based CoMP.

- **Ethernet:** Nowadays, Ethernet is more and more employed in metropolitan area network. It is a suitable candidate as backhaul. Data rates of Ethernet based on optical fibers may have over 10 Mbit/s and delay of it is from 0.1 to 20 µs. The extent of latency mainly depends on the link capacity and frame duration. Date rate over 10 Gbit/s leads to the minimum achievable delay for Ethernet. Due to the link distance, copper based Ethernet is an option for intra-site CoMP. Like the optical network, Ethernet provides a very good error performance. For the optical based Ethernet, the error rate incurred in backhauling link can be ignored.

3.1.2. **Uplink CoMP**

The uplink CoMP is potential to increase throughput, particularly at the cell edge. Some literatures prove that UL CoMP leads to 80% gain in terms of average cell throughput and even threefold cell edge throughput improvement. It helps to render a higher and more uniform user experience anywhere especially in a heterogeneous network. Different from DL CoMP which has several antennas sending the same signals, UE has only one antenna to send signals and adjacent BSs receive and jointly process the received signals. Thus, UL CoMP is compatible to and supports any kinds of users as no other extra modifications are required for the handsets. In the standardization release 11 of 3GPP, UP link CoMP is categorized by the following two types.

Joint Reception (JR)

As the coordinating eNBs assigned to each UE are geographically distributed in the CoMP cluster, JR is to jointly utilize antennas from different sites simultaneously receiving signals transmitted from UE. After accomplishing reception of signals at different reception points (RP), the raw or preprocessed data are exchanged among all these points and jointly processed to produce a final output.

Essentially, schemes of joint reception in centralized and decentralized networks are a little bit different in implementation. In centralized joint reception, after signals received at the cooperative eNBs, it is quantized and forwarded through the backhaul to the controlling unit. In some cases, in order to lower the load of backhaul, the received signals are preprocessed before being forwarded. However, the corresponding CoMP gain is subsequently declined. In decentralized joint reception, instead of having such a controlling unit as it is known to jointly receive signals, signals are iteratively and simultaneously processed by exchanging information among all cooperating BSs in the CoMP cluster. In order to reduce the overhead when exchanging, only the user-oriented and useful channel state information is required for joint processing. Additionally, there is no extra controlling unit and only a little change to the current architecture of network is needed. Basically, this scheme is the tradeoff between CoMP gain and complexity. In the book [17], writers illustrate that decentralized CoMP schemes are more advantageous than centralized one in LTE-A because of less change to the current architecture of network, lower computational load and so on.

Overall, there exist many problems to be tackled. Users suffer from multipath propagation and different latency of the separate received signals at different cooperating BSs. When the longest delay to the furthest serving BS exceeds the normal cyclic-prefix length, inter-cell interference is incurred. Compared to downlink joint transmission, JR in uplink has a stricter requirement about delay. What’s more, large amount of user data to be exchanged through backhaul causes delay of communications so that the benefit is limited and performance is degraded.

In order to overcome the impact caused by excessive delay, either a flexible cyclic prefix or timing advance can be employed. The principle of flexible cyclic prefix is to apply the dynamic cyclic prefix based on the concrete delay. UE possibly causing excessive delay is scheduled with extended cyclic prefix. Otherwise, it is scheduled with the normal cyclic prefix. The approach of employing timing advance is essentially sending the transmit signals with minimum delay in advance so that the signal with the maximum delay is able to be received within the cyclic prefix range.

Coordinated Scheduling and Beamforming (CS/CB)

In uplink CS/CB, UE scheduling and precoding selection decisions are made with coordination among RPs in a CoMP cluster. Only one reception point is used to receive the signal from UE. As only CSI and scheduling information are exchanged among cooperating RPs, the load of the network will be significantly reduced. The aim of uplink CS/CB which likes that of downlink CS/CB is to be aware of and minimize the underlying interference that is possibly added in by a certain UE scheduled with specific time and frequency resources. All cooperating eNBs periodically send CSI of the assigned UEs to the controlling unit or another eNB in the cluster. Then the coordinated decision is made with the comprehensive knowledge of the network, in another word, not only the current channel station but also the potential inter-cell interference it will cause is taken into account. In general, the radio resource allocated to a specific UE at cell edge is banned within the corresponding neighboring cells. Overall, the avoidance of inter-cell interference does not enhance the overall throughput of system too much but it significantly improves the service for the cell edge user.

However, the requirements to achieve the uplink CS/CB benefits are strict. First of all, the accuracy of CSI plays a critical role which is subsequently used to estimate the underlying inter-cell interference and directly affects the coordination and scheduling decisions. Secondly, like in other CoMP schemes, the quality of backhaul always limits the performance. Another problem in uplink CS/CB is that when the frequency resource of a specific UE is scheduled fast enough, the reactions with coordination of other cooperating eNBs are always behind the serving eNB due to the impact of delay. In this case, inter-cell interference will be increased as the asynchronized scheduling in radio resources.

3.2. Challenge of CoMP

Although tremendous numbers of simulation and field trials have shown the great potentials and benefits of coordinated multipoint, there still remain some problems or challenges to be overcome. Earlier we have roughly mentioned the existing problems concerning to corresponding schemes, in the following, the common challenging is summarized.

3.2.1. **Clustering**

In practical implementation, only a limited number of BSs form the cooperating cluster due to proportional overhead. Basically clusters are either static or dynamical. In the static clustering, an assigned CoMP UE always has a fixed number of cooperating BSs which depend on the geographically position. In the dynamic clustering, the transmission or reception coordination update periodically. Normally, several of the BSs having best channel condition become the serving cluster. However, in practice, many other factors should be taken into account to form different scheme of clustering, for instance, the load of each cell, synchronization and types of modulation scheme. Thus, it is important to find out the most suitable and efficient cluster set of cooperative BSs with the least complexity.

Under static clustering, as its constant sets of cooperating BSs, very little overhead is required and simple to implement. But if the UE is in a high mobility or the fading of channel fluctuates heavily, the performance of CoMP is significantly degraded.

Under dynamic clustering, cooperating BSs are dynamically picked by UE based on channel condition and UE location over time and radio resources. Consequently, the dominant and underlying inter-cell interference is converted to the useful signals and interference with lower power can be tolerated. From the perspective of the entire network, the radio resource from the cell transmits under worse channel condition is banned and saved for other UEs. It is a compromise between resource utilization and interference mitigation. Nonetheless, frequently updating the serving BSs makes scheduling and transmission or reception more complicated. Despite of complexity, dynamic one achieves more gain from CoMP than the static one.

The clustering approach for CoMP is a threat affecting the performance of system. The choice of approach should be based on the concrete environment and demand. Static clustering is better to be selected in a more stable environment while dynamic one fits at most situation with high complexity. Literatures [17] & [18] introduce some optimal dynamic clustering approaches as good alternative choices.

3.2.2. **Backhaul**

Basically backhaul is used for exchanging large amounts of data among eNBs in a cluster. Based on different types of CoMP schemes in either uplink or downlink, the backhaul requirements may vary. Either alleviating amount of exchanged data or applying an advanced backhaul technique is the way to overcome backhaul challenge. For different schemes of CoMP, the requirements on backhaul vary.

As CoMP is a technique that requires a relatively low latency in order to achieve the real-time coordination. Simulation results show that every additional 5 ms delay brings about 4%-5% decrement in gain. However most of the existing backhaul do not support to offer low latency. In HetNet, it even faces more challenges about delay. Therefore, for the purpose of obtaining more gain of CoMP in the future network, it is necessary to develop backhaul technologies in the aspects of capacity, latency and synchronization performance.

3.2.3. **Synchronization**

CoMP is a sort of synchronization-sensitive scheme and synchronization in both time domain and frequency is crucial from perspective of practical implementation. In order to avoid both inter-symbol interference and inter-carrier interference, cooperating BSs should be synchronized both in frequency and time domain. In 2.2.1, it has mentioned that the difference of delay for all received signals have to limited within a specific length and if there exist the problem of asynchronization, inter-symbol or inter-carrier may incur.

Each node in the network keeps a local notion of time and it has the same duration or time occurrence of events with each other. In paper [17], several types of synchronization techniques in CoMP network are elaborated. They can be either jointly or separately applied to ensure the synchronization of network.

3.2.4. **Channel Estimation and CSI Feedback**

The accuracy of channel knowledge indirectly affects the performance of CoMP especially in downlink, as it leads to CSIs be in the same level of accuracy which is subsequently regarded as a reference for precoding like phase/amplitude adjustment (coherent JT) or coordinated decisions (CS/CB). Additionally, with accurate channel knowledge, the raw data at receiver can be correctly recovered. However, unlike the normal LTE network, in CoMP multi-cell channel estimation is more challenging due to different radio channels to UE. In 3GPP REL 8, the pilot symbols are applied within a subframe. Intermittent RBs are assigned with common reference signals to estimate the transmit frequency resource. In downlink, the reference signals are regularly and continuously being broadcasted so that all UEs in the cell are able to estimate the corresponding channel quality. However, the uplink estimation requires dedicated reference signals transmit to BSs. In terms of multi-cell channel estimation, the unknown reference signals suffer from interference leading to estimation error. Basically, joint transmission (coherent JT) is the most challenging one among all CoMP schemes since its performance is most sensitive to precoding accuracy.

As mentioned above, the reference signal is the key to achieve the precise channel estimation and in another word, it is also a challenging to obtain a more accurate CSI and further to improve the performance of CoMP. Moreover, the link with low power of reference signal is hard to estimate so that the static clustering is more sensitive to the quality of channel estimation.

After estimate the channel at receiver, it has to feed back the CSI to transmitter. As mentioned throughout this paper, the accuracy of feedback CSI directly affects the performance of CoMP. It is also a challenge to enhance the feedback quality without massively increasing overhead.

3.3. CoMP in Rel-12 and beyond

Now the release 12 is being discussed by 3GPP and the eventual standardization will be probably completed by the end of June 2014. In June 2012 in Slovenia, 3GPP held a meeting with the leading operators and manufacturers to identify common requirements for release 12 and beyond. During the meeting, further work and future enhancements on existing CoMP is considered. As far as it is known, a big contribution about 3D-MIMO will pretty likely be made for the next release.

3.3.1. **Array antenna system**

The active array antenna system (AAS) has been proposed to be included in Rel-12. It contains various types of 3D-MIMO technologies fully utilizing radio resources. The three-dimensional beamforming (3D-BF) is one of the AAS's 3D-MIMO technologies and is able to significantly enhance the performance of CoMP. AAS takes the vertical dimension into MIMO which means BSs steer the beams in not only horizontal but also vertical domains. For CoMP schemes like joint processing, the traffic load of a cell easily reaches a high level since multiple points simultaneously serve a specific UE. As ASS expands the capacity of the cell due to the full utilization of spatial domain, JP will be more flexible to be applied in high-density cells. Furthermore, the inner-cell interference is mitigated since the spatial distance between beams employing same RBs is even larger. Therefore, the SINR for a single link is improved and consequently the UE experiences smoother quality of service when moving in cell edge.

3.3.2. **CoMP in HetNet**

CoMP and HetNet are two promising technologies and standardized by 3GPP in Rel-11. However, in the HetNet deployments in Rel-11, only macro-cell BSs and RRHs are considered to apply coordination with each other in a CoMP cluster. In Rel-12, it is possible to install CoMP between macro cell and small cell. Consequently, both macro cell and small cell are able to fully utilize the radio resource and co-channel interference occurred between macro cells and small cells can be mitigated with the deployment of CoMP. The conventional schemes of CoMP like JP, DCS, and CS/CB and so on still work under this case. This thesis does a bunch of simulation work on analyzing the performance of CoMP between small cell and macro cell and studying improvements in the scenario of a heterogeneous network.

3.3.3. **Other Areas for Rel-12 improving CoMP**

Some features that would have been improved in next release seem to indirectly improve the performance of CoMP. For instance, there is an outstanding enhancement for CSI feedback from Rel-11 to Rel-12. As the challenging section has described, the accuracy of CSI feedback is a crucial aspect affecting the performance of CoMP. Other features like backhaul enhancement, frequency separation between macro and small cells, interference management improvement and so on further enhance the role of CoMP.

4. PERFORMANCE STUDY

In this chapter, we study and evaluate the performance of coordinated multipoint between macro cell and small cell in a HetNet deployment scenario. First, the deployment scenario and the interference situation between macro and small cells are briefly presented. Then the system parameters and models used in the simulation are described well. Finally, observation and analysis are made for the attained results.

4.1. Deployment and Interference Scenario

4.1.1. Deployment scenario

The general network's layout of the deployment scenario is depicted in Figure 10.

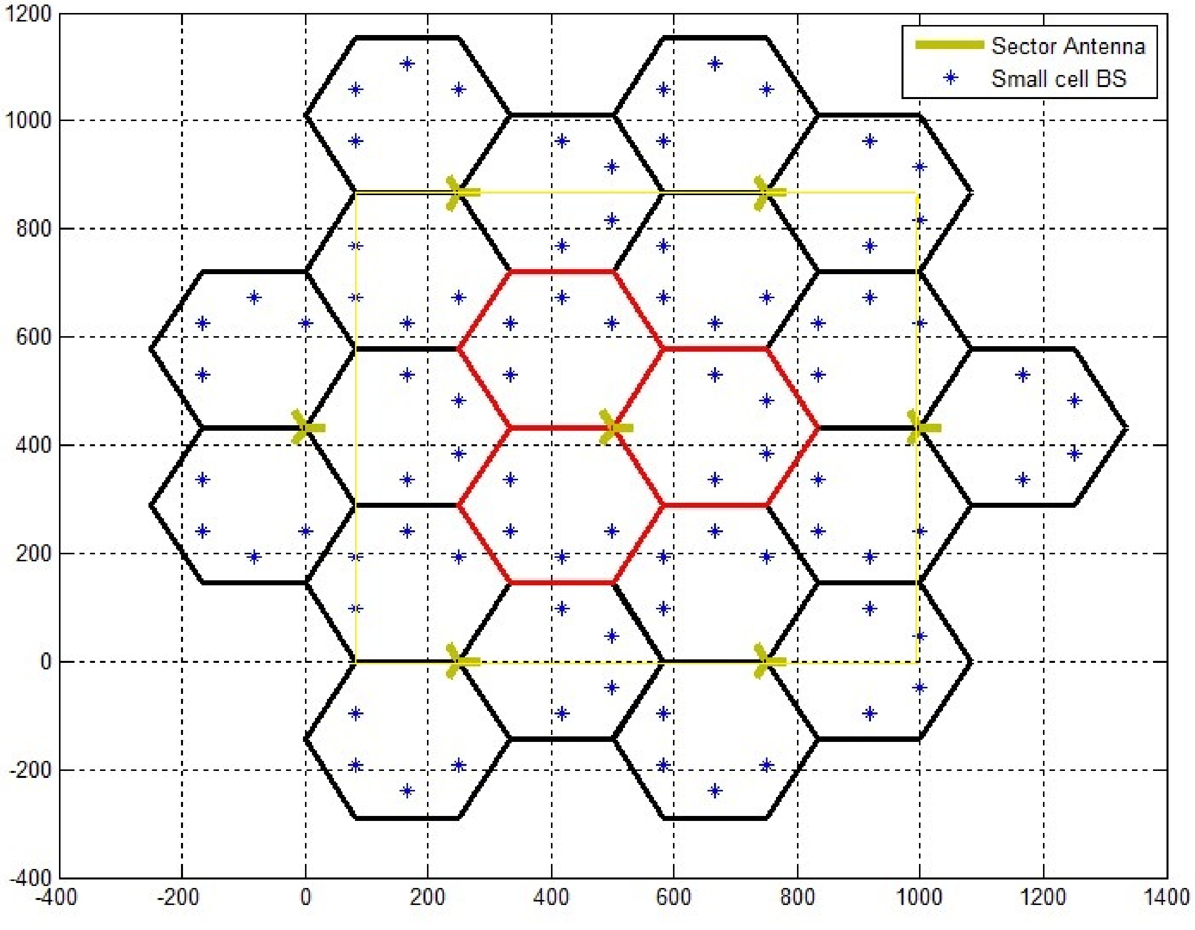

Figure 10: Deployed Network layout

The HetNet deployed scenario is based on the 7 site 21 cell network layout where each cell consists of 4 small cells. An urban scenario with a 500 meters inter-site distance is assumed

(Note that the radius of the circumcircle of a hexagon is about 167 meters.). The small cells are assumed to attain fixed locations or distributed uniformly around the cell edge area of the macro cells. The former may represent a well-planned small cell deployment by operators and the latter one for random small cell deployment by end users. Figure 8 shows only the deterministically deployed small cells that are shown with the '*' sign. They are located around $\sqrt{3}R/6$ meters away from the hexagons' edges so that the distance between any neighboring two small cells is around $\sqrt{3}R/3$ meters. The randomly deployed small cells are also considered in the study.

The performance analysis is made for users associated with the three cells around the central macro site. This makes the simulation results accurate as all the interference from neighboring macro and small cells can be considered. The UEs are needed to be generated for different cells. First of all, a fixed number of common UEs are distributed uniformly in the macro area which is surrounded by the solid yellow lines as depicted in Figure 10. Furthermore, for each small cell, another amount of UEs are uniformly distributed within coverage of each base station of small cell.

4.1.2. **Interference**

Full frequency reuse in both the macro and small cells is assumed and full-buffer traffic is assumed from the nodes. This leads to an interference situation where interference exists among macro cells, among small cells and between macro and small cells. For instance, a user associated with one of the central macro cell experiences interference from the other 20 macro cells and 84 small cells or a user associated with one of the small cells around the central macro site experiences interference from the other 21 macro cells and 83 small cells in the absence of CoMP. The interference from the neighboring small cells in the former case and the interference from closest macro cell in the latter one have considerable negative impact in the performance of the users.

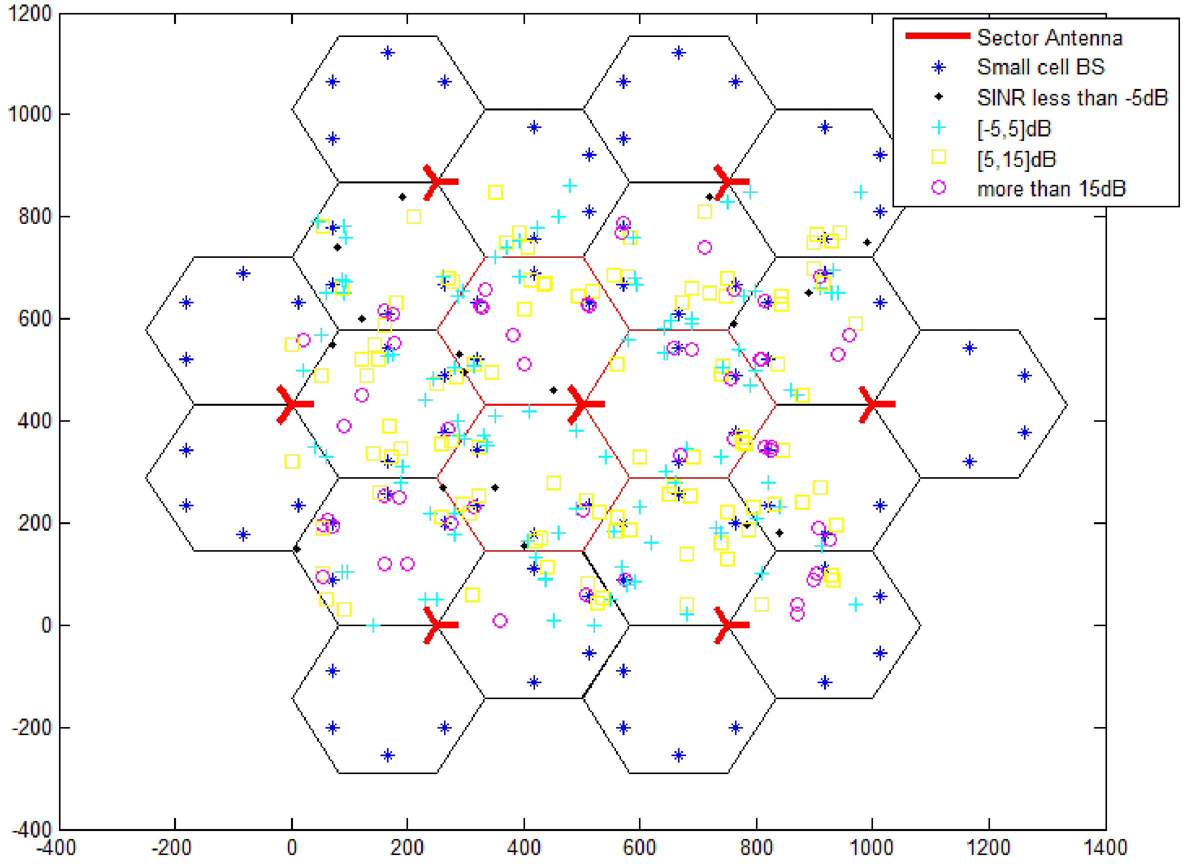

Figure 11: Network without applying CoMP

The SINR performance in some random locations is shown in figure 11. Some locations clearly show a poor performance of SINR less than 5 dB mostly including those highly interfered by the closest small cells if associated with a macro cell or by the closest macro cell if served by small cells. To manage these problems, CoMP can be applied between macro and small cells so that a better performance is achieved.

4.2. CoMP Schemes and Selection criteria

4.2.1. **CoMP UE Selection Criteria**

Table 1: Conditions for criterion I

$\lvert P_{rx1} - P_{rx2} \rvert <$ Rx Power Threshold
P_{rx1}: The strongest Rx power of signal from macro cell.
P_{rx2}: The strongest Rx power of signal from small cell.

Two kinds of criterion is defined and used in simulation. The first criterion is the same as the conventional CoMP UE selection criterion. Then former is modified on the top of first one.

- **Selection Criterion I:** The condition to identify whether a UE applies CoMP or not is shown in table 1. According to the conventional CoMP scheme, the victim UE which is meant to apply CoMP is identified based on the difference of power of received signal and interference. A received power threshold is defined as a condition to trigger CoMP. Assume the largest and the second largest received power of signals are separately are separately transmitted from small and macro cells. And when its power difference is within the threshold, then that specific UE is regarded as a victim UE needing to apply CoMP. Later in the first simulation result, the throughput gain of CoMP is not that significant due to our particular deployment scenario and the applied modified round-robin scheduling algorithm. Then the selection criterion is improved to achieve more cell edge gain of UEs as the selection criterion II below.

Table 2: Conditions for criterion II

$P_{rx1} - P_{rx2}$< Rx Power Threshold
$P_{rx1} > P_{rx2}$
P_{rx1}: The strongest Rx power of signal from macro cell.
P_{rx2}: The strongest Rx power of signal from small cell.

- **Selection Criterion II:** Compare the conditions in table 2 and table 1, a new identifying condition is added. It ensures only UE which is originally served by macro-cell BS in a non-CoMP case is allowed to apply CoMP. Because as larger number of UE served by macro-cell BS and both macro and small cell has the same frequency band, the number of assigned resource blocks to small-cell UE is much more than macro-cell UE. Consequently, if the small-cell UE goes ahead to apply CoMP, less number of RBs is allocated. Although, the SINR of its received signal will be significantly enhanced, the throughput gain will not be significant. On the contrary in terms of macro UE, due to our applied modified round-robin algorithm in 4.3.2, the bandwidth of CoMP UE is the same as that of macro-cell UE, the improved SINR by CoMP directly brings the same level of improvement on throughput.

Both of the two criteria are tested in simulation and the reason behind the second criteria will be justified further in this thesis.

4.2.2. CoMP Schemes Selection

In our simulation, two types of CoMP schemes are applied to make a comparison with the non-CoMP outcome. One is a hybrid scheme of dynamic point selection (DPS) and dynamic point blanking (DPB) and another one is quantized co-phasing which can be a sort of joint processing scheme.

A) DPS/DPB

DPS has already been introduced in section 3.1.1.1. A CoMP victim UE is served by BS depending on its received signals' real time power instead of average power. However, DPB selects BS with the highest average received power. Through coordinated scheduling, it enhances SINR by blanking the same resource blocks of cooperating cell which is underlying to cause the strongest inter-cell interference.

DPB is usually employed in conjunction with DPS that both the serving point and blanked points are selected dynamically. After a UE is identified as a victim UE, the BS sending the highest power of signal is set to be the transmitter and the BS with second highest power of signal will blank that resource blocks at the same time.

B) Quantized Co-phasing

The limited feedback precoding is standardized in LTE. Quantized Co-phasing is such a codebook-based feedback scheme. It adjusts phase differences between the signals from different antennae with respect to a reference antenna. In this simulation, both BS and UE have two transmitting and receiving antennae. Therefore a UE is able to receive two signals at the same time. One is regarded as the reference signal and the other one's phase is adjusted depending on the feedback words and codebook and against the phase of the reference one to obtain the maximum power of combined signal. The feedback word consists of information on the state of each relative phase between the reference antenna and all the other antennae. Feedback bits are determined independently. A generalization utilizing Nrp feedback bits per relative phase is given by

$$\left|h_1 + \hat{v}_m h_m\right| = \max\left\{\left|h_1 + v_m h_m\right| : v_m = e^{j2\pi n/2^{Nrp}}\right\} \quad [21]$$

4.3. Description of system model and simulation parameters

Table 3 lists the key parameters used for the simulation work and all parameters follow the latest parameter settings agreed in 3GPP [23]. The models related with propagation environments and CoMP schemes are presented below. All these parameters are for a general case. Later some other deployment scenarios are assumed and some of parameters are altered aiming to research the performance of CoMP under other environments.

Table 3: Simulation Parameters

Parameters	Values
Macro cell	3 sectors/macro site; 4 small cells/macro cell; 50 resource blocks/sectors; antenna height 32 meters.
UE	Around 10 macro area UEs; 4 UEs/small cell; antenna height 1.5 meters.
Pathloss/ Shawdow Fading/ Fast Fading	2 GHz, 500m (Inter-site distance)ISD, 10 MHz Bandwidth(BW), 8dB standard deviation for macro link, 4dB standard deviation for small cell link, Macro/Small cell path loss propagation model, Rayleigh fading model, Racian fading model
CoMP Rx Power Threshold	10dB
Feedback	4 bits codebook feedback
Antenna	2Rx at UE
Direction of sectors’ antenna	0, 120, 240
Scheduling	Modified Round-robin

4.3.1. **Path loss, Shadow Fading and Fast Fading**

In simulation, path loss, shadow fading and fast fading is considered as the three major components.

Path loss is the reduction in power attenuation of an electromagnetic wave as it propagates through space. Macro path loss ($L_{p,M}$) model and small cell path loss model ($L_{p,S}$) separately employ the following models:

$L_{p,M}(dB) = 128.1 + 37.6\log(d/km)$ [24]

$L_{p,S}(dB) = 140.1 + 36.7\log(d/km)$ [25],

where L is the path loss in decibels. The path loss exponent is 3.76/3.67 while d is the distance between UE and BS in kilometers. It causes 128.1/140.1dB path loss at the distance of 1km separately for macro cell and small cell links.

On top of the average pathloss, both shadow and fast fading are considered. The log-normal shadow fading with 4dB standard deviation and 8dB standard deviation are considered as models for small cell and macro cell links. The probability of the shadowing component L_S obeys a zero-mean Gaussian distribution with standard deviation σ_L:

$$p(L_S) = \frac{1}{\sigma_L\sqrt{2\pi}} e^{-\frac{L_S^2}{2\sigma_L^2}}$$

Finally, the fast fading models employed for macro cell and small cell are distinct in simulation. For macro cell, Rayleigh fading model is chosen to describe the effect of a propagation wireless environment on a radio signal. The magnitude and phase of received signal passing through wireless channel vary randomly obeying the Rayleigh distribution. The way to generate the channel:

$h = x + jy \qquad x, y \sim rand(0,1)$

If a UE is served by small cell, it must be not far away from serving cell. Therefore there is not much effect of multipath propagation and more likely to have a dominant signal. For the case of small cell, Racian fading model is employed to take fast fading of small cell into account. The channel is generated by:

$$h = \frac{1}{\sqrt{2(k+1)}} x + j\left(\frac{1}{\sqrt{2(k+1)}} y + \sqrt{\frac{k}{k+1}}\right) \qquad x, y \sim rand(0,1)$$

In conclusion, the overall link loss including fading becomes

$$L(dB) = L_p(dB) + L_S(dB) + 10\log|h|^2$$

4.3.2. **Scheduling**

As all macro and small cells have different cell IDs, each cell schedules individually. In the simulation, a modified round-robin scheduling algorithm which is given in table 4 is deployed.

Table 4: Modified Round Robin Scheduling

$$BW_{CoMP} = BW_{Macro} = \left\lfloor \frac{50}{N_{CoMP} + N_{Macro,NonCoMP}} \right\rfloor \cdot BW_{RB}$$

$$BW_{Scell} = \left\lfloor \frac{50 - N_{scell,CoMP} * BW_{CoMP}}{N_{Scell,NonCoMP}} \right\rfloor \cdot BW_{RB}$$

N_{CoMP}: Number of CoMP UEs for a macro cell.

$N_{Macro,NonCoMP}$: Number of Non-CoMP UE served by macro cell.

$N_{scell,CoMP}$/ $N_{Scell,NonCoMP}$: Number of CoMP/Non-CoMP UEs for a small cell.

BW_{CoMP}/ BW_{Macro}/ BW_{Scell}: Bandwidth of CoMP/Macro-cell/Small-cell UE.

BW_{RB}: Bandwidth per resource block (180kHz).

Different from the common round-robin scheduling in conventional wireless packet radio network, in HetNet, three kinds of UEs exist: macro-cell UE, small-cell UE and CoMP UE. Therefore, the radio resource of macro cell is divided by macro-cell UEs and CoMP UEs while that of small cell is divided by small-cell UEs and CoMP UEs. As CoMP UEs are allocated with equal portions of frequency band from macro and small cells and the number of macro-cell UE and small-cell UE is not identical, the common scheduling algorithm does not work in our case. In the simulation, a modified round-robin algorithm is proposed in table 4 to adapt to the situation of HetNet. That is CoMP UE and macro-cell UE is allocated with the same number of resource blocks. Eventually, the small-cell UEs in the same small cell divide the remaining resource blocks.

4.3.3. **Throughput calculation**

Reference [5] proposes a modification to Shannon capacity bound. An adjusted Shannon capacity formula (3) is raised where the system bandwidth efficiency and the SINR efficiency of LTE are taken into account [5].

$$S(bits/s/Hz) = BW_{eff} \cdot \gamma \cdot \log_2(1 + SINR/SINR_{eff}) \quad (3) \quad [5]$$

The factor γ denotes the correction factor and here is set to be one. BW_{eff} stands for the system bandwidth efficiency and $SINR_{eff}$ implies the SINR implementation efficiency of LTE. Due to filters, cyclic prefix, pilot overhead and some other control channels, the approximate bandwidth efficiency is about 0.83. Corresponding to the simulation and fitting results for an AWGN channel also shown in paper [5], the SINR efficiency is estimated with the value of bandwidth efficiency. When BW_{eff} is equal to 0.83, $SINR_{eff} = 1.6dB$ seems to best fit the link adaptation curve for LTE. In order to calculate the throughput for a specific UE with the bandwidth BW_i, according to (3) the eventual formula is:

$$T(bits/s) = BW_i \cdot S(i) \qquad (4)$$

4.4. Simulation results and discussion on the results

Simulations with different scenarios are tried and the corresponding results are analyzed as well. The first simulation is about the general deployment scenario. After that, parameters or selection criterion is altered to study the CoMP performance under different situation.

4.4.1. **Evaluation with different Received power (P_{rx}) threshold (Criterion I)**

Here the first CoMP UE selection criterion is used as defined in section 4.2.2. The received power threshold is set to be 3, 6 and 10 dB to observe the difference it leads to the performance. Roughly parameters are listed below.

Table 5: Parameters Assumptions for testing impact of Rx power threshold

Rx Power Threshold	[3 6 10]dB
Small cell UE	Generated within 25m of each small cell
UE per small cell	4
Small cell per macro cell	4 (Fixed)
Selection Criterion	I

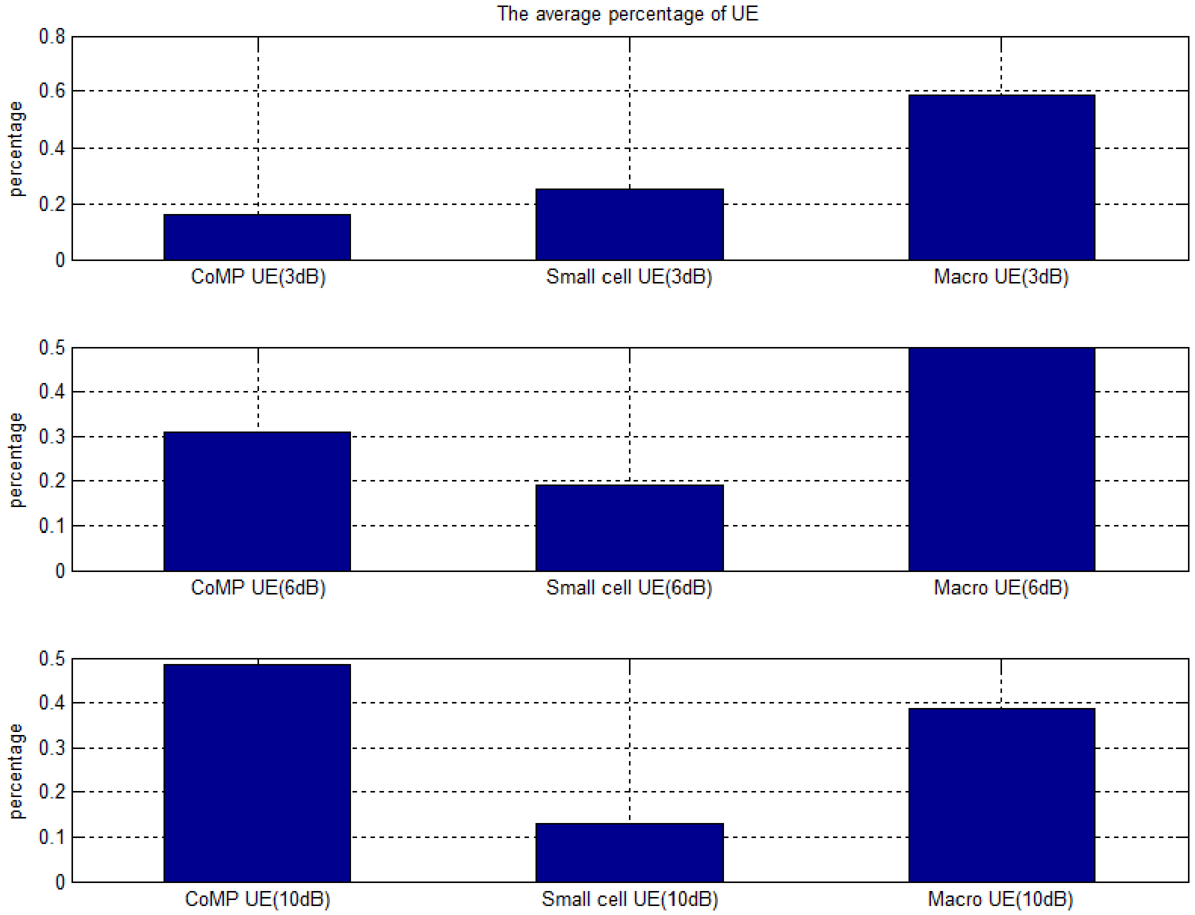

Figure 12: Average percentage of different types of UE

In order to check the status of UEs in network, the percentage of UE served by the center macro site is shown in figure 12. A larger received power threshold brings more UEs applying CoMP and both UEs served by small cell or macro cell are fewer when the received power threshold is growing. When the threshold is 10 dB, the percentage of CoMP UE almost reaches 50%. Then a doubt is raised here. Are more CoMP UEs meant to bring about better performance or gain in SINR?

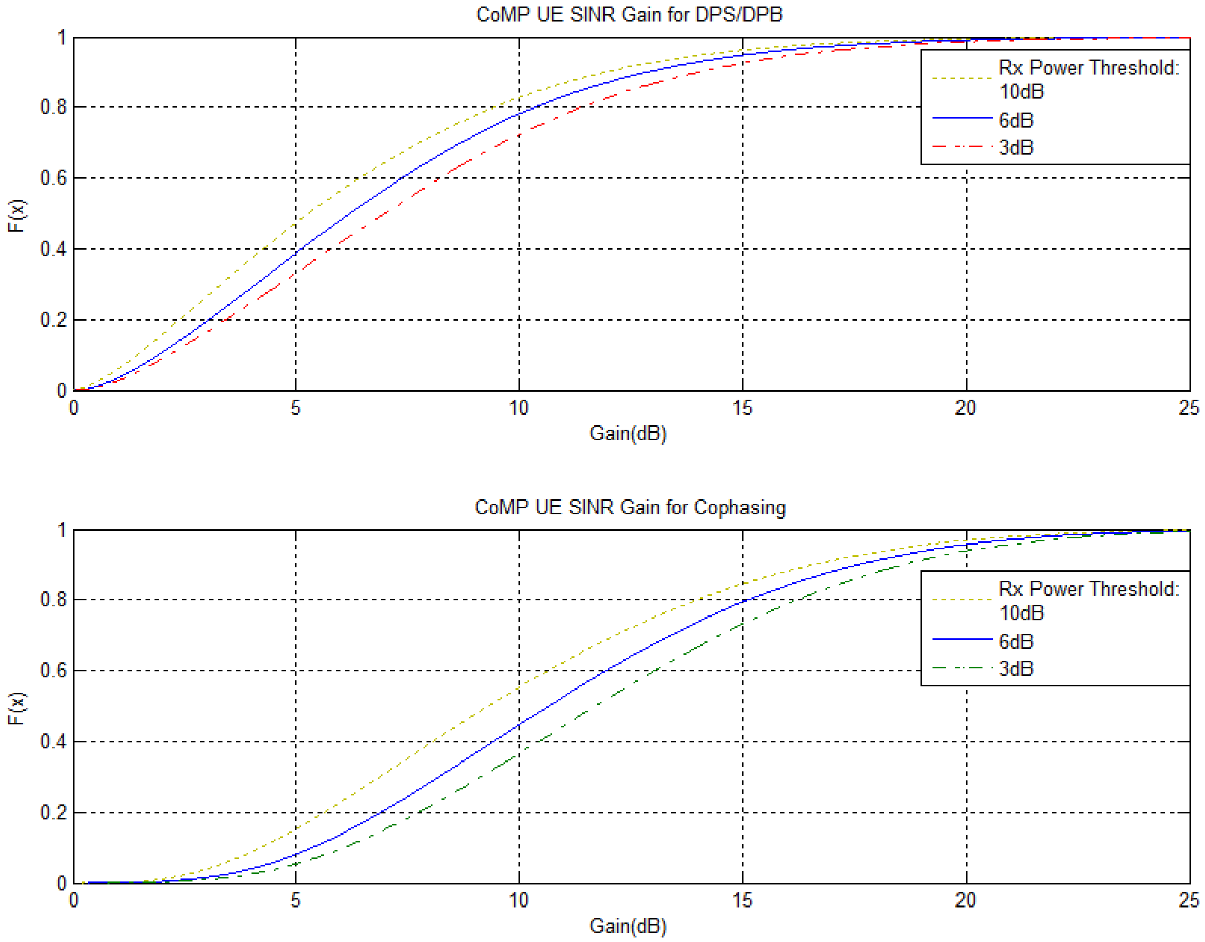

Figure 13: CoMP UE SINR Gain with different Rx power threshold

In figure 13, the SINR gains of CoMP UE with different thresholds are separately displayed for DPS/DPB and QCP to solve that doubt. Apparently smaller value of threshold leads to a larger SINR gain for CoMP UEs [22]. The reason behind it is that lower threshold ensures power difference between the strongest two received signals is less. In a non-CoMP case, the second strongest signal being the dominant interference heavily drops down the SINR. In that case, when a relatively high level of interference is turned to be useful signal, the SINR gain must be extremely high. Conversely, when the threshold is 10 dB, some proportion of UE has a large gap of received power between the strongest and second strongest signals. Therefore, its average SINR gain is naturally lower than that brought by 3 dB received power threshold. Probably, when load of the network is high, degrading the received power threshold will be a good strategy to retain the improvement of CoMP on cell edge UEs. In this case, fewer resources are consumed by CoMP and SINR gain per resource blocks is more or less increased. Overall, larger threshold and more CoMP UEs does not always boost the performance of CoMP. Additionally, in figure 13, the CDF plot shows SINR gain of QCP(Quantized Co-phasing) is higher than that of DPS/DPB. Then to verify this viewpoint, the CDF plot about CoMP UE SINR with 10dB received power threshold is drawn in figure 14.

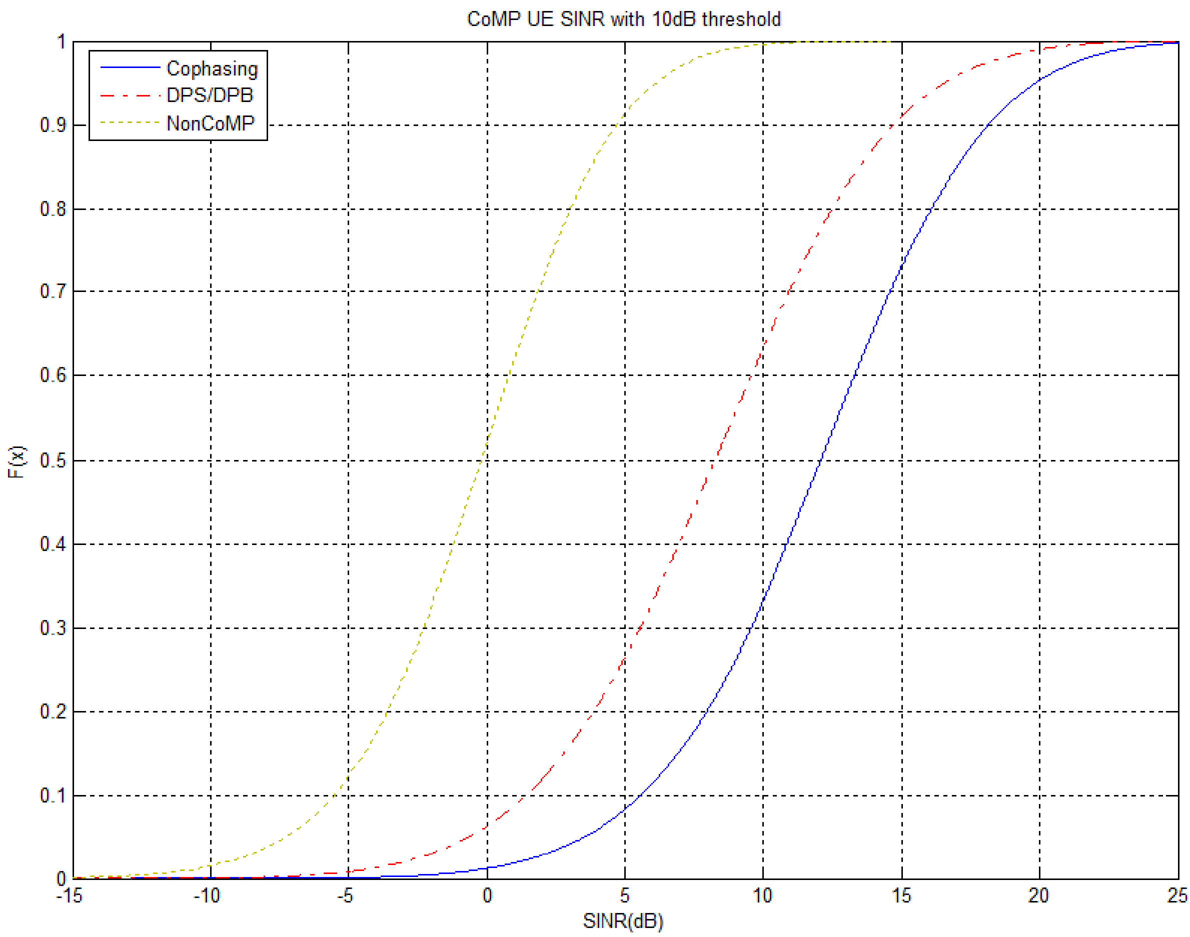

Figure 14: CoMP UEs' SINR for different CoMP schemes

Figure 14 displays the SINR of CoMP UE for different CoMP schemes. System deploying quantized co-phasing has higher SINR if UEs than system deploying DPS/DPB. Theoretically because QCP has the same level of interference as DPS/DPB while the received power of QCP's is stronger. Additionally, the maximum SINR for a single CoMP UE can even reach over 20 dB which will be a huge improvement. Since CoMP UEs applying either QCP or DPS/DPB achieve high SINR gain, we wonder whether there is such a huge gain from the perspective of the whole network or not.

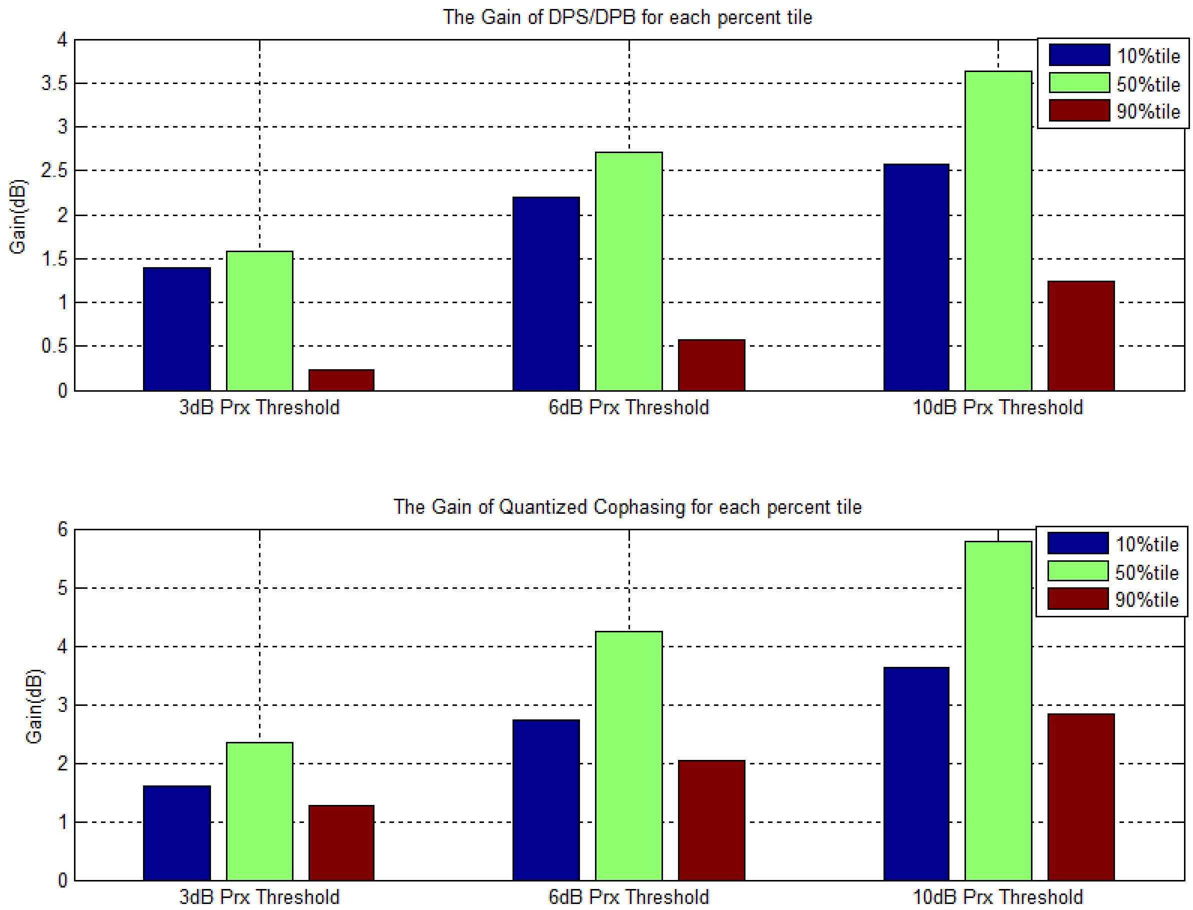

Figure 15: System SINR Gain(dB) under the first selection criterion

Figure 15 shows the SINR gain of whole system separately for DPS/DPB and quantized co-phasing. 10% tile represents cell edge UEs while 50% tile stands for average. Obviously, a larger received power threshold does not improve UEs with low SINR too much however more SINR gain is achieved by 50% tile UEs who already have a good channel condition. Then it is important to see how much throughput gain is able to achieve instead of SINR gain.

The throughput gain results are shown in figure 16. The throughput gain brought by DPS/DPB is from 8% to 11% which is not significant while throughput gain of QCP is from 14% to 34%. Despite of big improvement on SINR, the throughput gain sometimes is not significant. That's probably due to the CoMP UEs who originally served by small cells in non-CoMP case. Basically in a small cell, there are fewer served UEs and each UE has more resource blocks to use than both CoMP UE and macro-serving UE. After that sort of UEs turn to apply CoMP, owing to restricted number of resource blocks shared by macro-serving UEs and CoMP UEs, their corresponding throughputs are possible to decline with applying fewer number of resource blocks. Then we consider modifying the CoMP UE selection criterion to make the CoMP selection in favor of RBs allocation and be more efficient from the perspective of system throughput.

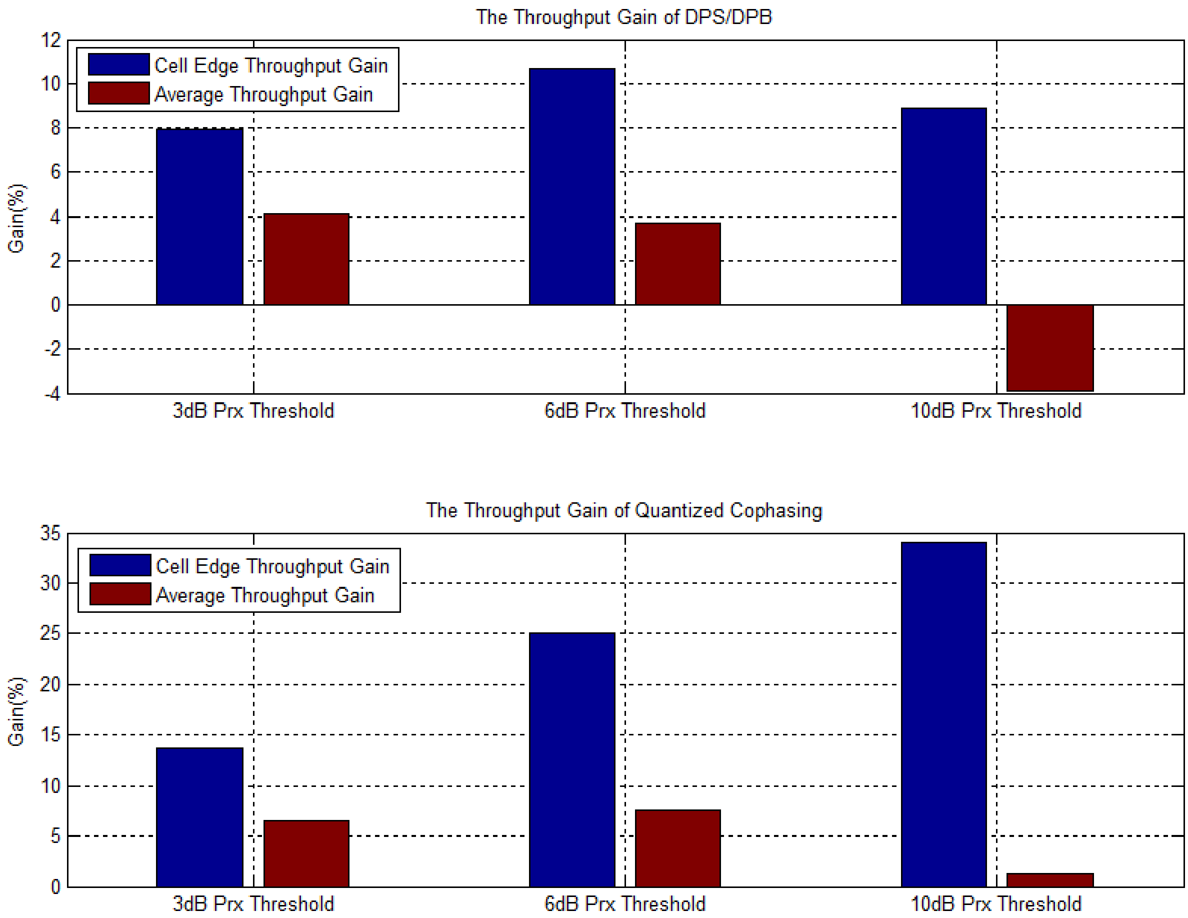

Figure 16: Throughput gain under the first selection criterion

4.4.2.**Evaluation with the second selection criterion**

As larger proportion of CoMP gain is achieved by UE with good quality of service, it does not profit the system overall throughput. In order to improve only the low SINR UEs at the cell edge, a modified UE selection criterion is designed. The second CoMP UE selection criterion which is introduced in section 4.3.1 is tried.

Table 6: Parameters Assumptions for testing the second selection criterion

Rx power Threshold	[3 6 10]Db
Small cell UE	Generated within 25m of each small cell
UE per small cell	4
Small cell per macro cell	4
Selection Criterion	II

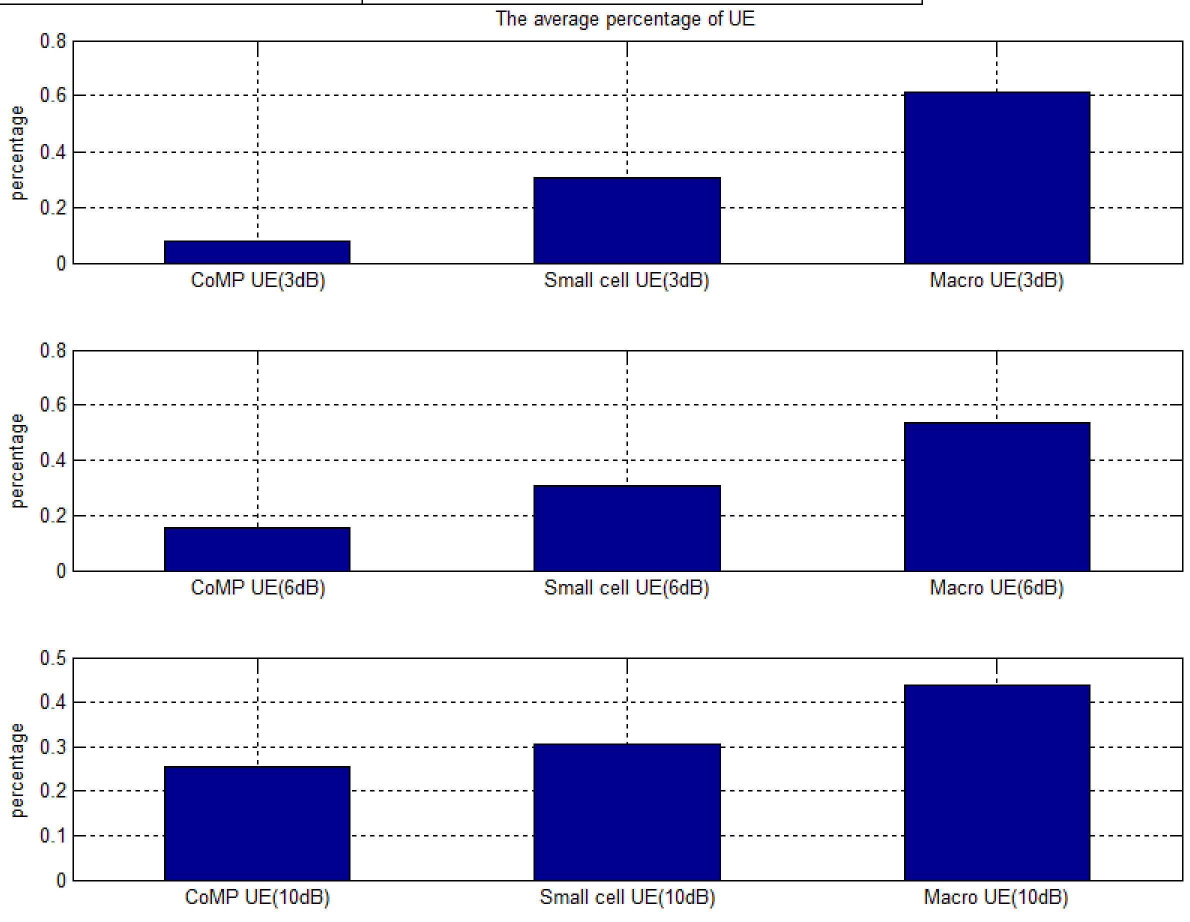

Figure 17: The percentage of different types of UEs under the second selection criterion

Table 6 lists the core parameters about the simulation for this section. As the unsatisfactory outcome from previous simulation, we try the second selection criterion here and all other assumed parameters remain the same.

In figure 17, compared with figure 16, apparently less proportion of UEs applies CoMP with the new selection criterion. That's because the UEs who meet the condition of received power difference and served by small cell are excluded this time. However, there is still over 20% CoMP UE which is not less when the received power threshold is 10dB. As the percentage of CoMP UEs declines, we speculate that maybe the SINR gain of the whole system degrades too.

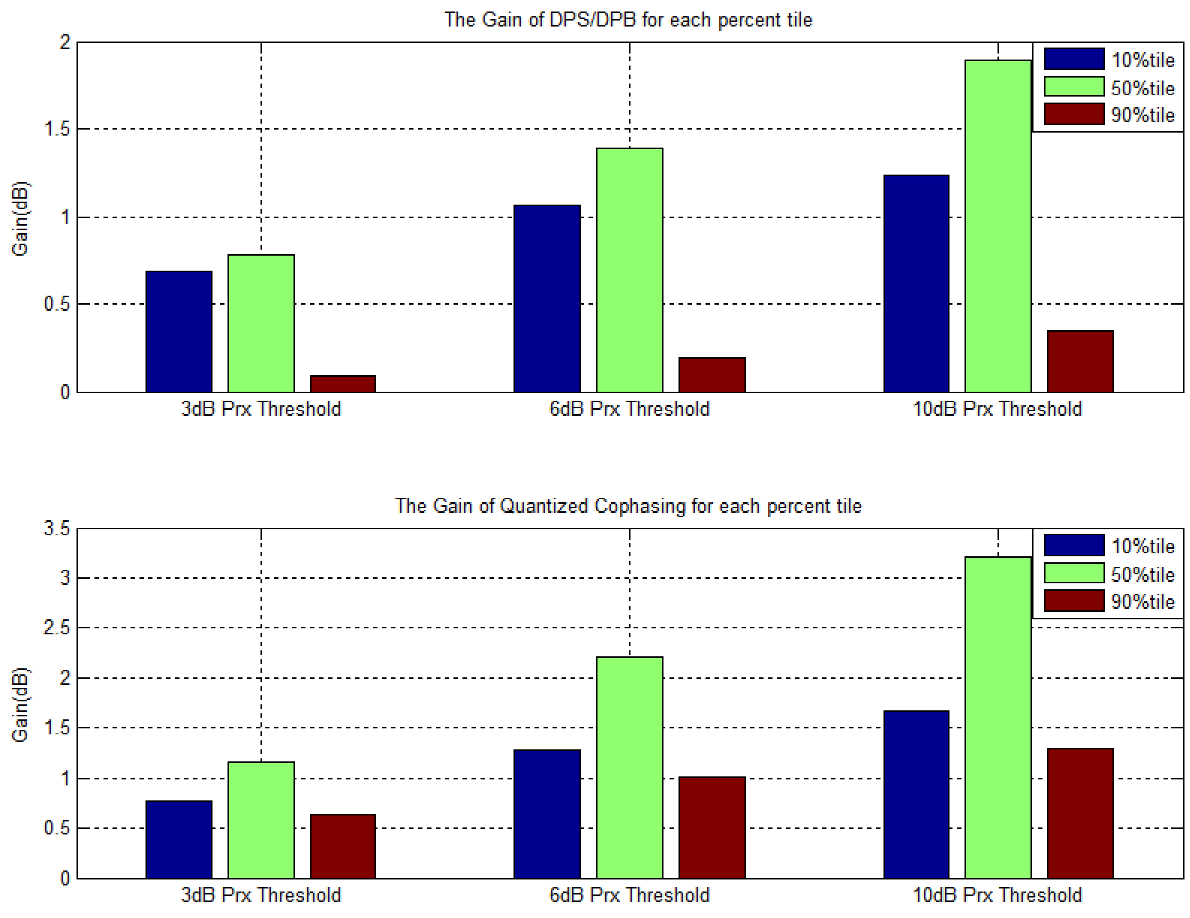

Figure 18: System SINR Gain under the second selection criterion

The bar figure 18 displays the SINR gain brought by CoMP with the second selection criterion. If compared with the SINR gain from previous simulation work, the SINR gain declines. However, our eventual goal is to have more gain in throughput which directly concerns to QoS rather than SINR. Thus, whether this new criterion works or not depends on the outcome about throughput gain.

Figure 19 verifies that the second selection criterion helps to obtain more significant cell-edge throughput gain. The cell edge gain of QCP under 10dB received power threshold reaches over 70% while the first selection criterion offers less than 35% throughput gain which means the gain is almost doubled. Although there is no enhancement on average throughput and even in some cases there is a negative gain, actually CoMP is such a technique that it is a tradeoff between high and low throughput UEs. It sacrifices some RBs from high-throughput UEs to benefit the cell edge UEs.

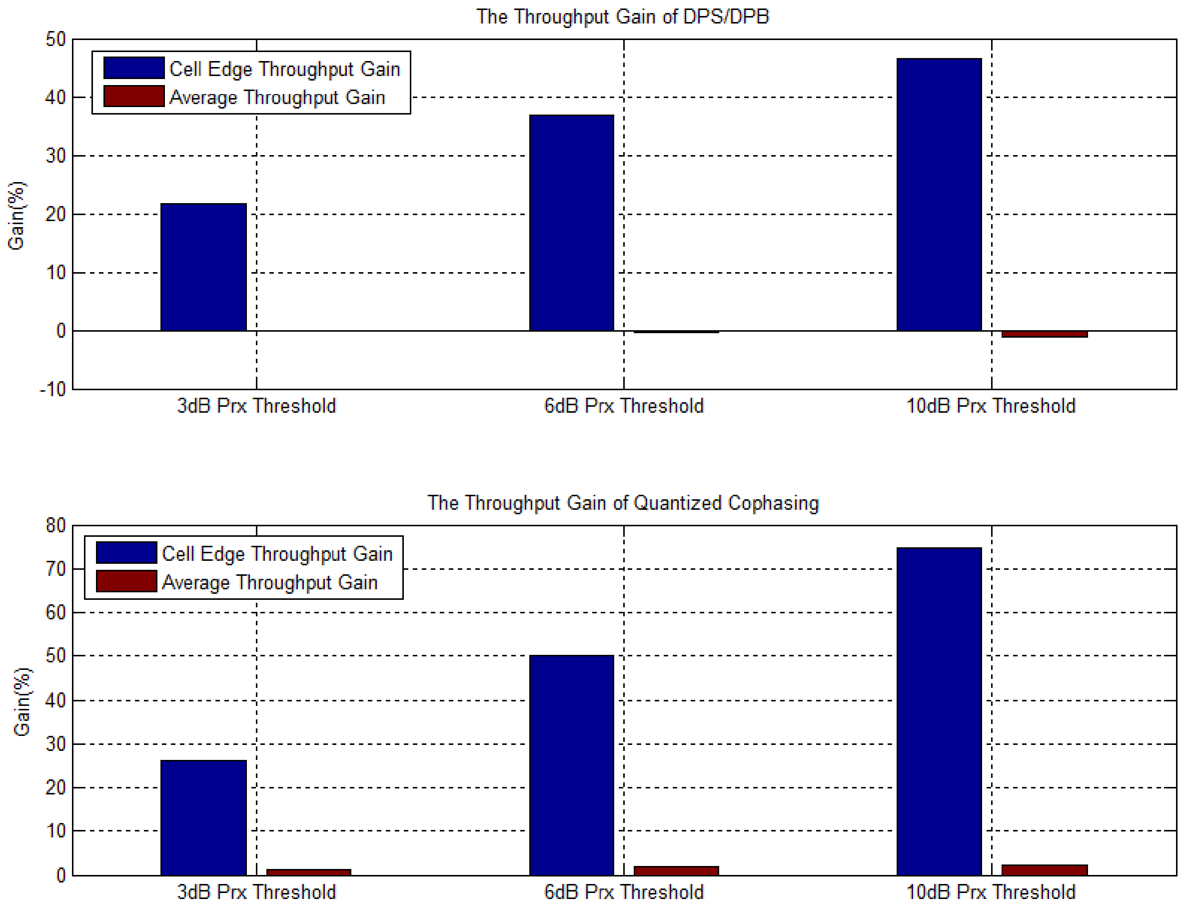

Figure 19: Throughput gain under the second selection criterion

Figure 20 depicts the UEs' throughputs with 10 dB CoMP threshold for different schemes. If we observe the range of CDF plot below 0.1 or 0.2 which stands for the cell-edge users, the improvement on throughput is quite significant. Actually almost 70% users benefit from CoMP and quantized co-phasing brings about double more throughput gains than DPS/DPB.

Therefore, we can conclude that the second selection criterion leads to overwhelmingly larger throughput gain and it will be deployed as the only criterion in the latter simulation for any other cases.

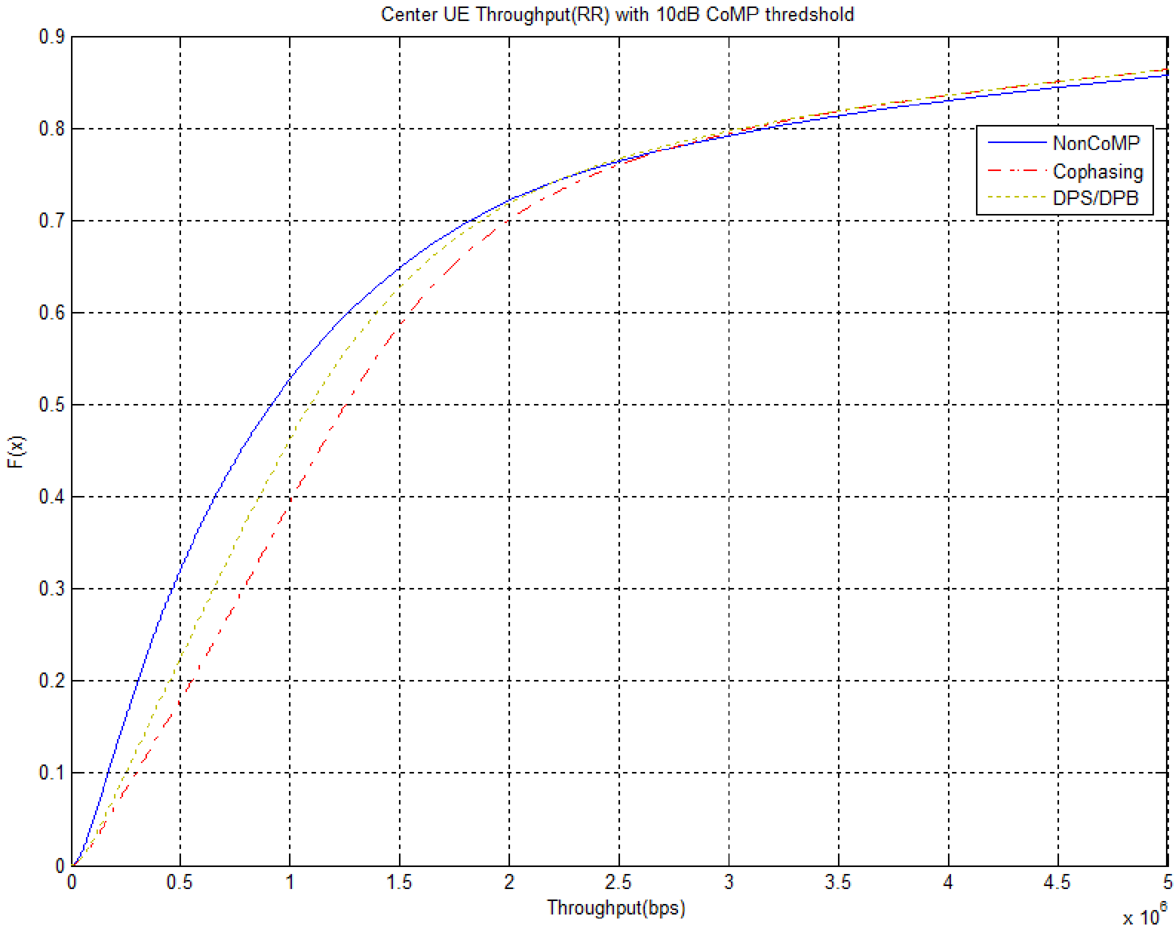

Figure 20: CDF plot for UE throughput with 10dB Rx power threshold

4.4.3. **Evaluation with different density of UEs in small cell**

Table 7: Parameters Assumptions of different UE density in small cell (diff number of UE)

Number of UE within 25 m of a small cell	[3 6 9]
Rx Power Threshold	10dB
Small cell UE	Generated within 25m of each small cell
Small cell per macro cell	4 (fixed)
CoMP UE Selection Criteria	II

In this subsection, the impact of small-cell UEs' density is evaluated by two methods. One is to increase the number of UE near a small cell while the other one is to fix the number of UE small-cell coverage but adjust the radius of the coverage. The former one is tested first and the corresponding core parameters are listed in table 7.

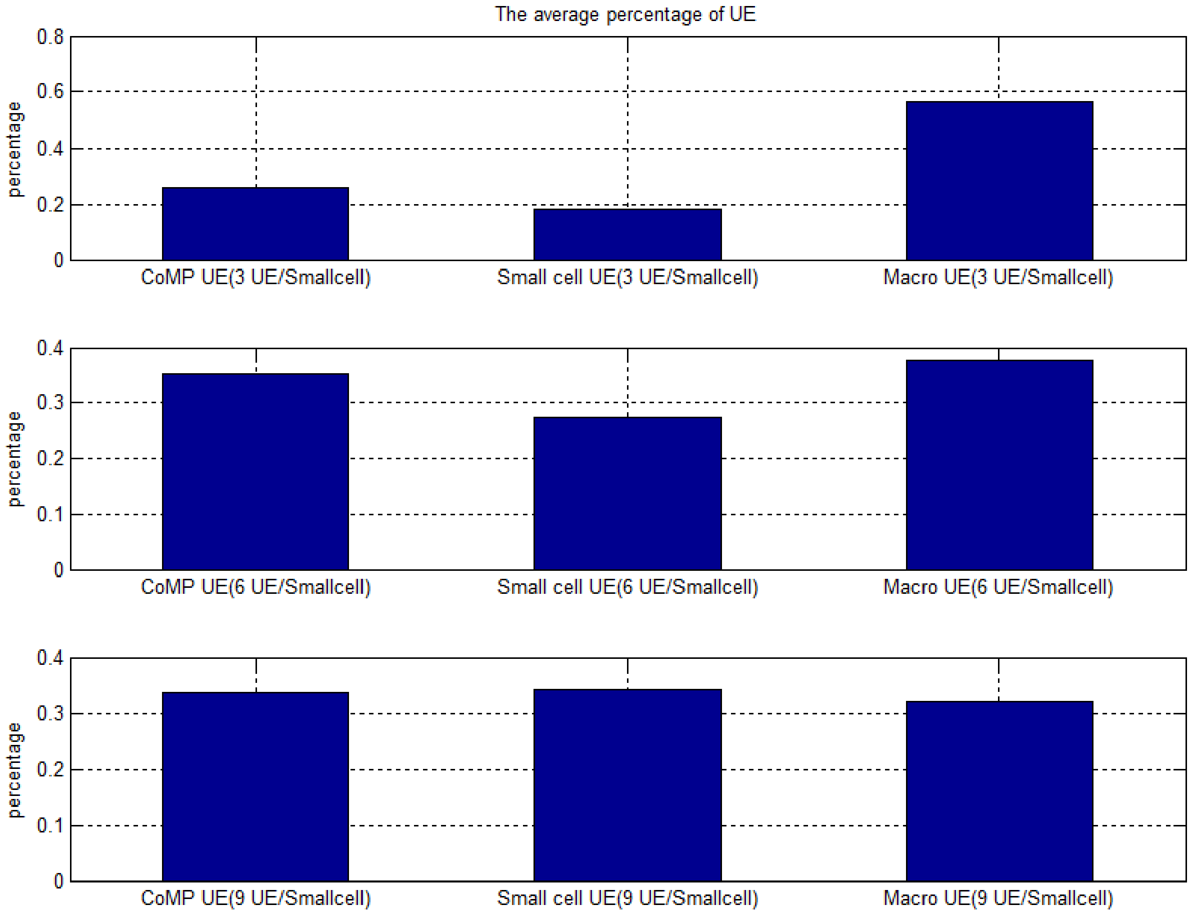

Figure 21: The percentage of different types of UEs (Small-cell UE density)

Because only UEs in the vicinity of small-cell BS are more likely to apply CoMP, the increasing number of UEs brings about more CoMP UEs. However, as UEs are uniformly distributed, the percentage of UEs meeting the selection condition will retain a stable value. Therefore, we can suppose that a higher UE density will fully benefit from CoMP and reach the state of convergence within the system capacity.

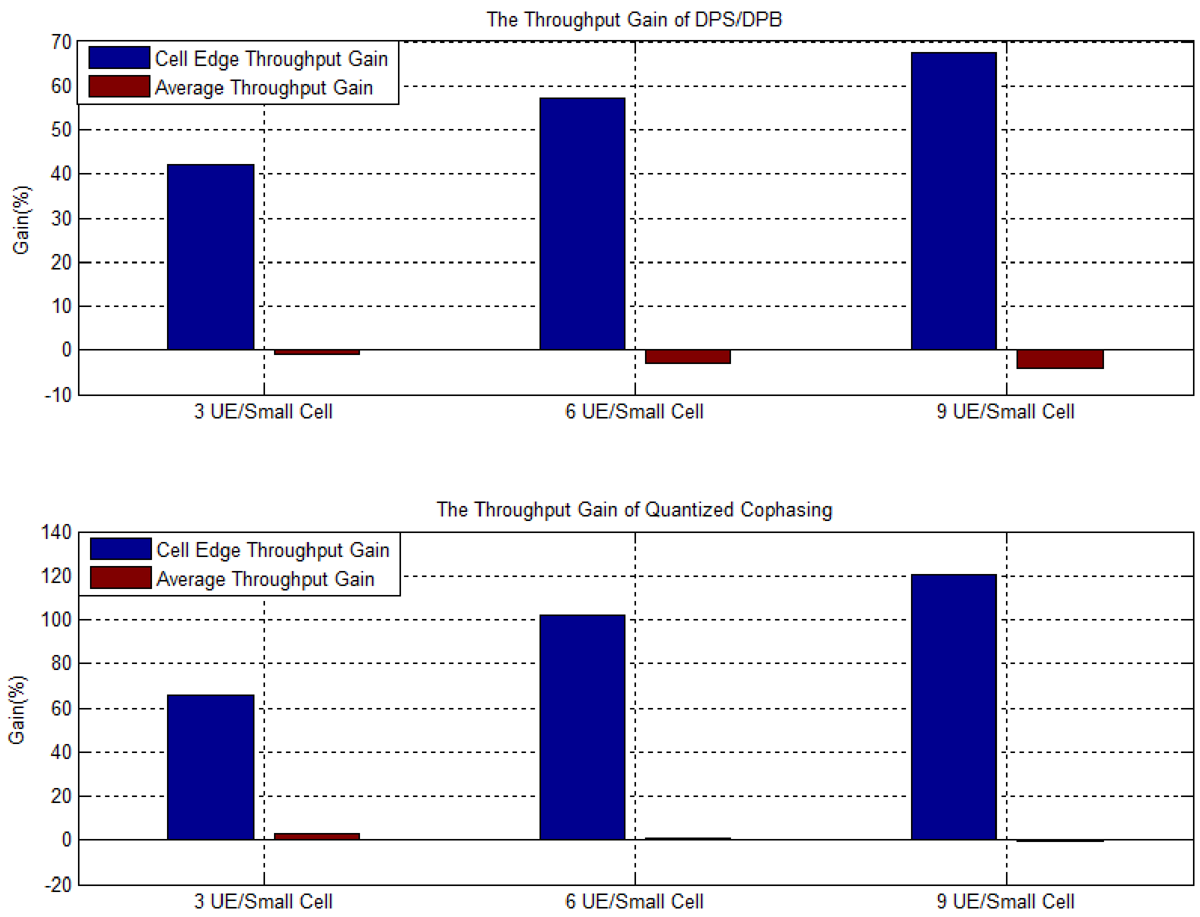

Figure 22: Throughput gain with different number of UEs near small cell

The throughput outcome in figure 22 verifies the previous hypothesis. Apparently larger number of UE near small cell leads to a higher cell-edge throughput gain. What's more, the enhancement of gain is not in proportion to the increment of number of UEs near small cells. Additionally, the system average throughput gain declines. The first reason is that it requires more additional RBs to support the increasing number of CoMP UEs. Then non-CoMP UEs served by small cells raises as well so that RBs are assigned to each small-cell UE proportionally drops. Thus, that group of high-throughput UEs obtains worse service with lower throughput and the average throughput goes down. In conclusion, if network has a high density of users for some specific area, especially when the area is located at macro-cell edge, operators are responsible to locate small cells there and with the help of CoMP, the throughput of cell edge user can be doubled.

Table 8: Parameters Assumptions for testing impact of small-cell UE generating radius

Small cell UE generating radius	[20 30 40]m
Rx Power Threshold	10dB
UE per small cell	4
Small cell per macro cell	4
CoMP UE Selection Criteria	II

The following content is about testing the impact of changeable small-cell UE generating radius and table 8 lists the corresponding key parameters. Assume the radius of small-cell UE distributed area is 20/30/40 m.

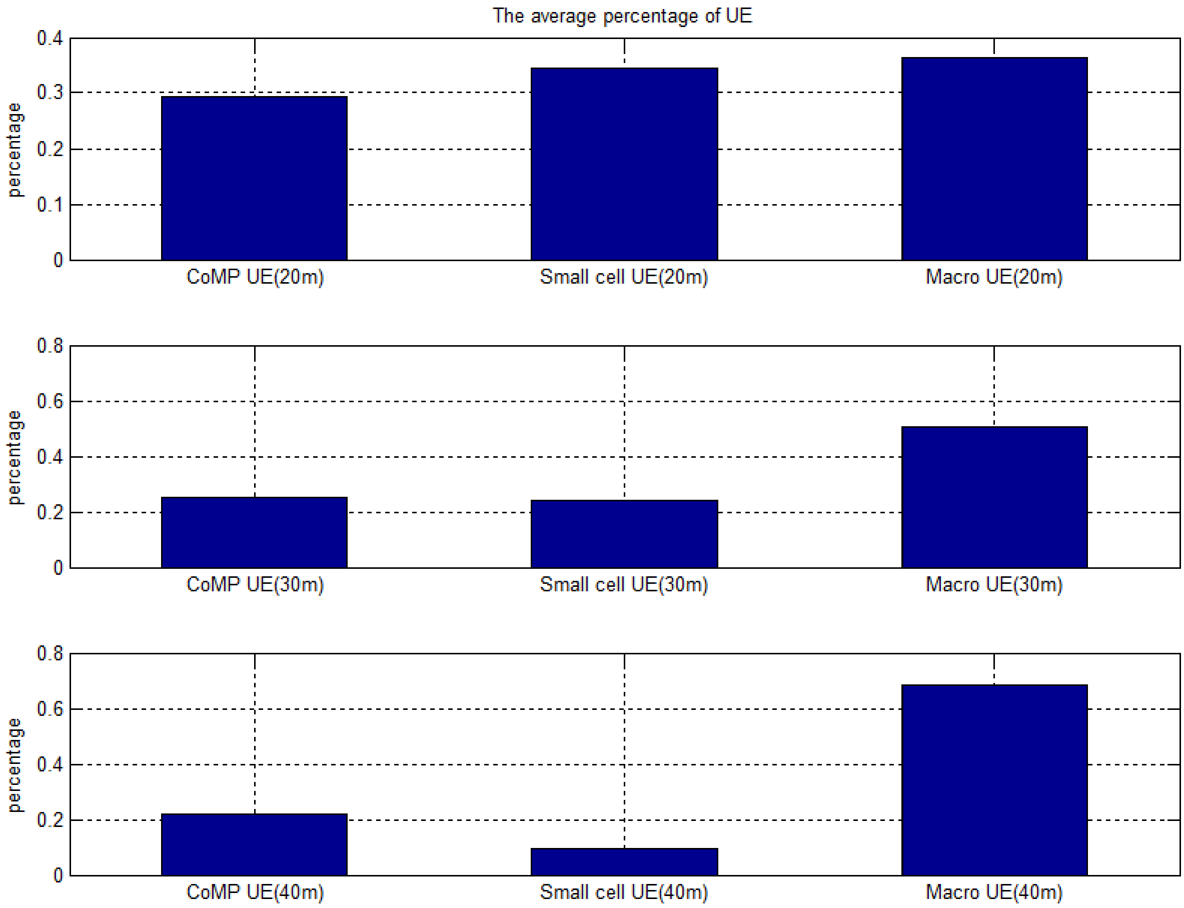

Figure 23: The percentage of different types of UEs (Small-cell UE distributed area)

In figure 23, percentage of different types of UEs are shown. We can see when more UEs are far away from BSs of small cells, they are more likely to be served by macro cell or going to apply CoMP since the interference from other cells are getting larger and signal from small-cell BS is weaker. That's why the number of CoMP UE does not decline much along with the increament of radius of generating area.

Figure 24 depicts the throughput gain with different small-cell UE generating radius for different schemes. Certainly that when less UEs apply CoMP, the throughput gain will decrease. It's interesting that even though 30-m and 40-m cases have very close percentage of CoMP UE, the difference of throughput gain is quite large. That's because when the generating radius for small-cell UE raises, more UEs either are served by macro cell or apply CoMP. As introduced about scheduling algorithm in 4.2.2, the bandwidths of macro-cell UE and CoMP UE are same. Then for each CoMP UE, it has less number of RBs to use and subsequently less throughput gain is achieved.

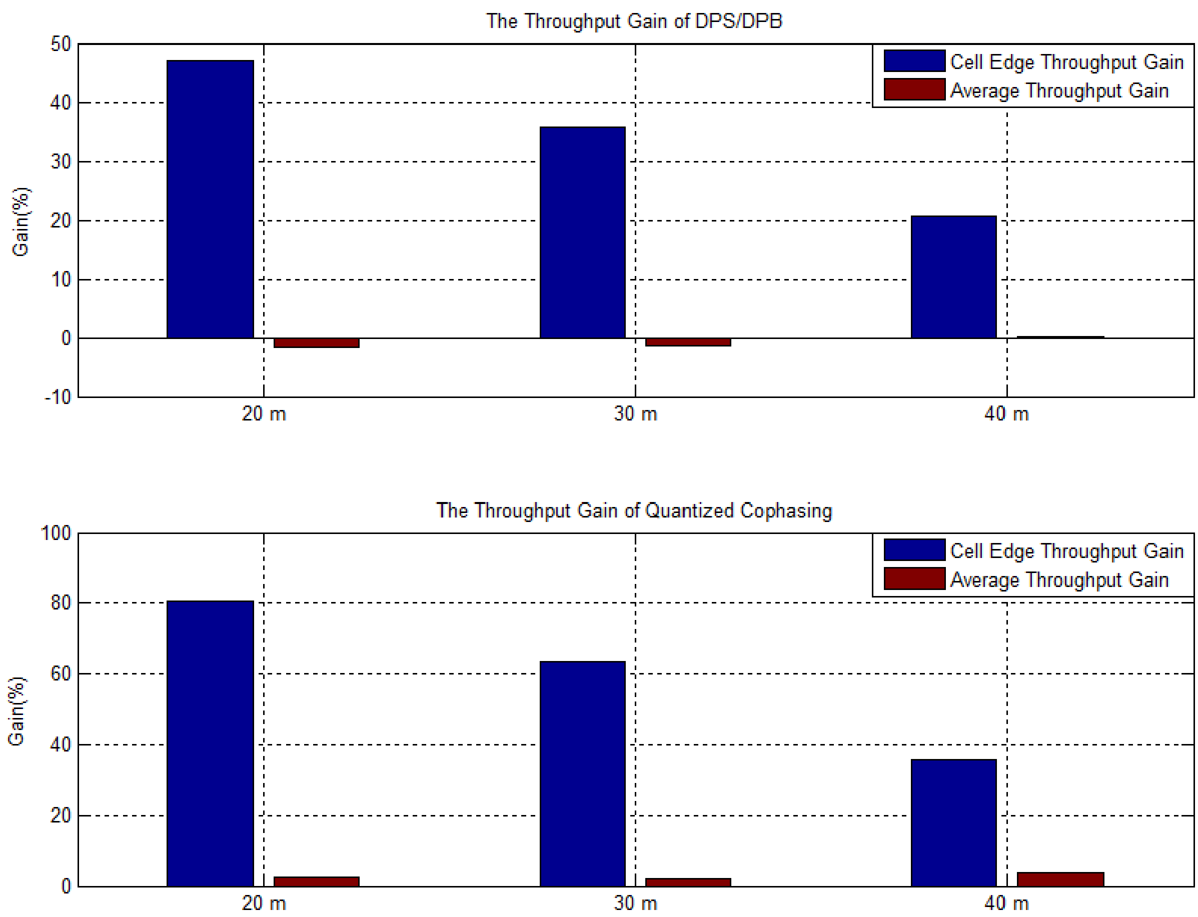

Figure 24: Throughput gain with different small-cell UE distributed area

In conclusion, we try both two ways to adjust the density of small-cell UEs. Basically, a higher density of UE will brings more throughput gain. Therefore, CoMP between small cell and macro cell is more efficient to deploy in high density circumstance.

4.4.4. **Evaluation with more UEs locates in macro cell**

Table 9: Parameters Assumptions for testing impact of UEs in macro cell

Macro UE per macro cell	[10 20]
Rx Power Threshold	10dB
Small cell UE	Generated within 25m of each small cell
UE per small cell	4
Small cell per macro cell	4

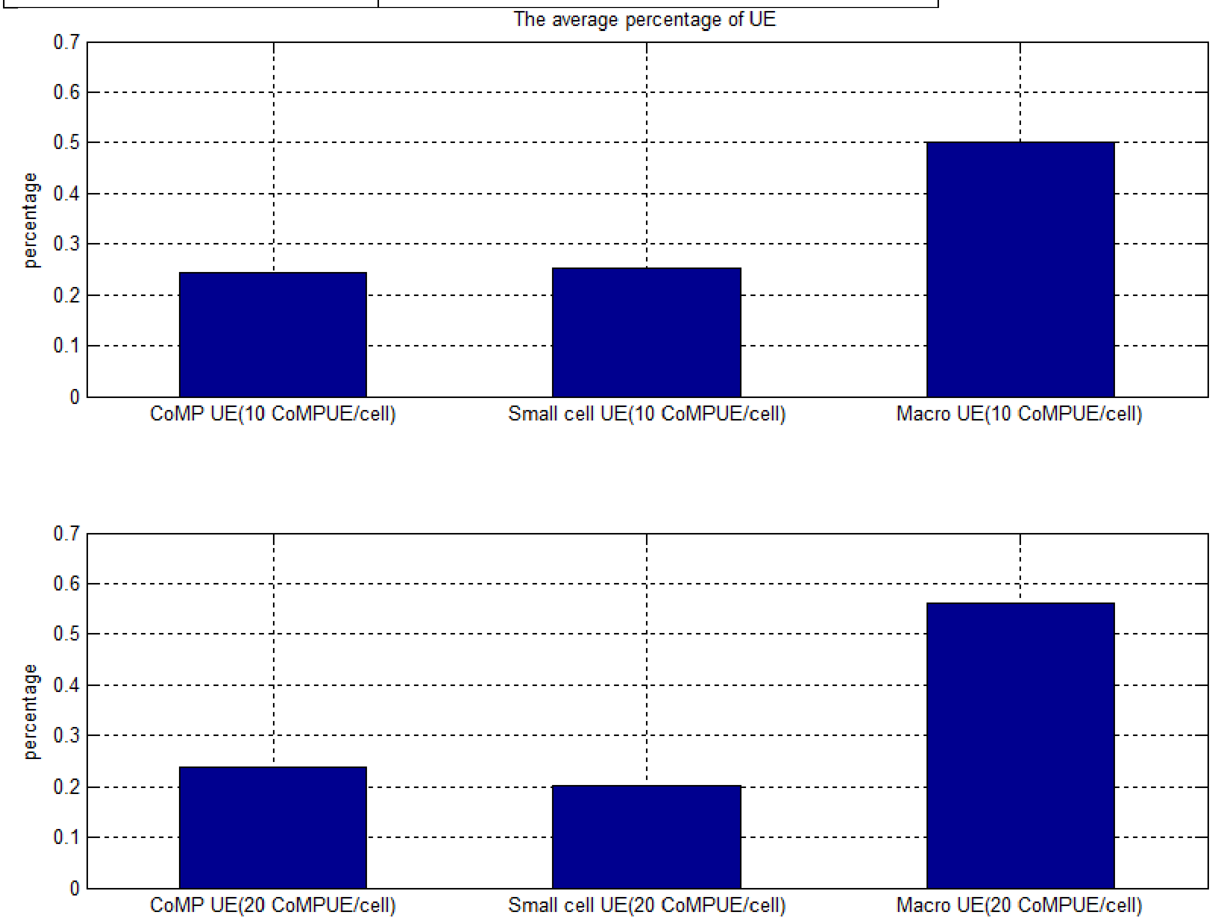

Figure 25: The percentage of different types of UEs (number of macro-cell UE)

In this subsection, we place more UEs in macro-cell coverage without adding any UEs near a small cell. It does not aim to adjust the density of UEs near small cells again. Potentially more randomly distributed macro-cell UEs increase the load of macro cell and affects the performance of CoMP, since the resource block for macro-cell UE is tightened in number. Note that macro-cell UEs are avoided being placed within 25 meters of a small cell. In table 9, the element of macro UE per macro cell is an approximate value from the simulation results.

In figure 25, the percentage of CoMP UE remains almost the same because small cells are all evenly placed at cell edge and UEs generated in macro area are uniformly distributed. Additionally, as our CoMP selection criterion helps UE who has strongest signal from macro sector and dominat interference from small cell, then the percentage of CoMP UE does not drop.

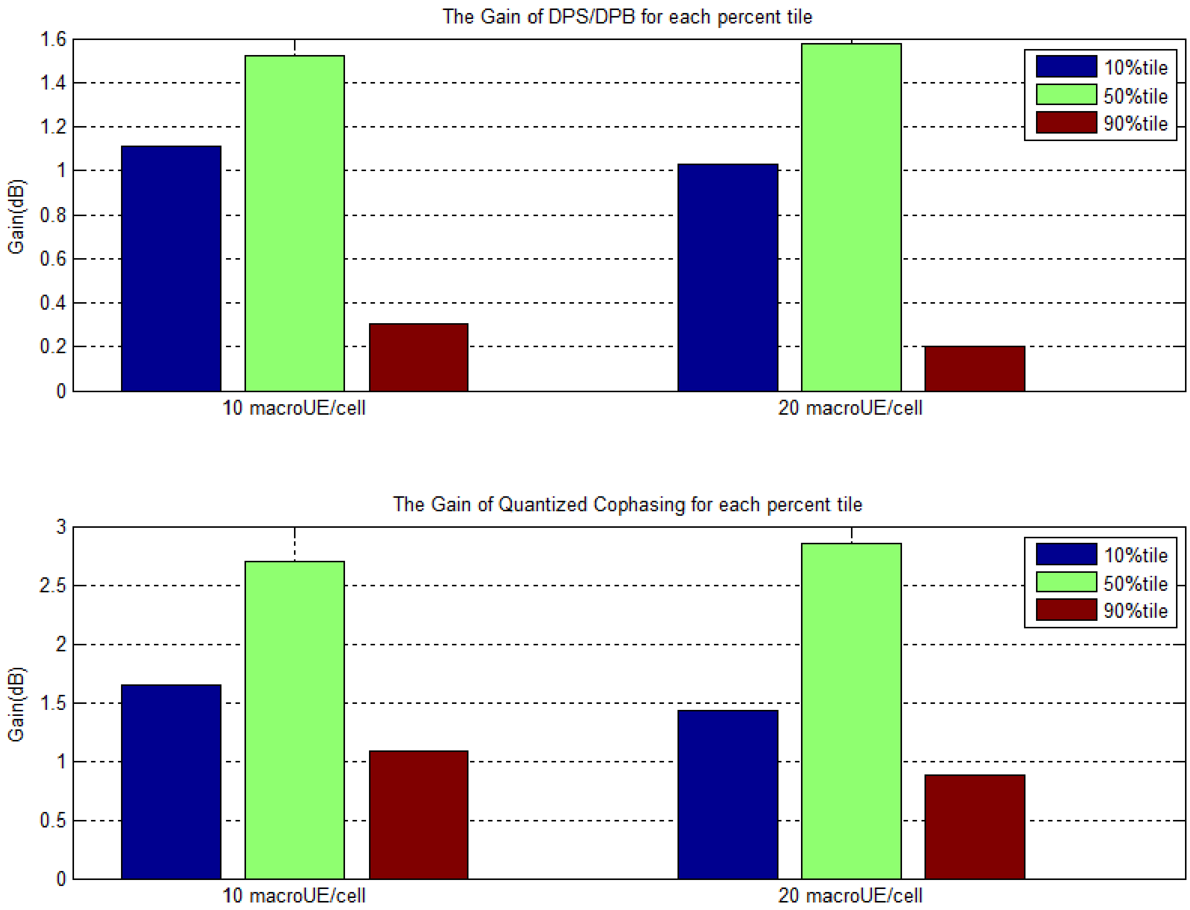

Figure 26: System SINR Gain with more macro-area UEs

Although more UEs are served by macro sectors and percentage of CoMP UEs is slightly decreased, the average SINR gain of all UEs increases a little actually, as seen from figure

26. However, the cell-edge (10%tile) SINR gain goes down instead which implies the sign of deterioration in CoMP performance.

Figure 27 depicts the average and cell-edge throughput gain, when more UEs are uniformly located in macro area. Compared with the result about the impact caused by density of small-cell area UEs, basically the network having larger proportion of UEs gathered at some points where can be deployed by small cells will mostly benefit from CoMP between macro cell and small cell. When UEs are uniformly and sparsely dispersed within the coverage of network, probably this type of CoMP plays less prominent role.

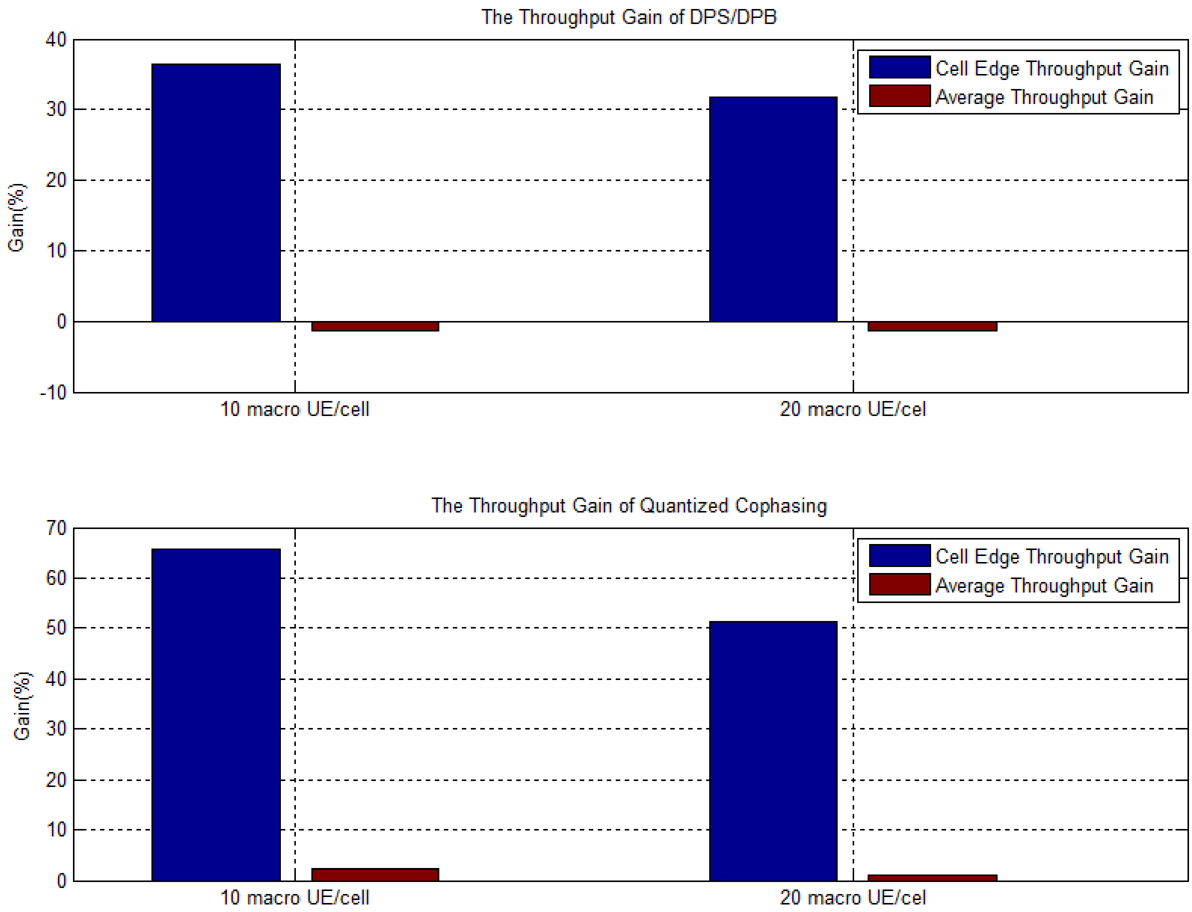

Figure 27: *Throughput gain with more macro-area UEs*

After comparing to the previous simulation result about density of small-cell UEs, we can say that higher load of macro cells does not degrade the performance of CoMP too much. Even with more macro-cell UEs lowering the density of small-cell UEs, throughput gain for QCP is still over 50%.

4.4.5. **Evaluation with randomly Distributed Small cells**

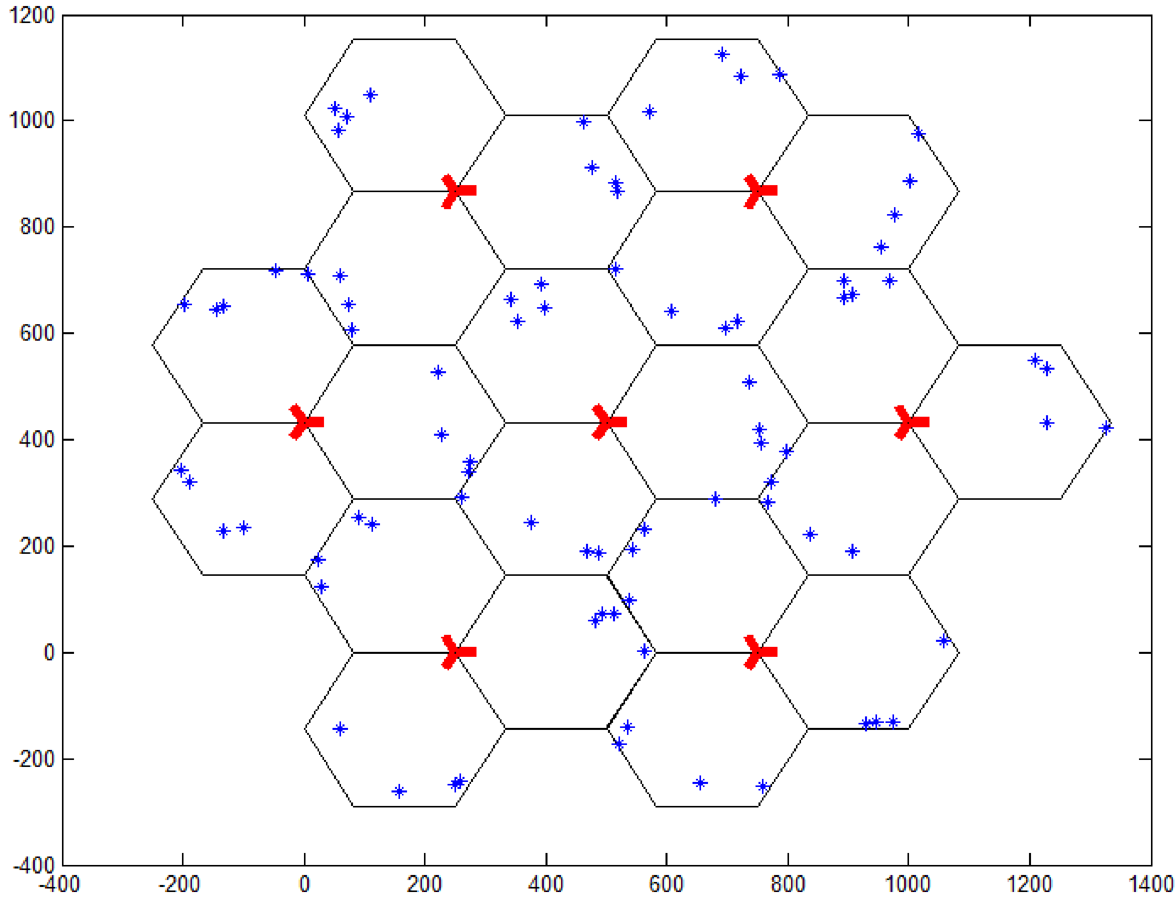

Figure 28: Network layout with randomly placed small cells

In this subsection, the deployment scenario is modified and small cells are randomly located at cell edge area. The new layout of the network is depicted in figure 28. The sign '*' stands for a small cell. In the hexagon of each macro cell, 4 small cells are randomly placed at the macro-cell edge far away from macro BSs. In reality, this kind of small cell is more like a femtocell that is mainly used privately and not known by other small cells. Thus it's possible to have small cells overlapping in coverage and heavily interfering with each other. Before doing the simulation, we assume that CoMP merely between macro and small cells may not work in this case due to the overlapping coverage of small cells. All simulation results is compared and analyzed versus well-planned network. The assumed parameters are given in table 10.

Table 10: Parameters Assumptions in case with uniformly distributed small cells

Rx Power Threshold	10dB
Small cell UE	Generated within 25m of each small cell
UE per small cell	4
Small cell per macro cell	4(Randomly Generated)
CoMP UE Selection Criteria	II

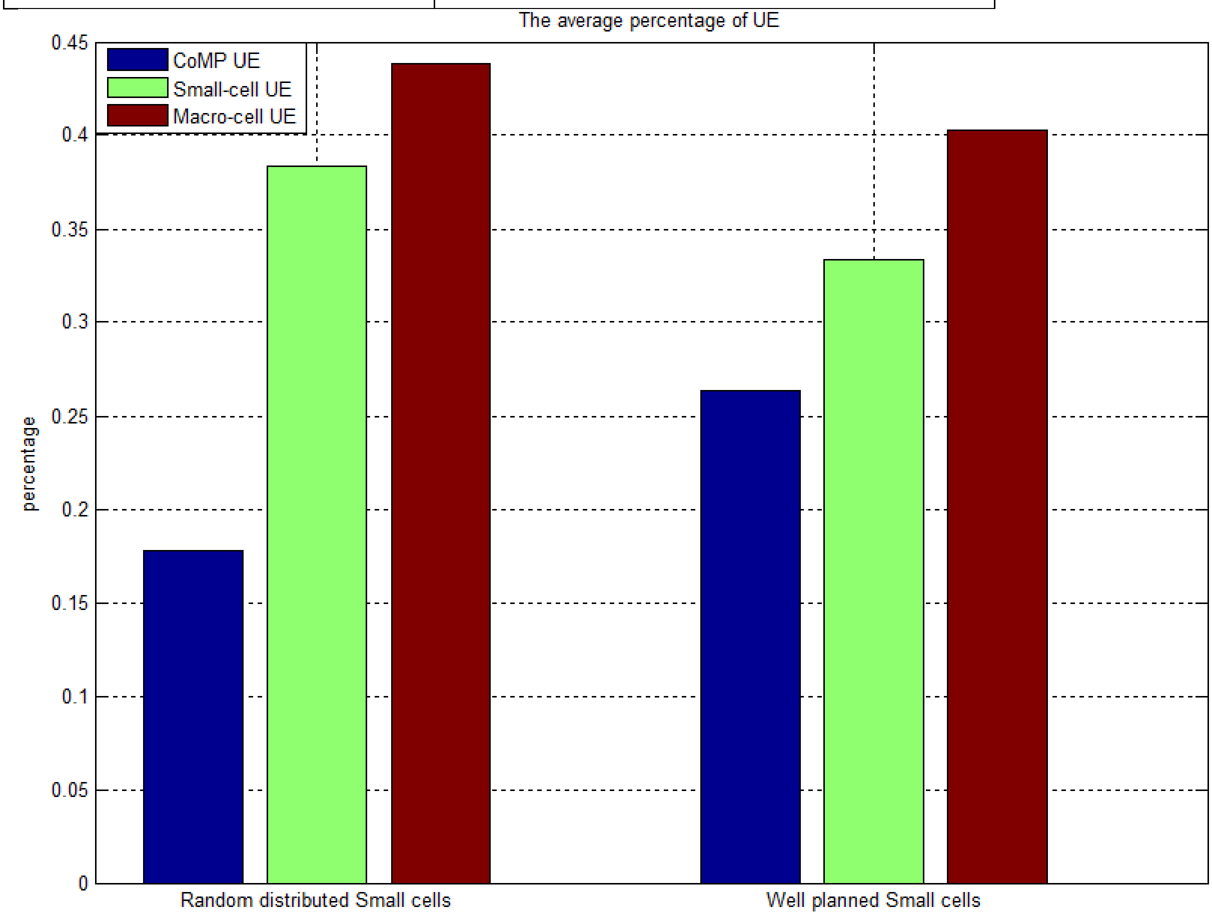

Figure 29 The percentage of different types of UEs(randomly distributed small cells)

The average percentage of different types of UEs can be observed from figure 29. As small cells are randomly placed far from macro BS and UEs are uniformly distributed, fewer UEs meet the conditions for applying CoMP. As observed from figure 28, some of small cells are located close to others. So for UEs generated near that kind of small cells both have strongest signal and dominant interference from small cells. That's the reason for more small-cell UEs in unplanned network.

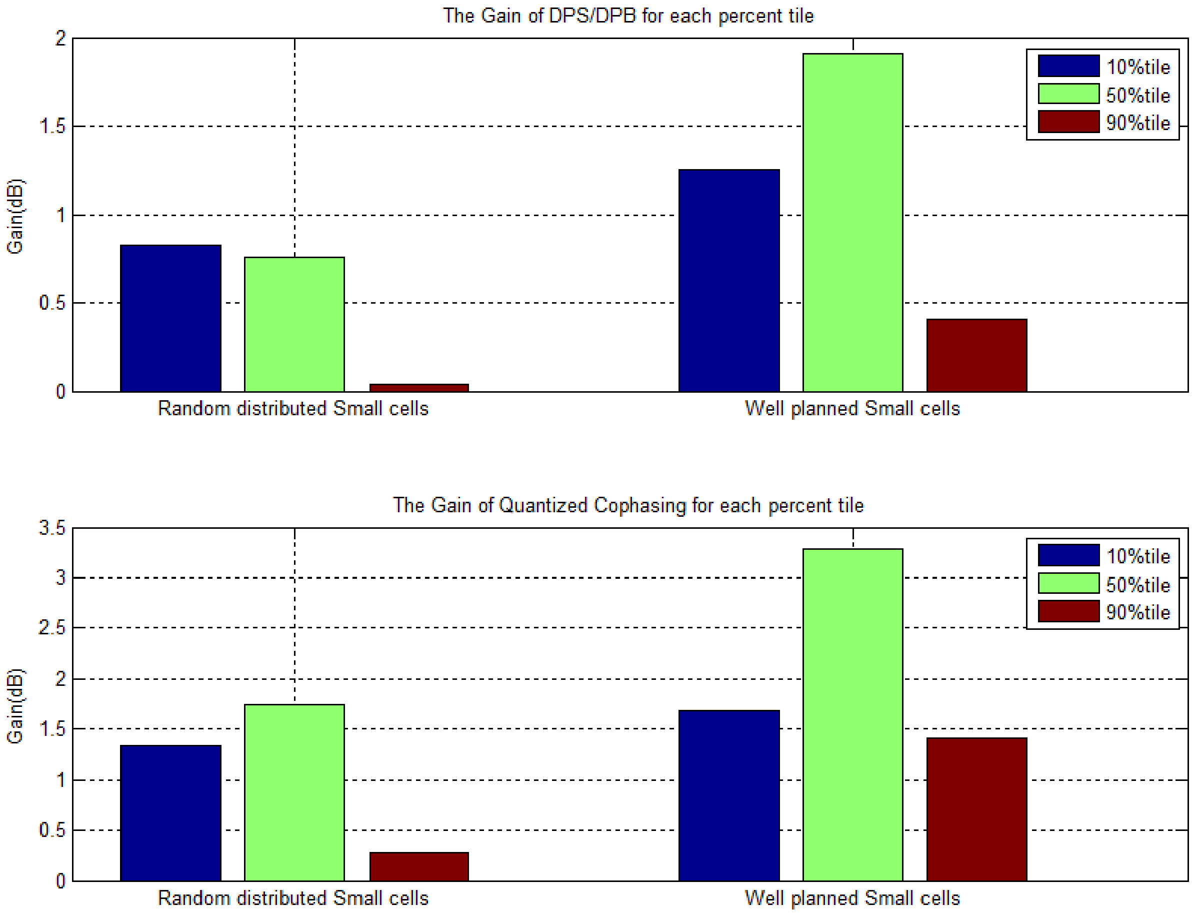

Figure 30 System SINR Gain with unplanned small cells

Figure 30 illustrates the different SINR gain between well planned and unplanned networks. Apparently average SINR gain obtained by the network with planned small cells is almost twofold, but the gap of gain in cell-edge UE is not big. Since in CoMP, we mainly pay more attention on promoting the SINR or throughput for cell edge UEs, the SINR performance of CoMP in unplanned network is not bad. Then let's see the throughput performance in figure 31.

Figure 31 also reflects the fact that CoMP between small cell and macro cell still performs prominently in network with unplanned small cells although not so good as in planned network. In QCP, the throughput gain reaches 60% while DPS/DPB leads to 30% gain which is still a big improvement to cell edge UEs. Therefore, in LTE-A Hetnet, CoMP efficiently mitigates the interference and improves the cell-edge throughput no matter which kinds of lower power small cells are deployed in network. This feature in another work means to help implement the scalability of HetNet.

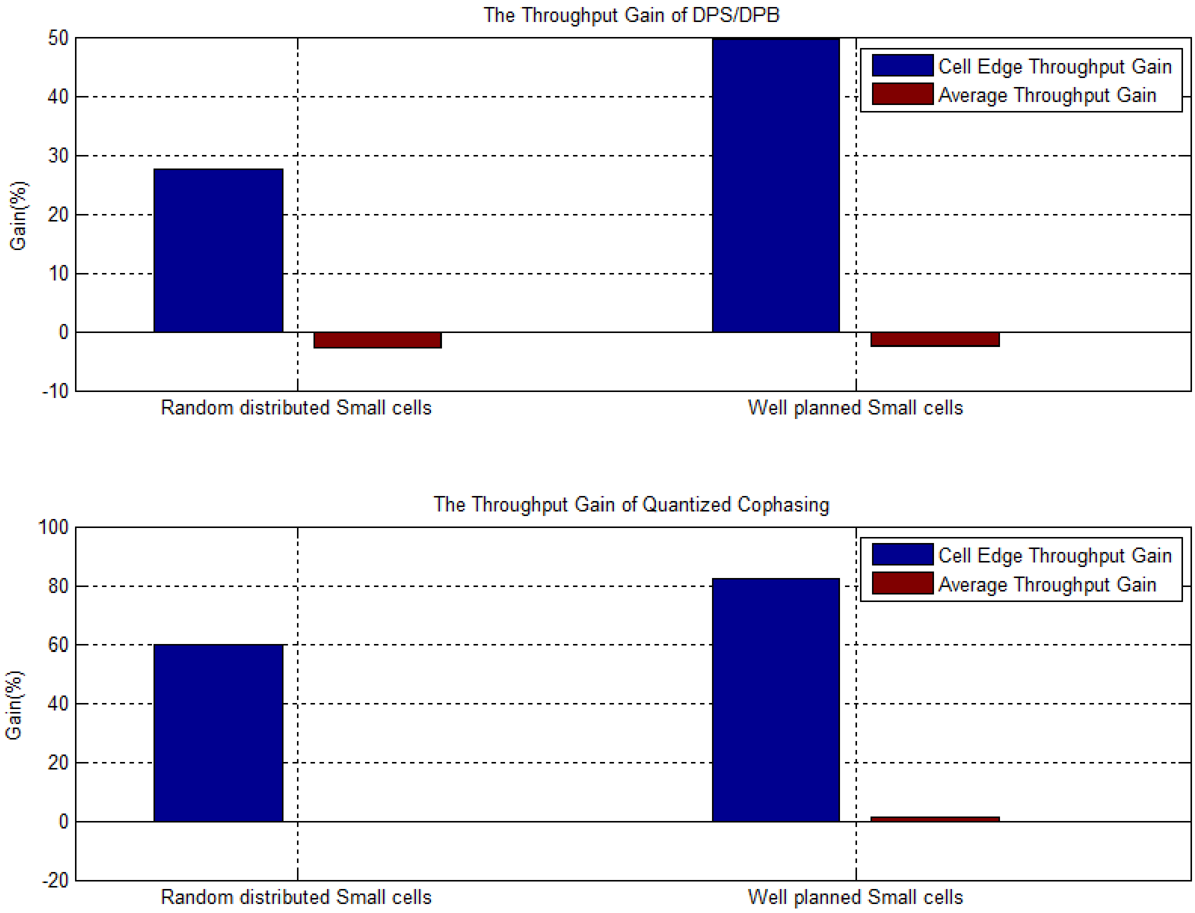

Figure 31: Throughput gain with unplanned small cells

5. CONCLUSIONS AND FUTURE WORK

This thesis investigates CoMP in LTE HetNet, specifically CoMP between macro cell and small cell. In the thesis, the outcomes about first simulation on the CoMP between macro cell and small cell with the conventional CoMP UE selection criterion (I) do not show a significant improvement and calls for developing a more efficient selection criterion. Then with the second criterion (II), an extraordinary throughput improvement illustrates the deployment value of CoMP between macro and small cells. Furthermore, CoMP under other different deployment scenarios are simulated and analyzed.

In the simulation results, CoMP between macro cell and small cell brings the major gain on cell edge UE not only in SINR but also in throughput. Two different CoMP schemes are tested and QCP always has a better performance than DPS/DPB in any cases and the difference of gain of either throughput or SINR is up to more than 50% in percentage. Simulations under other cases show that CoMP performs better when the density of UEs near small cell is higher. For the network that UEs are distributed sparsely and evenly throughout the whole cell, the performance of CoMP declines. Additionally, when the small cells are randomly placed in the macro cell without a good plan, the gain of CoMP is less significant. However CoMP is still worthy being deployed in those kinds of situations and in most of cases, CoMP between small cell and macro cell offers over 60% throughput gain on cell edge UEs. All in all, the outdoor small cells like pico cells which are set up by operators are better to deploy CoMP to mitigate inter-cell interference, especially when the UEs' density of pico cell is high. Femtocells for private use may be not efficient to deploy CoMP, because UEs are basically few in number and their random locations do not benefit cell-edge users either.

Future work for related studies includes the continuous simulations of CoMP between macro cell and small cell in the uplink. Moreover, as backhaul is always the most challenging aspect limiting the performance of CoMP and in our simulation we assume the ideal backhaul with infinite capacity, in the future the simulation with non-ideal backhaul is better to be implemented and the evaluated result must be fairly closer to the reality.

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