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Study of LTE and LTE-Advanced as a Low Cost Backhauling Solution for HSPA Small Cells

Final Project

Espoo

ABSTRACT

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Mobile broadband has become the main way for people in emerging markets access internet. This is due to the very low penetration of fixed line broadband connections in those regions. The increased consumption of mobile broadband data in those regions can be accomodated through network densification of consumer deployed small cells. This provides operators to outsource some of the operational burdens to small cell owners in addition to providing coverage and capacity improvement.

However, finding cost effective backhauling of the small cells is neccessary as those regions are characterized by lack of fixed lines and energy scarcity. We studied LTE/LTE-Advanced as one alternative approach for backhauling small cells. We also studied different backhaul performance enhancement mechanisisms, such as, MIMO (4x4 and 8x8) and bandwidth scaling as well as traffic steering policies to meet the demand of small cells backhaul. The simulation results highlight the potential of LTE/LTE-advanced as a cost-effective backhauling option without causing significant harm to normal LTE users. Both traffic steering policies (small cell backhaul prioritized and LTE-capable UEs prioritized) provide comparable performance as long as UEs in the service area are not majority LTE-capable. With LTE-capable UEs constituting majority of the users for LTE-UEs prioritized traffic policing, we recomend either bandwidth scaling or higher order MIMO or a combination of both to achieve acceptebale backhaul performance.

Keywords: *mobile broadband access networks, backhaul, small cellss, femtocells;*

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CONTENTS

ACRONYMS

1G	1st generation
3G	3rd generation
3GPP	third generation partnership project
4G	4th generation
ARIB	association of radio industries and businesses
ARQ	hybrid automatic repeat request
ATIS	alliance for telecommunications industry solutions
BBF	Broadband Forum
BTS	base transceiver station
CA	Carrier Aggregation
CCSA	China communication standards association
CDFs	cumulative distribution functions
CDMA	code division multiple access
CN	core network
CPC	continuous packet connectivity
CPE	consumer premise equipment
CSG	closed subscriber group
DC-HSPA	Dual-carrier-HSPA
DFT	discrete Fourier transform
DL	downlink
eNB	eNodeB
EPC	evolved packet core
EPC	evolved packet core
ETSI	European Telecommunications Standards Institute
E-UTRAN	evolved UMTS terrestrial radio access network
FCC	American federal communications commission
FDD	frequency division duplex
FDMA	frequency division multiple access
FFT	fast Fourier transform

FTTx	fiber to the home/premises/nodes
GGSN	gateway GPRS support node
GPON	Gigabits passive optical networks
GPRS	general packet radio service
GSM	Global System for Mobile Communications
GSN	GPRS support nodes
HLR	Home Location Registers
HMS	HNB management system
HNB	home node B
HNBAP	HNB application part
HNB-GW	home node B gateway
HSDPA	high speed downlink packet access
HSPA	high speed packet access
HSS	home subscriber service
HSUPA	high speed uplink packet access
IFFT	inverse fast Fourier transform
IMT	international mobile telecommunications
IP	internet protocol
ITU	International telecommunications union
L-GW	local-gateway
LTE	Long Term Evolution
MIMO	multiple-input multiple output
MME	mobility management entity
MNO	Mobile Network Operators
MSC	mobile switching centers
MU-MIMO	multi user MIMO
N/nLOS	non/near line of site
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PAR	peak-to-average power ratio

PC	Personal Computer
PDNs	packet data networks
P-GW	packet data network gateway
P-GW	packet data network gateway
PMP	point to multipoint
POP	point of presence
PRBs	physical resource blocks
PtP	point to point
QAM	Quadrature amplitude modulation
QoE	quality of experience
QPSK	Quadrature phase shift keying
RANAP	radio access network application Part
RAT	radio access technologies
RNC	radio network controller
RNS	radio network subsystem
RRC	radio resource connection
RRM	radio resource management
RUA	RANAP user adaptation
SAE	system architecture evolution
SC-FDMA	single carrier frequency division multiple access
SeGW	security gateway
SGSN	serving GPRS support nodes
SGW	serving gateways
S-GW	serving gateway
SINR	signal to interference plus noise ratio
SISO	Single input single output
SNR	signal to noise ratio
SU-MIMO	single user MIMO
TDD	time division duplex
TDM	time division multiplexed

TDMA	time division multiple access
TTA	telecommunication technology association
TTC	technology committee
UE	user equipment
UL	uplink
UMTS	universal mobile telecommunications systems
UTRAN	UMTS Terrestrial Radio Access Network
VLR	visitor location registers
WCDMA	wideband code division multiple access
WCDMA	Wideband code division multiple access
WiMAX	worldwide interoperability for microwave access
xDSL	Asymmetric/Symmetric Digital Subscriber Line Technologies

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Dedicated

to

My Mom and Sister

1.0 INTRODUCTION

This chapter presents a brief introduction to the research area along with the description of the problems addressed in this master's thesis. We also briefly present available small cell backhaul technology options.

1.1 Motivation and Background

1.1.1 Background

Driven by the introduction of affordable smartphones, personal computer (PC) tablets, and the many new connected devices, mobile broadband data traffic is showing unprecedented exponential growth, pushing operator's capacity to its limit [1]. With more than a million mobile applications available today across multiple device ecosystems, customers have many reasons to stay online for extended period of time and consume large amounts of data. Mobile broadband is revolutionizing wire-line high speed data rate by freeing users from wires and stationary world. The result of this freedom is users accessing mobile broadband services anywhere and at any time.

The need to handle this explosion of data traffic and expand the reach of mobile broadband services has resulted in the evolution/revolution of radio access technologies from purely circuit switched 1st generation (1G) cellular systems to totally packet switched 4th generation (4G) and beyond networks. The evolution/revolution of radio access technologies is manifested among other things in increased spectral efficiency, large operating bandwidth, reduced round trip time, improved network architecture, and dense network deployment [2].

Densification of a network, by increasing number of deployed cells in a given coverage area, as a means of increasing capacity and hence offer better service has been practiced since the cellular concepts where introduced. Traditionally, the trend has been to deploy more macro cells per given area depending on the capacity demand of the network coverage. But the trend cannot be sustained for a few reasons. Primarily, deploying macro cells requires huge investment which comes in as among others site acquisition, providing backhaul, and management and operation cost. Macro cells operate at high power and cause a lot of interference to other cells and, hence, interference management becomes increasingly difficult with increasing number of macro cells. This is especially true for interference limited wireless technologies, such as, wideband code division multiple access (WCDMA). To overcome these problems and at the same time take the advantage of capacity improvement through cell densification the concept of small cells was born.

Heterogeneous networks, commonly referred to as HetNets, typifies the use of multiple types technologies (WCDMA, long term evolution (LTE), Wi-Fi, etc.), and different access nodes (macro, Pico, femto etc.) in a wireless network [3] [1]. Cellular network operators use small cells, such as, Pico cells, and/or femtocells in order to offload some of macro cell mobile broadband data traffic in so called hotspot areas and to extend service coverage in notspot areas [4]. The use of small cells for mobile broadband data traffic offloading is becoming increasingly important among mobile network operators (MNO) as users demand for uniform service coverage in all operators' network coverage areas is becoming ever more critical. Delivering quality of experience (QoE) for customers anywhere and anytime is not an option anymore but necessity.

Along the evolution/revolution of radio access technologies and heterogeneous network deployments comes the challenge of providing required high capacity backhaul link, which will transport traffic from the access side to the operator's core network and beyond. The increase in access traffic due to advancement of radio access technologies and network densification requires better backhaul technologies so as to carry the new transport capacity demand. Moreover, the radio access evolution does not just bring a higher capacity demand from the backhaul link but also its own set of requirements. 3rd generation (3G) networks, WCDMA / high speed packet access (HSPA), backhaul requirements and 4G networks, LTE/LTE-Advanced, backhaul requirements are substantially different. In addition to high capacity transport requirement of 4G networks, there is a fundamental shift from 2G and 3G time division multiplexed (TDM) backhaul transport scheme to internet protocol (IP) over Packet switched in 4G and beyond networks [5]. The new backhaul solutions are required to cope with high traffic transport, be cost effective and be easily scalable so as to gain wider acceptance from operators.

The growing role of small cells in mobile broadband provisioning has also its own share of the challenges faced in providing efficient backhaul technologies. The rolling out of small cells as part of a HetNet increases the number of access nodes that needs to be backhauled. Primarily small cells will be deployed in high density urban areas, where there is high mobile broadband demand commonly referred as hotspot areas. These results in high density small cell deployment together with macro cells and along comes the challenge to provide adequate backhaul link. The backhaul network should now be designed to support many network nodes and it should also support scalability for potential future traffic increase. Small cells are also deployed at notspot areas, which represent new coverage areas. The backhaul solution in this case should provide long distance support from point of presence (POP) as these sites will usually be located at remote places.

1.1.2 Why Universal Broadband Access?

Broadband is defined as a network which provides service at high data rate [6]. But how much rate is considered as high data rate? International telecommunications union (ITU) defines fixed broadband as a network capable of transmitting at more than 256 kbps [7]. A data speed greater than 200 kbps has been regarded as broadband by American federal communications commission (FCC) and recently it has revised its broadband definition to a transmission rate of at least 4 Mbps and 1 Mbps in downlink and uplink [8], respectively. The need for high speed broadband connection is growing very fast due to the emergence of new bandwidth hungry applications, such as multimedia over internet, and it is likely in the future that these recommended broadband speeds will be considered too slow.

According to [9] the definition of broadband could base on quantitative indicators, qualitative indicators or a combination of both or more possible options. Quantitative indicators emphasize on the data rate that a broadband connection can offer while qualitative indicators emphasize the potential of broadband on service delivery and stimulating local and national economy of a country. Since broadband availability greatly varies among developing and developed countries, it is difficult to come up with agreeable definition of broadband. But loosely it is defined as an always on and able to provide high capacity connection.

Access to broadband is considered as an essential tool to fight the growing problems of today’s world, such as, population rise, poverty, epidemics and climate change. It plays crucial role in the competitiveness of both developing and developed countries by contributing positively on innovation, productivity, trade, foreign investment and economic growth [9]. It has also become increasing important way of accessing information via the internet, which is becoming essential for economic activity and government administration.

1.1.3 Research Motivation

Compared to macro cells, small nodes operate at a very low transmit power, which translates to small coverage area. This imposes a challenge on site selection where there is little or no flexibility of choosing deployment site. Small cells are also deployed almost anywhere subject to coverage needs, sides of buildings, inside stadiums, utility poles and so on. All these factors contribute to the type of backhauling technology that should be employed [4]. Different site locations, for instance, pose varying backhauling challenges. Moreover, all backhauling alternatives should support ease of scalability, high capacity, and should not become a bottleneck in any case.

Various organizations, such as Universities, equipment vendors, and research institutes, have devoted a lot of effort to find solutions for small cell backhaul challenges. Ericsson predicts that the integration between radio access and backhaul technology is going to drive the future evolution of small cells [3]. There are a number of backhaul technologies available today in the market and each comes with certain advantages and challenges. As a matter of fact there is no single mobile backhauling technology that would be suitable for all small cell deployment scenarios (indoor or outdoor, operator or consumer deployed, etc.).

The motivation of this research comes from the need to find cost effective, flexible and easy to deploy backhaul solution for small cells, specifically applicable in the emerging markets. There is a growing need of mobile broadband service in emerging markets due to the emergence of an increasingly higher proportion of middle income population in these regions. Mobile network operators in these regions are faced with providing backhaul solutions for their customers or their own deployed small cells. While customer deployed small cells are preferred by operators as it leverages associated deployment cost, customers in those regions usually do not have the infrastructure required for backhauling. Therefore, the small cells deployed in those regions are required to have easy to install backhaul options integrated with them.

1.2 Small cell Backhaul Technology Options

As pointed out above, the increased adoption of small cells as a means of providing mobile broadband access has brought a high backhaul transport demand. There are a number of small cell backhauling alternatives available in the market [10]. Below, we will consider the general aspects of these backhauling solutions.

In general, we can categorize the backhaul technology options in today's market into two groups: wire-line and wireless backhaul technologies. Wire-line solutions use "wired" connection between the network node and the core network to provide the required backhaul service, whereas, wireless solutions deliver backhauling using radio or microwave frequencies.

1.2.1 Wire-line or Fixed Line Technologies

The main advantage of fixed line broadband backhaul over that of wireless counterparts is the predictable nature of the wire-line link. Quality of service is easy to guarantee. They provide significantly higher link budget than wireless links for the same transmit power, and hence, significantly higher data rate requirements are possible.

Among the fixed line solutions are:

a. xDSL – Asymmetric/Symmetric Digital Subscriber Line Technologies
b. Fiber Technologies
c. Cable Technologies

There are various DSL options in the market today and the exact speed of a connection on DSL family depends upon the type of DSL employed. While Symmetric DSL provides identical data rates in uplink and downlink, Asymmetric DSL provides relatively lower rates in uplink than downlink thereby providing asymmetric connection. ADSL provides data rates reaching up-to 7 Mbps in downlink and 800 kbps in uplink, while SDSL provides a maximum speed of 5.6 Mbps in both directions [11]. In addition, a very high data rate DSL family called VDSL can provide 55

Mbps in downlink and 30 Mbps in uplink in long range using 12 MHz bandwidth and up to 100 Mbps is also possible in both directions in short range version when operating on 30 MHz bandwidth. These rates are sufficient to support peak data rate for 3G small cells but they fall short of supporting LTE small cells peak data rate requirement, which is in the range of 100Mbps.

Fiber optics provides superior speed performance than any other backhaul technology available today and operates on very large bandwidth. Fiber is traditionally used for core and metropolitan networks and recently it has also gained a lot of attention in the access domain for broadband service delivery, such as the fiber to the home/premises/nodes (FTTx) families [12]. Coupled with very low attenuation and large operating bandwidth, fiber can handle any backhaul traffic, and hence leveraging the cost of any foreseeable future traffic increase. Gigabits passive optical networks (GPON), for instance, is a point-to-multipoint fiber technology which can provide a peak data rate up to 2.5 Gbps downlink and 1.2 Gbps uplink [13]. This is enough to accommodate 16 LTE small cells with downstream capacity of 150 Mbps each, with all cells being active at the same time and operating at 150 Mbps peak data rate.

Fixed-line options are particularly important in the case of customer or enterprise deployed small cells where these options exist as leased backhaul infrastructure already in place. If operators have fiber optics or xDSL infrastructure already in a nearby location of small cell sites, using the already existing infrastructure is a viable option. Fiber optics backhaul solutions have the distinct advantage of supporting high capacity demand and low latency connection but they are costly and slow to deploy.

In general, wire-line solutions are far more predictable than wireless counterparts and should be considered as a viable option in case where the operational and business environment allows for it. For new sites where there is no pre-existing fiber or xDSL infrastructure , installing wire-line backhaul is expensive, costly, and may not be possible at all in some conditions due to, for instance, inflexibility of small cell deployment sites. In such conditions wireless solutions offer fast, easy to install and cost effective solutions.

1.2.2 Wireless Technologies

We can differentiate wireless solutions based on the propagation conditions or the spectrum used. Based on the former, we have non/near line of site (N/nLOS) and LOS categories.

N/nLOS wireless backhaul solutions do not require direct Line of Sight connection to exist between the small cell and the POP. This makes them ideal for indoor and outdoor deployments where direct link between point of presence and small cell is not feasible, such as providing backhaul for small cells deployed inside malls and train stations. They operate on frequencies between 2-6 GHz. This frequency region constitutes licensed and unlicensed bands of frequencies. There is obviously a high risk of using the unlicensed band for backhauling due to significant interference level that may be generated as it is used by many other technologies including Wi-Fi. Some of the licensed part is also used by worldwide interoperability for microwave access (WiMAX) broadband technology which operates at 2.3 GHz, 2.5 GHz, 3.3 GHz and 3.5 GHz frequencies and is as a result considered very costly [14]. In addition, even the small chunk of available frequency does not allow aggressive frequency reuse due to NLOS propagation mechanisms, which is based on signal reflection, and which could cause a considerable interference on adjacent radio links.

For the above reasons, NLOS backhaul solutions can provide only limited capacity and they are applicable in conditions where high backhaul transport traffic is not required. But on the positive side, installing NLOS solutions do not require to perform antenna alignment operation, making fast and easy deployment possible. They can operate either in frequency division duplex (FDD) or time division duplex (TDD) mode and point to multipoint (PMP) and mesh topologies [15]. Moreover, latest advances in physical layer technologies like orthogonal frequency division multiplexing (OFDM) and multiple-input multiple output (MIMO) techniques can be employed there by enhancing the overall capacity.

Under line of site (LOS) backhaul categories microwave and E-Band point to point (PtP) solutions are widely used. There exists large amount of bandwidths at microwave frequencies. The frequency band encompasses frequencies ranging from 10 GHz to 60 GHz and the large bandwidth represents the possibility of harvesting large capacity [10]. Fixed microwave backhaul is considered as a matured technology. PtP and PMP fixed microwave radio links are extensively used for high capacity broadband backhaul data transport.

Microwave PtP links are usually deployed using star, tree or ring networks and require symmetric links between transmitter and receiver [16]. Microwave PMP, on the other hand, provide the possibility of a node serving as aggregation point to connect to multiple small cell sites. This reduces the burden of having symmetrical backhaul links for each small cell sites, and as a result, increases backhaul resource utilization.

The challenge with using microwave radio links is that they can only be used in situations where there is direct line of sight connection between small cells and the point of presence. This is the result of the small operating wavelength of microwaves where any obstruction between the transmitting antenna and receiving antenna can easily block the microwave signal. The counter argument about this is that the high operating frequencies allow aggressive frequency reuse possible due to high signal power attenuation that takes place and which in effect reduces interference from nearby microwave radio links. Moreover, designing high gain and compact antennas which improves end-to-end radio link budget is technologically possible at these frequencies [4]. The minus side of these is it requires carefully aligning transmitter and receiver antennas at deployment site.

E-band millimeter waves operate in the 60 GHz unlicensed band and 70 GHz or 80 GHz licensed bands. The extremely high signal power attenuation allows only short range applications. The growing need for ultra-high capacity backhaul radio solutions diminishes the problem of the short haul nature of E-band systems and find applications in a range of small cell deployment scenarios including wireless backhaul chains between street poles. Highly directional antennas with high gain and compact form factor are easily made due to the very short operating wavelength. The abundant available frequency helps reduce cost per bit ratio which is comparable to small cells [15].

Another wireless small cell backhaul solution that is worth mentioning is satellite communication. Small cells which were originally designed for home use are receiving increasing attention for outdoor metropolitan and rural area deployments [17]. While small cells are attractive over 2G or 3G macro-cells in those areas, the biggest challenge is the provisioning of backhaul. Deploying fixed wired solutions like fiber or xDSL is impractical and very costly considering to the average revenue per user that is obtained from small cell radio services. Among the candidate solutions, satellite connections provide cost effective and highly adaptable solution. The challenge of using satellite systems is going to be the round trip delay that is inherent in satellite communications, which literally makes it impractical to use such system for delay sensitive applications.

1.3 Problem Statement

The growing demand for mobile broadband networks in emerging markets is fueled by the fact that usually it is the only feasible means for providing first-time broadband connectivity for majority of users as in most cases internet penetration is still below world average of 32.7% [18]. Mobile broadband is the way to go in the future in these regions as fixed line penetration is unlikely to grow further as it requires huge investments in infrastructure. Moreover, mobile broadband is preferred over fixed line broadband services because of its better reach, convenience, and functionality and lower costs.

The desired increase in broadband users and subsequent explosion of volume of mobile data traffic as faster broadband devices become more affordable in those regions can be accommodated through densification of the mobile network. However, mobile network coverage and capacity improvements through scaling of operator-deployed small cells, that is, micro or pico-cells, presents a very challenging business case. This is particularly the case for the increasingly densely-populated low-income suburban areas, which are characterized by lack of fixed lines, energy scarcity, insecurity, and difficulty in site acquisition and in addition to low revenue potential (average revenue per user).

Apart from the operator-led approach, network densification is also possible through consumer-deployed low-cost and low-power small cells, generally referred to as, femtocells. These consumer small cells not only provide coverage and capacity improvements, but also enables operator to outsource some of the operational burden to the small cell owners (a household, micro enterprise etc.) and thus minimizing their operating costs. However, the lack of last mile fixed line infrastructure low-income suburban areas implies that alternative means for backhauling the consumer small cells are required. Several backhauling techniques for small cells are currently implemented or studied as discussed in the introduction part. Generally, the considered backhauling approaches are either based on wire-line technologies or then require carefully planned wireless backhaul links that are more suited for operator-deployed small cells.

The work in this thesis studies an alternative cost effective wireless small cell backhauling mechanism. The proposed solution is to use LTE or LTE-advanced macro cell links to backhaul small cells.

1.4 Objectives of the Thesis

This Master's thesis work is to study, as pointed above, on an alternative approach of backhauling small cells through the use of LTE or LTE-Advanced macro cell links. To that end, it is assumed that the small cell access is intended to support broadband end users through WCDMA, HSPA (+) and Wi-Fi. This assumption is based on projected technology deployment and adoption trends in emerging markets over the next 5-10 years [19].

Therefore, the research objective of the thesis is to investigate how different LTE or LTE-A radio technologies are able to meet backhaul capacity requirements for various low-cost small cell implementations, such as, HSPA small cells, evolved HSPA small cells and multi-radio small cells (HSPA + Wi-Fi). The consideration of different LTE/LTE-advanced solutions for backhaul takes into consideration the trade-off between performance and constraints including implementation cost, power consumption, spectrum availability and growth in number of LTE users in low-income areas. The latter factor contributes to increased competition for LTE network radio resources between LTE users and provision of backhaul capacity for small cells.

1.5 Outline of the Thesis

The rest of the thesis is organized as follows:

- In chapter two we will present small cell concepts with particular emphasis on femtocells. We will also discuss the challenges surrounding femtocells and their standardization in 3G technologies. We will then present the 3G architecture of femtocells and the modification required when LTE macro cell is employed for backhauling.

- Chapter 3 will present the basics of LTE technology; OFDM and MIMO concepts and LTE system architectures will be discussed
- Chapter 4 will be dedicated to presenting the development of the simulation environment and performance analysis of the LTE system for small cell backhauling. The discussion will include aspects from both small cell LTE backhaul side and normal LTE users' side.
- The final chapter will conclude the work.

2.0 SMALL CELL CONCEPT

We will introduce the concept of small cells in this chapter and discuss further femtocells in particular. In section 2.3 we will see about universal mobile telecommunications systems (UMTS) based radio access network architecture and in section 2.4 we will discuss some of UMTS based radio access technologies (RAT). We continue on RAT discussion focusing on 3G technologies in section 2.5. We then discuss 3G femtocells architecture, interfaces and protocols, and architectural functions. We end the chapter by presenting the proposed small cell LTE backhaul architecture.

2.1 Introduction

Small cell networks provide means of increasing cellular network capacity through network densification by deploying low-cost, low-power base stations. Traditional macro base stations are mainly designed to operate at high power to cover large area and support small data traffic. With the current growth in broadband service over mobile networks, there is a need to improve the capacity of the traditional macro cells and reach out new coverage areas. A massive deployment of small cells is a promising way to cope with the capacity increase. Small cells meet the capacity demand by reducing the distance between the user and the base station, and hence, improve signal quality which intern allows a higher data rate both in downlink and uplink.

Small cells deployed around the world today are comprised of Pico, Femto, and micro cells. Pico cells are low power base stations particularly used to extend coverage to indoor areas where signal from outdoor macro cells do not reach well due to penetration loss [20]. They are also used to increase network capacity in densely populated areas where there is high capacity demand, such as train stations, office buildings, and malls. Microcells are bigger in size than Pico cells and are employed frequently in urban and suburban areas. By operating at a lower coverage radius than macro cells, micro cells provide better signal-to-interference and noise ratio for both indoor and outdoor users where macro coverage is insufficient [21].

2.2 Focus on Femtocells

The evolution of radio access technologies is characterized by a shift to higher and higher carrier frequencies to better harness the available bandwidth and gain higher capacity. As we move higher in frequency, we get more signal attenuation and coverage of cells shrinks. Signal quality reaching inside buildings will be very low and traditional base stations which cover large distances cannot support quality voice call or broadband services for home users. Besides, radio access technologies based on code division multiple access (CDMA), such as WCDM and HSPA, are interference limited networks. An increase in number of users or increase in throughput of online users in a cell forces the cell size to shrink, and thereby, reducing the number of users that can connect to a cell from inside buildings.

To address the aforementioned problems femtocells where introduced in 3G networks. Femtocells are low-power, short-range, low-cost indoor base stations deployed by users for better coverage and capacity [22]. Statistics shows that more than 70% of mobile broadband traffic and more than 50% of voice call originates from indoor users [23]. Therefore, operators are expected to provide good connection for indoor users in order to ensure customer loyalty and satisfaction. Since femtocells will be in the premises of customers, in addition to providing better coverage and capacity, they help lower transmit power of mobile stations and as a consequence users will experience prolonged battery life.

In addition, small cells (micro, pico and femtocells) are increasingly becoming popular for outdoor deployments as subscriber demand for coverage and capacity is increasing. Femtocells in particular are the preferred means for providing broadband access in places, such as, metro and public spaces as well as rural areas which are hard to reach and user base is low [21]. Such places do not require macro cell deployment because of the relatively shorter range in which users will be concentrated. Small cells and femtocells in particular will be suitable to address the capacity and coverage demand in those particular places.

Femtocells are connected to operator’s core network through customer’s broadband connection. They can be interfaced to the internet through DSL or cable technologies. This plug and play device nature of femtocells is one of the reasons why they are widely deployed around the world, that is, femtocells deployment outnumbers traditional base stations [24]. They can also be interfaced to multiple wireless radio access standards, such as UMTS, CDMA2000, and WiMAX.

There are, however, issues of interference that can potentially hinder the mass deployment of femtocells. Interference management is difficult due to unplanned deployment and burst nature of the traffic generated by femtocells. Besides, looking for alternative backhauling techniques is also necessary so that femtocells remain attractive for all kinds of customers, including those in the emerging markets.

Since the most successful implementation of femtocells uses 3G UMTS standard [25], we will briefly see 3G UMTS network architecture and radio access technologies that are based on UMTS architecture before discussing the femtocells standards and the modified UMTS architecture that includes femtocells.

2.3 UMTS Radio Access Network Architecture

There are a number of radio access technologies in operation today which coexist in the same coverage area. The first generations of radio systems were analog and were designed purely for voice communications. They were based on frequency division multiple access (FDMA) for multiplexing users. 2G systems made a paradigm shift from analog system to digital and the advances in digital processing allowed efficient usage of radio resources. 2G systems also offered slow data service in addition to voice call. The need to provide better broadband data service has been and still is the driving force for the evolution of radio access technologies.

The UMTS was specified by third generation partnership project (3GPP) and was formally accepted as 3G mobile communication system by the ITU under its umbrella called international mobile telecommunications (IMT)-2000 [2]. The first version was released in 1999 under the name 3GPP release 99 and it adopted many of the functionalities of the 2G GSM/GPRS (general packet radio service) core network. The time division multiple access (TDMA)/FDMA that is used in Global System for Mobile Communications (GSM) was abandoned and WCDMA is adopted as the multiple access schemes. Much of the capacity gains of UMTS over GSM come from the use of WCDMA. UMTS supports a variety of services, such as voice, video telephony, browsing, streaming, gaming, mobile TV, etc. over its circuit switched and packet switched transport models.

Fig.2.1 below shows a simplified version of UMTS architecture including interfaces used at different parts. As we can see, UMTS architecture is composed of three parts, the User Equipment (UE), the UMTS terrestrial radio access network (UTRAN) and the core network (CN). The Uu interface defines the radio interface between the UE and the UTRAN and the Iu interface defines how the CN and UTRAN should interact.

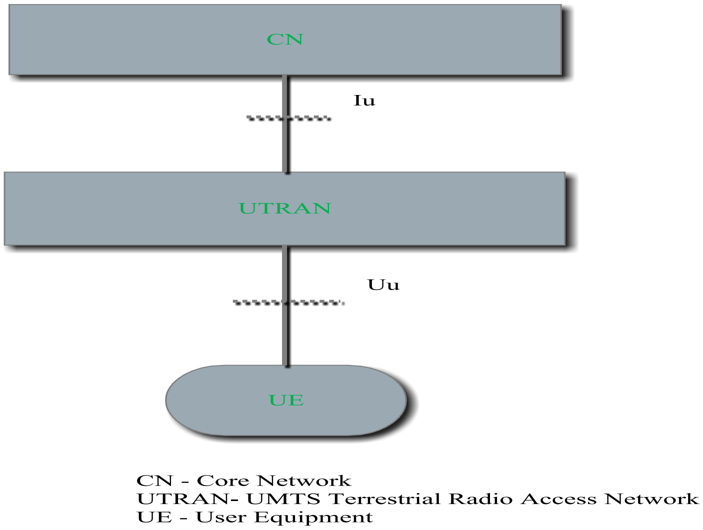


Figure 2.1 Simplified UMTS architecture *[26]*

Interfaces are very important for the coexistence of equipment's from different vendors. The existence of a well-defined interface allows elements at two ends of an interface to be from different vendors. By defining the Uu interface, for instance, any mobile phone can establish connection with UMTS UTRAN regardless of to which vendor the UTRAN belongs to. Similarly, the Iu interface allows operators to obtain the core network and the UTRAN network from different vendors and the two ends will work in harmony through the Iu interface. The Uu interface is particularly important interface because we have more mobile phone makers than CN equipment vendors.

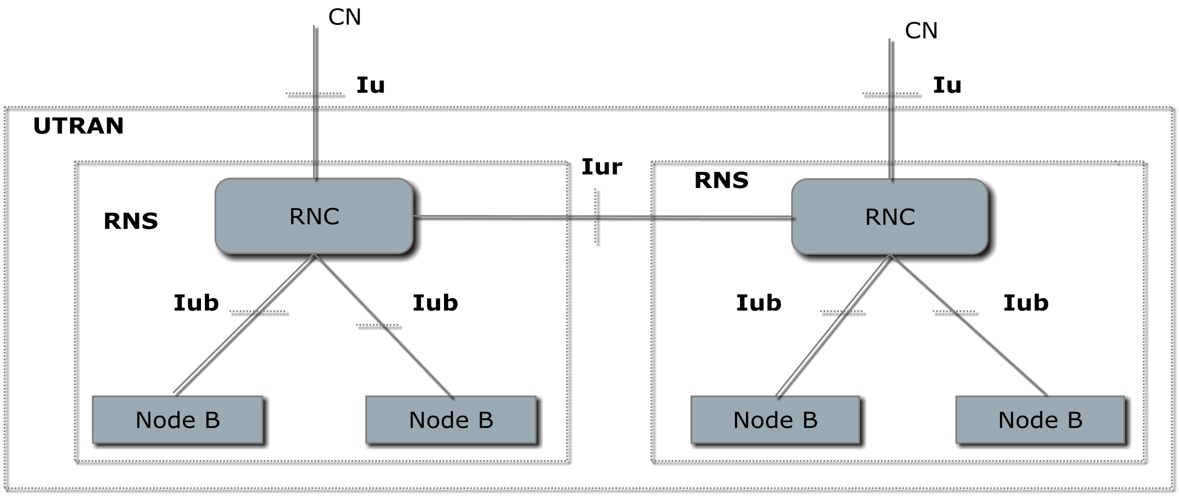


Figure 2.2 UMTS Terrestrial Radio Access Network Architecture *[2]*

Fig.2.2. shows the UTRAN part of the UMTS architecture. The UTRAN consists of two components; radio network controller (RNC) and Node B, which are the equivalents of base station controller (BSC) and base transceiver station (BTS) in GSM networks, respectively. A number of Node B's can connect to the RNC through the Iub interface, together referred as radio network subsystem (RNS). The RNC serves as an aggregation point. The RNCs are interconnected to each other through the Iur interface, which is required to handle users' mobility. In UMTS, one user can connect to more than one Node B at the same time, providing macro diversity. This happens for users around cell edge.

The main functionalities at the Node B are radio frequency processing, modulation and spreading, power control, and macro diversity combining when the Node B has multiple sectors. The RNC is responsible for controlling UTRAN radio resources and it also terminates the Iu interface. Other roles of the RNC include closed loop power control, handover management, admission control, code allocation, packet scheduling, and macro diversity combining when handover is between Node B's.

The CN contains similar components to that of GSM core network. The main network elements are mobile switching centers (MSCs) and GPRS support nodes (GSN). Both elements make use of other network elements, such as home location registers (HLRs) and visitor location registers

(VLRs). MCSs handle the circuit switched traffic and GSNs handle the IP traffic from/to the internet. The CN contains two main interfaces, Iu-CS and Iu-PS, which are the circuit switched and packet switched parts of the Iu interface.

2.3.1 3G Radio Access Technologies (RATs)

2.3.1.1 WCDMA

Wideband code division multiple access (WCDMA) standard is the first 3G radio access technology network based on UMTS architecture and it is widely deployed worldwide. WCDMA specification has been created in 3GPP, which is a joint standardization body from different regions of the world, European telecommunications standards institute (ETSI) from Europe, association of radio industries and businesses (ARIB) and telecommunication technology committee (TTC) from Japan, telecommunication technology association (TTA) from Korea, China communication standards association (CCSA) from China, and alliance for telecommunications industry solutions (ATIS) from USA.

Within the 3GPP, WCDMA is characterized as UTRA and it has two variants, UTRA time division duplex (UTRA TDD) and UTRA-frequency division duplex (UTRA FDD). In the TDD version, same frequency is used for uplink and downlink link connections and in FDD different frequencies are allocated for uplink and downlink. To a large extent, current WCDMA deployments use frequency bands between 1920 MHz and 1980 MHz for uplink and between 2110 MHz and 2170 MHz for downlink [2].

The system uses spreading codes, referred usually as channelization codes, to spread user signals over whole of the operating bandwidth. Transmission bandwidth is much larger than information bandwidth and it does not depend on the information signal. Table 2.1 below lists some of the parameters of the WCDMA system.

Table 2.1WCDMA parameters

System Bandwidth	5MHz
Duplex mode	FDD and TDD

Chip rate	3.84Mchips/s
Channel coding	Convolutional and turbo codes
Data modulation	QPSK in DL, BPSK in UL
Frame length	10ms
Spreading factors	DL 4-256, UL 4-512

2.3.1.2 HSPA

HSPA refers to two important evolutions of WCDMA, high speed downlink packet access (HSDPA) and high speed uplink packet access (HSUPA), which where specified in 3GPP release 5 and release 6, respectively [27]. HSDPA provides high speed packet access in downlink on a shared channel. The shared channel provides fast channel aware scheduling of users, short transmission time interval, adaptive modulation and coding schemes, and hybrid automatic repeat request (ARQ). The corresponding uplink enhancement, HSUPA, provides enhanced dedicated channel, which allows fast power control, short transmission time interval, and hybrid ARQ.

With these two evolutions, HSPA brings big capacity improvements and a significant latency reduction compared to WCDMA. Moreover, HSPA is still evolving and the next evolution after HSUPA was specified in 3GPP release 7 under the name HSPA+. Release 7 enhancements include, MIMO, which represents the use of multiple antennas both at the transmitter and receiver side [28]. In addition, higher order modulation, such as 64QAM, and continuous packet connectivity (CPC), which enables discontinuous transmission and reception features, are also improvements introduced in HSPA+. 3GPP release 8 specified Dual-carrier (DC-HSPA), which effectively doubled the peak data rate of HSPA+ [29]. Subsequent releases, release 9, 10 and 11, are mainly enhancements from multicarrier usage and MIMO techniques. Release 11, for instance, enables aggregation of up-to 8 carriers to be used in non-contiguous bands and with 4x4 MIMO, a peak data rate of 672 Mbps can be offered when both features are used [27].

Table 2.2 below shows peak data rates that can be achieved in 3G access technologies with advanced features, and when users are at cell center experiencing good signal quality.

Table 2.2 Achievable peak data rates with 3G technologies

		WCDMA	HSPA	Release7, HSPA+	Release8	Release9	Release10	Release11
Peak Rate	DL	0.4Mbps	14Mbps	28Mbps	42Mbps	84Mbps	168Mbps	336Mbps
	UL	0.4Mbps	5.7Mbps	12Mbps	12Mbps	24Mbps	24Mbps	72Mbps

2.4 Femtocells Standardization

The numerous advantages of femtocells gave birth to its widespread acceptance and interest among operators and femtocell technology providers. But, in order for this technology to provide its promised advantages, the problems associated with femtocells where required to be solved efficiently. There are many challenges that are particular to femtocells and require different treatment than the traditional macro base stations. Some of the challenges faced are listed below [30] [31] [32] [22].

- Since femtocells are deployed in random fashion and operate in licensed frequency bands, RF interference issues arise and mitigation techniques are required to limit the effect of interference. Interference can occur between femtocell and macro cell, and femtocell to femtocell in both uplink and downlink directions. In addition, femtocells can operate in closed subscriber group (CSG), where only registered users can connect to the femtocell, and which means that a macro user in a vicinity of a femtocell will not be allowed to make handover. A macro user passing by a femtocell can experience huge interference coming from the femtocell when the user is receiving in downlink (DL). Femtocell user in uplink (UL) can also cause interference to the macro cell users in UL. Femtocells can also cause interference to each other, such as when two neighborhoods living in the same apartment and floor are separated by a wall.
- Unlike traditional macro base stations which are deployed and managed by operators, femtocells are customer deployed. It is possible for customers to deploy femtocells anywhere and even move it over course of time. The operators need to know the exact

location of the femtocells not only to know the physical state and condition of the femtocell but also to manage radio interference conditions and comply with regulatory issues.

- Providing QoS for femtocell users is much more challenging than the case of traditional macro base station users. Usually, femtocells use existing broadband infrastructure of customers for backhauling the traffic generated and it will be difficult to guarantee voice call QoS if the broadband infrastructure belongs to another service provider. It may even result in competition between the operators if they happen to provide the same service to their customers. In addition, since the public backhaul can be accessed by anyone, it poses security treat for the customers and it needs to be addressed by the operator.
- A frequent and unnecessary handover decision is another problem associated with mass deployment of femtocells. Handover decision can happen in multiple directions, femtocell to macro cell; macro cell to femtocell; and femtocell to femtocell. Handover decision from femtocell to macro cell is the easiest one because there is only one macro cell in a two tier network, that is, macro cell networks and femtocell networks. But the reverse is not easy as there are many candidate femtocells under the overlay of the macro cell and the signaling overhead for pre-handover procedure will be huge. It may also require frequent handover decision to happen as a user moves across a macro base station coverage. The access control of a femtocell user also presents another challenge for handover decision. Open access and closed access schemes present their own challenges on the way handover decision is made.
- There is a huge potential in the market for large amount of femtocell deployment. When there is much overlap in the femtocell coverage, the device management becomes complex and it may require different device management approach.

Before 2008, different parties involved in femtocell development took their own approach to solve the challenges mentioned above. As femtocells gained more popularity and operators wanted to deploy in their networks femtocellls from various vendors, the need to standardize the technology became evident for every party evolved in femtocells. The front runners in the standardization of the femtocell technology for UMTS based UTRAN where the 3GPP and the Broadband Forum (BBF) [32].

The creation and adoption of femtocell standards was crucial for its widespread acceptance. The new femtocell standard was required to define the interfaces for the existing mobile devices and networks. Furthermore, the standard supports and promotes competition among femtocell technology providers and from the consumer perspective, the standard allows easy and error free installation. Efficient and cost effective consumer premise equipment (CPE) femtocell management, operation and administration also requires femtocell to be standardized.

2.5 Network Architecture of 3G Femtocells

Femtocells where included in 3G networks in 3GPP release 8 for the first time, in which different standardization bodies, such as the Femto Forum, BBF, and 3GPP participated in the standardization process [33]. The standardization has addressed a range of issues, such as femtocell network architecture definition, their management/provisioning, radio and interference, and security.

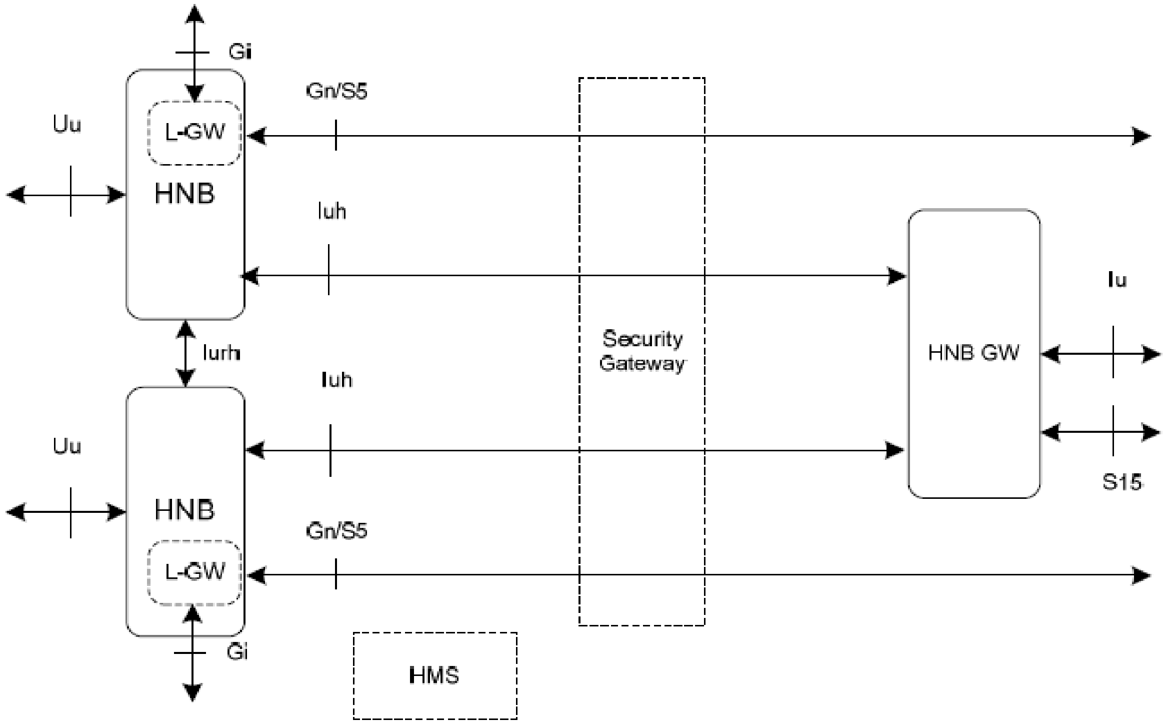


Figure 2.3 Femtocell network architecture *[34]*

The architecture builds on the 3G UMTS architecture, as depicted in Fig 2.3, to support high volume small cell deployments. Three new network elements are defined: home node B (HNB), home node B gateway (HNB-GW) and security gateway (SeGW). They make up femtocell/small cell access network [26]. In addition to the three elements, the standard also defines a HNB management system (HMS) which provides configuration information for HNBs.

2.5.1 Home Node B (HNB)

HNB (aka femtocell) is a network element physically placed at the customer's premise and provides broadband and voice connection to user terminals over the 3G Uu interface. It provides all the functionalities of the traditional Node B's and even most of RNC functions [35]. Functions which are unique to HNBs, such as HNB authentication, access control for CSG subscribers, and HNB-GW discovery, are also supported by the HNB.

2.5.2 Home Node B-Gate Way (HNB-GW)

The HNB-GW is an aggregation point for multiple HNBs and acts as a gateway through which the HNB accesses the operator's core network. Physically the HNB-GW is located in the premises of the operator's core network, similar to the RNC for Node B's. It supports Iu and Iur interfaces, where the former connects the HNBs to the core network and the later identifies the connection among HNB-GWs and/or RNC.

The standard defines alternative implementation for HNB-GW functionality to be integrated with HNB itself (co-located), which is termed in this case as local-gateway (L-GW). When this happens, the HNB is directly connected to serving GPRS support nodes (SGSN) or serving gateways (SGW) through Gn/S5 interface and it connects to a residential/IP network through a Gi interface [26].

2.5.3 Security Gate Way (SeGW)

A femtocell or HNB connects to a HNB-GW through a public network. Since the public connection may or may not be under the control of the operator providing the mobile broadband service, it is assumed to be un-trusted. The SeGW provides secured information exchange between a HNB and operator's core network. Through mutual authentication between the HNB and SeGW, a security tunnel is established to protect information transmitted in backhaul link. These enables operators to provide the same type of security level for users connected to their network either using HNB or traditional Node B.

2.5.4 The Iu-h interface

The Iu-h (Iu – home) interface is the extension of the Iu interface to accommodate femtocells. According to [36], there are two main reasons why a new interface, instead of the Iu interface, was needed. These are:

a. The Iu interface lacks the scalability to support millions of HNBs due limitations of services offered by ss7 emulation that exists between the HNB and HNB-GW.
b. The existing UMTS protocols do not have capability to handle registration and deregistration of HNBs. As the HNB is physically accessible to the user, it will be powered ON or OFF only when needed, requiring registration and deregistration process just like user equipment.

The Iu-h interface defines two new protocols called HNB Application Part (HNBAP) and radio access network application part (RANAP) user adaptation (RUA) protocols. The former handles signaling services during HNB and user equipment (UE) de/registration, and error handling, while the latter provides signaling services mainly for RANAP message transporting.

2.6 Proposed Small Cell Architecture

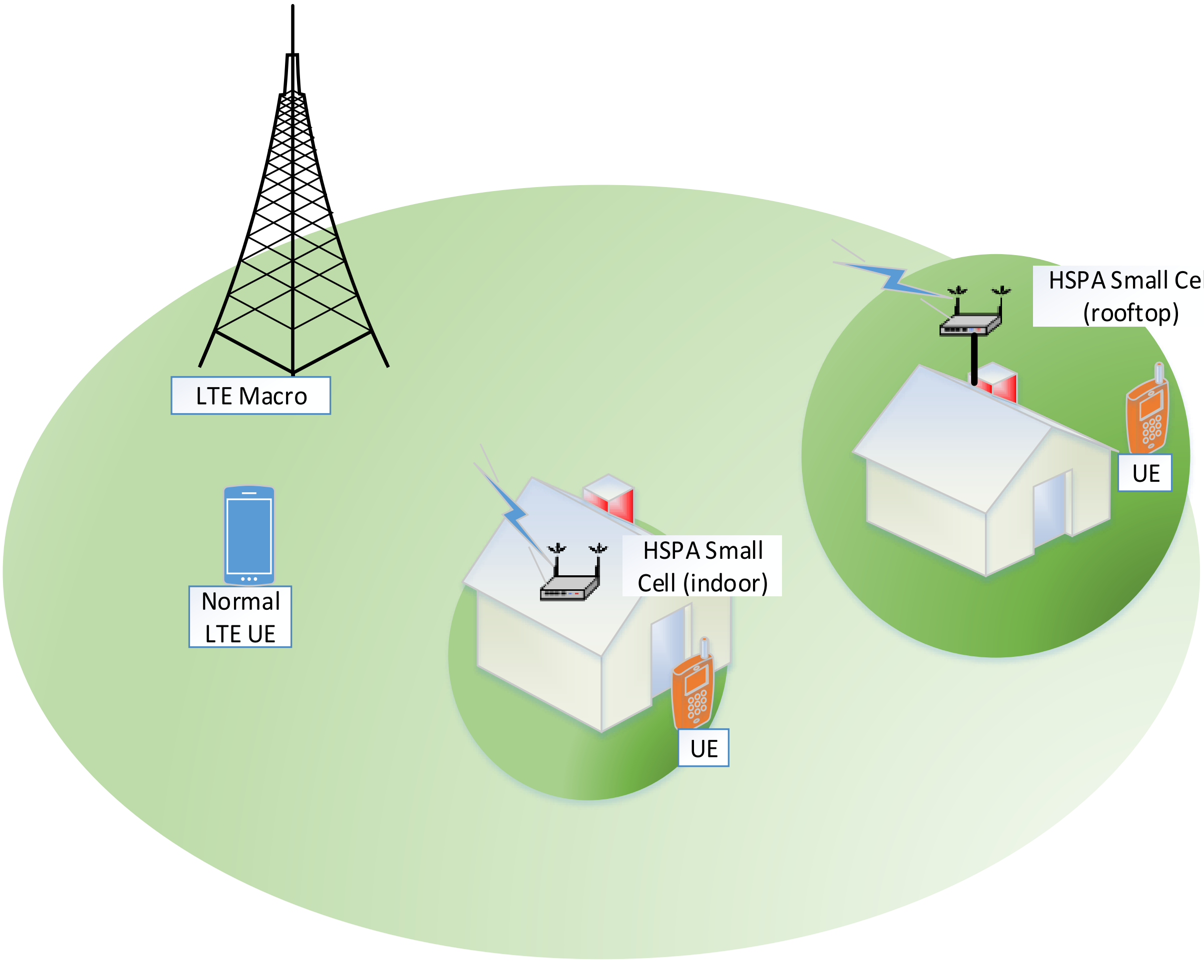
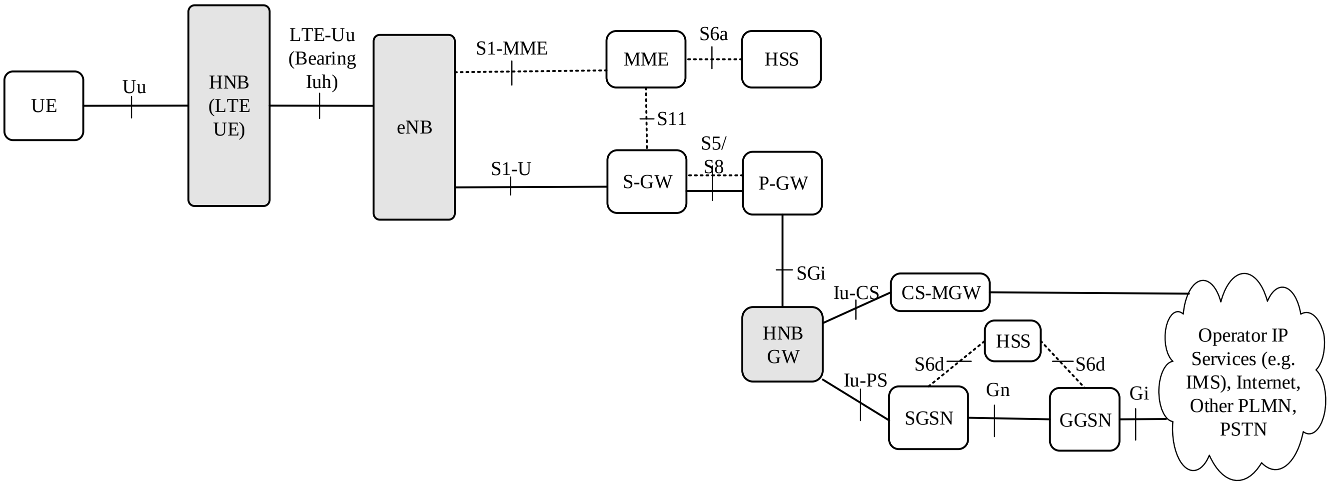


Figure 2.4 General Overview of the proposed LTE backhaul link of small cells

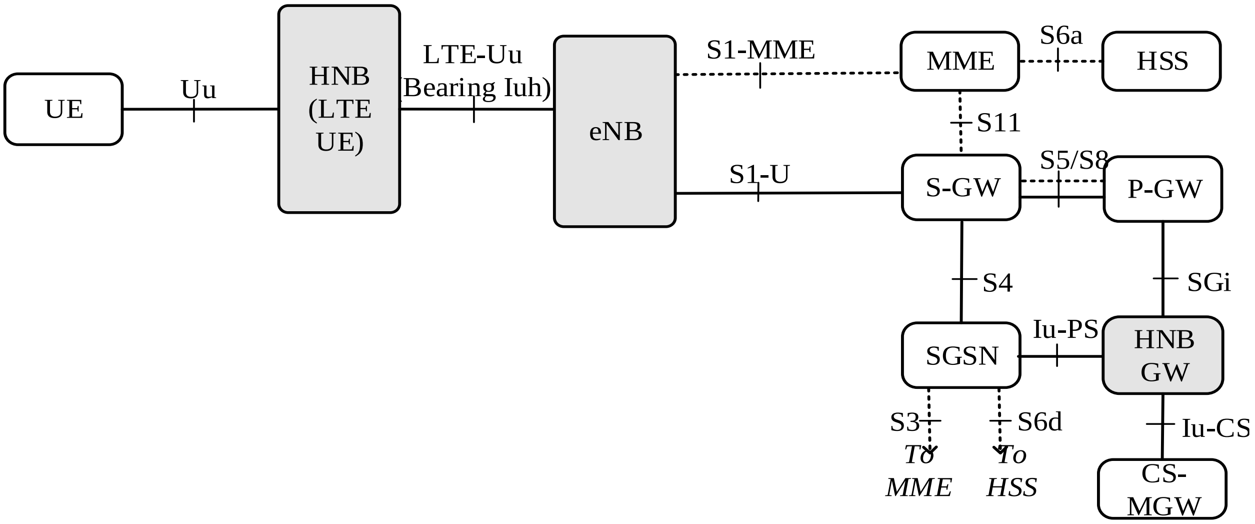
Fig 2.4 above shows the proposed LTE system which supports small cell (aka Femtocells) backhauling in addition to providing the usual voice and broadband service for normal LTE users. The plug-and play device that used to connect to the public infrastructure (that is, fixed line) is now connected to a LTE macro base station. Therefore, the small cell backhaul traffic is carried by the LTE multi radio macro cell over the LTE Uu interface. The small cells will compete with normal LTE users connected to the macro cell for LTE resources. Users can change their connection from macro cell to small cells or vice versa, but traffic off/on loading effect is not strait forward now. Offloading users will bring more backhauling requirement from the small cells, which means higher demand for macro cell resources.

The indoor/outdoor deployed HSPA small cells will provide 3G broadband and voice connection for users in their service range. Indoor users will enjoy high signal strength, and hence high signal to interference plus noise ratio (SINR), from indoor deployed small cells. But less number of users in average will connect to indoor small cells compared to average number of users that will connect to outdoor deployed small cells as the indoor small cells outside building coverage will be limited by building penetration loss.

The proposed architecture tries to introduce as little modification as possible to the existing femto architecture. No protocol change is proposed and all architectural elements discussed above in the femtocell architecture section are maintained with some change on their physical/logical location in the network. The mere purpose of the LTE as a backhaul for small cells' traffic is to provide transport channel for the small cells' backhaul traffic.



(a)



(b)

Figure 2.5 Proposed Femtocell Architectures: a. In the presence of full 3G core network: b. In the absence of full 3G core network

Our main focus is on the physical/logical placement of the HNB-GW, as it is the one which terminates the Iu-h interface. It is to be remembered that the location of SeGW logical element in femtocell architecture is more or less similar to the HNB-GW and, hence, it is not discussed here. Figure 2.5a shows the first alternative, where the HNB-GW is interfaced to packet data network gateway (P-GW) of LTE core network over the SGi interface. In LTE network architecture definition, the SGi interface is responsible for connecting the evolved packet core (EPC) to the external packet data networks (PDNs). We can consider the HNB-GW and the associated 3G core network elements connected to it as external networks interfaced to the LTE EPC over the SGi interface. The HNB-GW will then route data and voice over Iu-PS and Iu-CS, respectively. This architecture is based on the assumption that both LTE and WCDMA/HSPA core network infrastructures exists simultaneously (at least HSPA small cell core network infrastructure) in the service area.

Fig.2.5b shows the second proposed architecture. The SGi interface, again, interfaces HNB-GW with P-GW, but this architecture does not require the whole HSPA small cell core architecture to exist for it to function. Some logical elements, such as gateway GPRS support node (GGSN), of HSPA core network can be absent. Interfaces, such S4, S3 and S6d, follow from interface definitions of interworking between LTE and WCDMA/HSPA or GSM/GPRS radio access technologies [37].

If the physical implementations of LTE and HSPA small cell core network elements (logical nodes as physical nodes) are to follow the logical architecture outlined above, the HNB-GW seems to be far from the HNB. This will have impact on the round-trip signaling delay, but it is to be recalled that the Iu-h packet has to traverse a public network before reaching to HNB-GW in the original architecture. With this logic in mind, it is fair to assume comparable delay experience in the new and old femtocell architecture.

3.0 UMTS Long Term Evolution (LTE) Technology

The aim of this chapter is to provide an overview to LTE technology by describing some of its features as standardized in release 8. To that end, in section 3.1 we will provide introduction and motivation behind LTE; in section 3.2 we will outline some of the LTE system requirements; in section 3.3 we will discuss downlink and uplink transmission schemes adopted for LTE and in section 3.4 MIMO concepts will be presented. Finally, we will conclude the chapter by discussing the LTE protocol architecture in section 3.5. The book by Holma and Toskala [38] is used extensively for this chapter.

3.1 Introduction

Standardization for LTE started in late 2004 by 3GPP by laying out the targets for the new technology. Some of the driving factors for the new technology where the need for higher capacity, higher data rates, reduced latency on the user plane and control plane, and packet optimized radio access technology [39]. In addition, there was a need to simplify network architecture by reducing number of network elements with the end goal of driving down network infrastructure costs. To achieve these goals, 3gpp started working on two parallel projects, LTE and system architecture evolution (SAE), which were intended to define both the radio access network and network core of the system.

LTE is also referred to as evolved UMTS terrestrial radio access network (E-UTRAN) and it is based on new technical principles. For multiplexing users it uses orthogonal frequency division multiple access (OFDMA) in downlink and single carrier frequency division multiple access (SC-FDMA) in uplink. MIMO antenna schemes which are intended to boost data rates and some major modification on the existing UMTS protocol architectures are also essential parts of LTE.

3.2 LTE System Requirements

Requirements for LTE technology where developed with the ambition of evolving it towards a full-fledged 4G technology. LTE is, therefore, required to deliver superior performance compared to existing 3gpp networks based on HSPA technology. Some of the requirements of LTE release 8 are listed in Table 3.1 below.

Table 3.1 LTE system requirements

Parameter	Details			
Data rate (Mbps)	Downlink	SISO	2x2 MIMO	4x4 MIMO
		100	178	326
	Uplink	QPSK	16QAM	64QAM
		50	57	86
Data types	Fully packet switched (voice and data)			
Channel bandwidths (MHz)	1.4, 3, 5, 10, 15 and 20			
Spectral efficiency (bps/Hz)	Downlink	SISO	2x2 MIMO	4x4 MIMO
		5	8.6	16.3
	Uplink	QPSK	16QAM	64QAM
		2.5	2.9	4.3
Latency	Idle to active less than 10ms Small packets ~10ms			
Duplex schemes	Both FDD and TDD			
Mobility	0 - 15 km/h (optimized) 15 – 120 km/h (high performance)			
Access schemes	OFDMA (downlink)7 SC-FDMA (uplink)			

3.3 LTE Physical Layer

3.3.1 OFDMA

OFDM is a technique of breaking operating bandwidth into orthogonal sub-carriers which then makes it possible to send several data symbols in parallel resulting in better spectral efficiencies and simpler receiver structures. Orthogonality between sub-carriers is achieved by selecting the center frequencies for each sub-carrier in such a way that in frequency domain neighboring sub-carriers have zero value at the sampling instant of the desired sub-carrier. Performing inverse fast Fourier transform (IFFT) on the group of data symbols to be transmitted on the orthogonal sub-carriers will generate the required OFDM signals at the transmitter side and fast Fourier transform (FFT) is employed at the receiver side to recover the transmitted symbols [40].

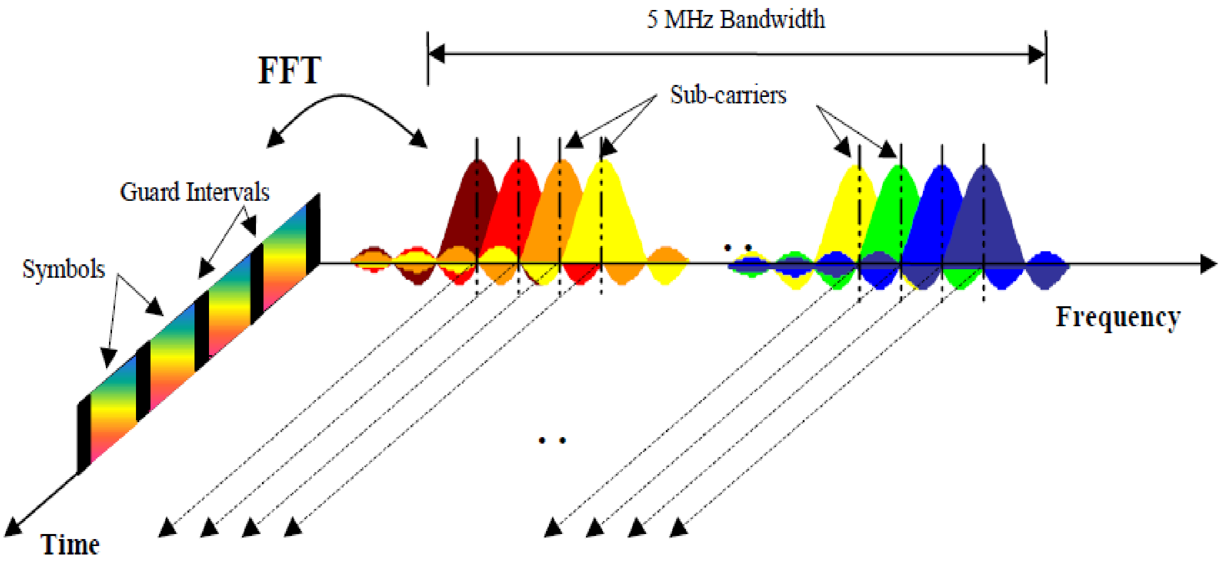


Figure 3.1 Frequency-Time representation of an OFDM signal *[39]*

Fig.3.1 shows the time-frequency representation of an OFDM signal. Observation can be made that even though the subcarrier signals are overlapping in frequency domain, mutual interference can be avoided because sampling is performed at the center of sub-carrier frequencies. These are referred as sub-carrier positions. This makes OFDM technique perfect candidate for frequency selective channels. A constant frequency spacing of 15 kHz is adopted for LTE release 8.

The main challenge for OFDM is the high peak-to-average power ratio (PAR) of the transmitted signal. It requires high linearity in the transmitter which makes power amplifier design very difficult (linear power amplifiers have low power conversion efficiency). OFDM is also sensitive to frequency offset.

OFDMA is the multiple access scheme adopted for LTE downlink and it is a combination of OFDM and TDMA. In OFDMA system, users can be scheduled on both time and frequency resources. Resource scheduling in LTE means providing time and/or frequency resources for users served by a macro base station sector. Unlike 3G RATs, such as WCDMA and HSPA, frequency domain scheduling is possible in LTE. In fact, according to [2], as much as 40% of the performance gains of LTE over HSDPA comes from frequency domain scheduling.

3.3.2 SC-FDMA

Since OFDM presents a challenge in terms of power amplifier design because of weak PAR properties mentioned above, it is not an optimum choice for user terminal uplink transmission scheme. SC-FDMA is adopted for uplink transmission which is a modified version of OFDM. SC-FDMA employs single carrier modulation. A discrete Fourier transform (DFT) pre-coding and IFFT are used to create frequency domain sub-carriers.

3.4 LTE MIMO concepts

MIMO is the concept of using multiple antennas at the transmitter and receiver side to exploit the wireless channel through spatial multiplexing as well as pre-coding and transmit diversity. Spatial multiplexing allows transmitting different streams of data simultaneously on the same resource blocks (time-frequency resource) by exploiting the spatial dimension of the radio channel [39]. The different streams of data can be sent to a single user which is referred to as single user MIMO (SU-MIMO) or they can be sent to different users which is referred as multi user MIMO (MU-MIMO). Fig.3.2 below shows the basic principles of MIMO concept. Pre-coding operations at the transmitter allows signals to be transmitted from different antennas ports to be weighted with the end goal of maximizing signal to noise ratio (SNR) at the receiver.

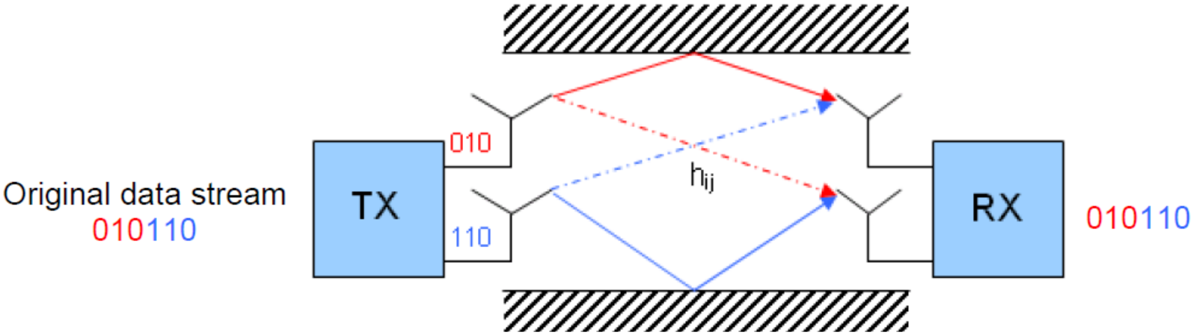


Figure 3.2 Spatial multiplexing (simplified) *[39]*

LTE release 8 defines 2x2 MIMO configuration (allowing 2 streams of data to be transmitted on the same time-frequency resource) to be used in downlink and 1 stream of data in uplink as a baseline. Subsequent releases of LTE have enabled the use of higher order MIMO configurations possible. LTE release 10, for example, allows the operation of up-to 8 layer MIMO configuration through beam-forming in downlink [41].

3.4 LTE Protocol Architecture/System Architecture Evolution (SAE)

3gpp adopted an all IP network architecture for LTE that supports high data rate, low latency and supports multi radio access networks. The main components of SAE architecture include UE, E-UTRAN and evolved packet core (EPC). Fig. 3.3 shows the overall system architecture

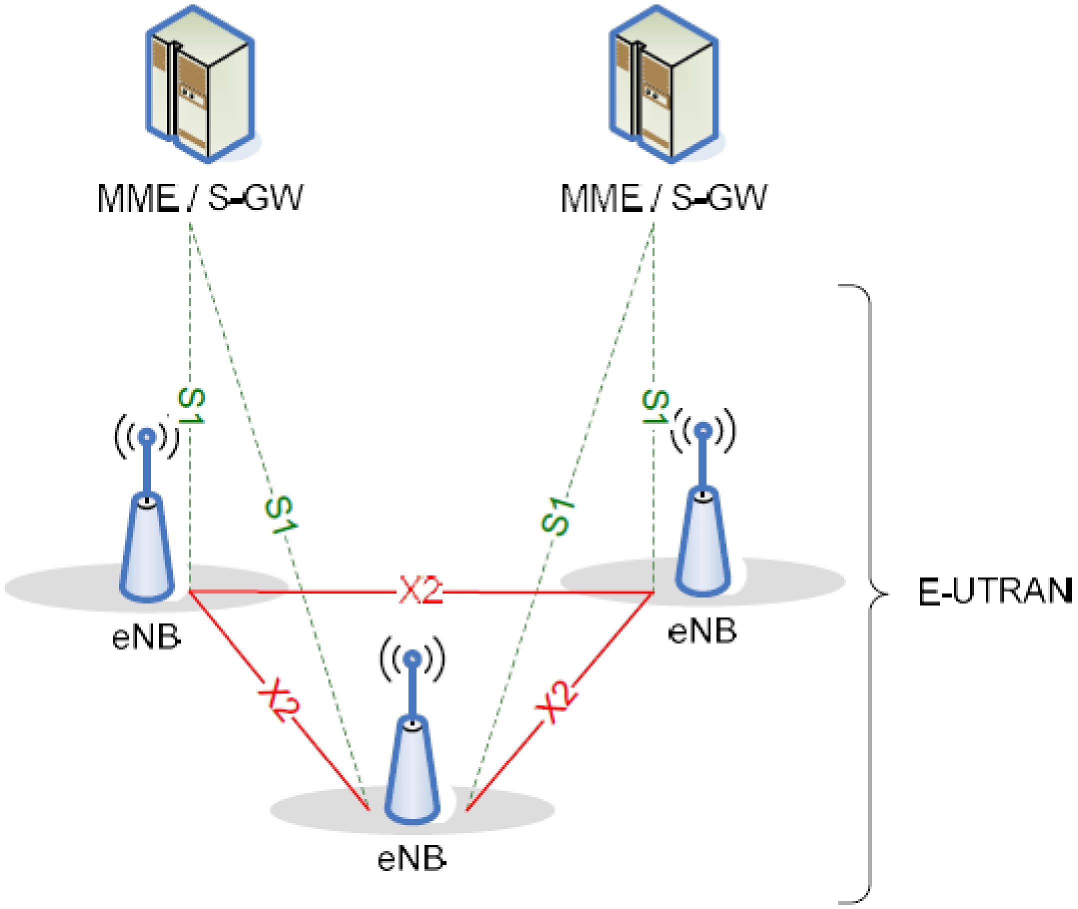


Figure 3.3 Overall network architecture *[39]*

The EPC is a logical evolution of GSM and WCDMA core networks. It removes the RNC element in WCDMA to pave way for flat network architecture. The flat architecture design of the EPC is responsible for the reduced latency on both data plane and control plane. The EPC consists of different logical elements, such as, mobility management entity (MME), serving gateway (S-GW), packet data network gateway (P-GW) and home subscriber service (HSS). The MME is the main control element in the EPC and it is responsible for UE authentication and security, mobility management, and managing subscription profile and service connectivity. The S-GW handles user plane management and switching and the P-GW is the router between the operator network and external packet data networks.

E-UTRAN consists of multiple eNodeBs (eNBs) connected with each other through the X2 interface and it provides the E-UTRA user plane and control plane protocol terminations towards the UE [39]. The eNBs are also connected to the EPC through the S1 interface. The eNBs perform a range of functions including inter cell radio resource management (RRM), radio admission control, and dynamic resource allocation.

4.0 SIMULATOR DESCRIPTION AND PERFORMANCE ANALYSIS

System level simulator has been developed to study the performance of the proposed LTE/LTE-Advanced small cell backhaul. The simulator is a combination of independent HSPA and LTE system level simulators coordinated through a common code which also provides the traffic steering of different types of users across different network layers (e.g. different RAT layers, cell size and operating frequencies). These chapter describes the simulator along with the network deployment scenarios.

4.1 Simulation Model and Methodology

The simulation work incorporates a real geographic area which better adheres to the environment we are studying, informal settlement regions which characterizes the majority of the dwellers in most of the emerging markets in the world. These regions of the world are characterized by lack of energy supply, insecurity, lack of fixed lines, etc. and as population grows it poses difficulty in delivery of services such as mobile internet.

Hanna Nassif ward of Tanzania's capital, Dar el Salaam, is used as a case example to perform our network simulations. With a population size of 20 to 30 thousand and building density of 3050 per km square [42], Hanna Nassif is typical of an emerging market unplanned settlement. The topographical difference of this island is 19m and the buildings are mostly single story.

Figure 4.1 Overhead view of Hanna Nassif Island of Dar el Salaam City *[43]*

4.1.1 Deployment Scenario

The network deployment consists of heterogeneous networks of co-sited HSPA/LTE macro cells and user deployed small cells in the service area. Unlike the macro cells which are fixed, the small cells are randomly deployed in the service area. Two alternative deployment scenarios are considered for the small cells, indoor and rooftop as discussed in chapter 2. We study the following deployment scenarios based on the number and type of small cell deployment.

1. HSPA/LTE Macro only deployment
2. HSPA/LTE Macro + 10 indoor deployed small cells
3. HSPA/LTE Macro + 30 indoor deployed small cells
4. HSPA/LTE Macro + 60 indoor deployed small cells
5. HSPA/LTE Macro + 10 outdoor deployed small cells

6. HSPA/LTE Macro + 30 outdoor deployed small cells
7. HSPA/LTE Macro + 60 outdoor deployed small cells

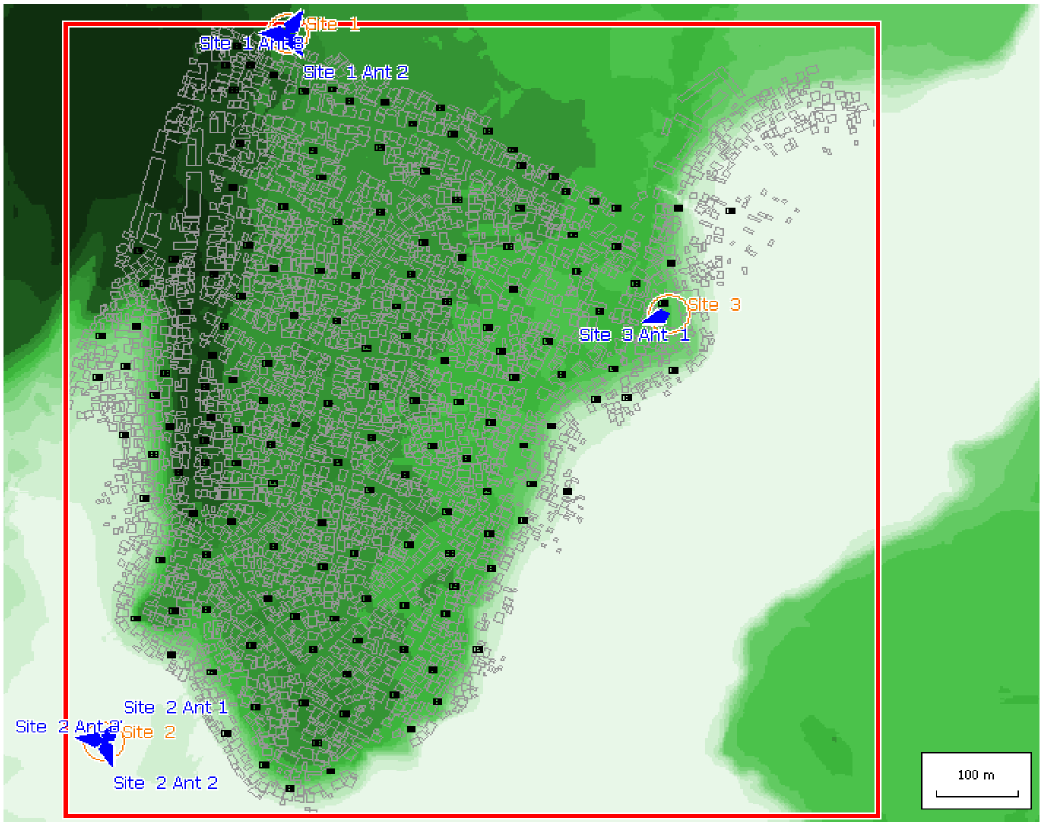


Figure 4.2 Network Deployment of the service area

With these network deployments we can provide service for HSPA capable UEs through HSPA macro cells and the HSPA small cells will provide capacity and coverage improvement through user offloading thereby improving the system performance. Co-sited LTE macro cells will serve low base but gradually expanding LTE-capable UEs. In addition, LTE macro cells will also serve to self-backhaul the HSPA small cells in the service area. This will provide cost effective solution to backhaul end user-deployed small cells in densely populated informal settlements where the traditional methods of backhauling mechanisms are not realistic alternatives.

4.1.2 Small Cell Backhaul Performance Enhancement Methods

As explained above, the LTE macro cells will be providing self-backhauling service for HSPA small cells in addition to serving minority but gradually increasing LTE-capable user base. This brings challenge in terms of LTE physical resource allocation because of the increased demand for PRBs coming from normal LTE users and small cell backhaul. Increased density in small cell deployment in the service area will provide performance improvement and at the same time increases backhaul capacity demand which intern brings LTE resource limitation. These will result in backhaul capacity bottleneck for small cells while at the same time limiting the achievable throughput of normal LTE UEs. To limit and avoid the potential bottleneck of small cell backhaul and improve normal LTE UEs QoE, we study different performance enhancement methods which are listed and discussed briefly below.

a. Multiple Input Multiple Output (MIMO)
b. Carrier Aggregation (CA) or bandwidth scaling
c. Traffic steering

A. Multiple Input Multiple Output (MIMO)

MIMO is LTE/LTE-advanced standard feature which employs multiple transmitting antennas to transmit multiple signals on the same time frequency resource to multiple receiver antennas and thereby increasing the link spectral efficiency and, therefore, overall system performance [44]. In this study we consider the impact of utilizing MIMO schemes for small cell backhaul on the overall system performance. By reducing LTE physical resource blocks (PRBs) needed for small cell backhaul, MIMO schemes can potentially meet the backhaul capacity demand and allow relatively more resources available to normal LTE users. In our study, we consider 2x2 and 4x4 configuration for LTE release 8 and 8x8 configurations for LTE release 10.

B. Carrier Aggregation or Bandwidth scaling

LTE/LTE-advanced PRB resources available at a macro cell can be increased by scaling operating bandwidth or through carrier aggregation concept of LTE-advanced feature. LTE physical layer design allows bandwidth scalability of 1.25-20 MHz [45]. On the other hand, LTE-advanced carrier aggregation feature allows bandwidth scaling of up-to 100 MHz [46]. There are two types of carrier aggregation techniques, continues and non-continues carrier aggregation. The former is easier to implement in LTE-advanced as it requires smaller changes in the physical layer structure [46]. In our study, we consider bandwidth scaling of up-to two carriers of 10 MHz each (20 MHz total).

C. Traffic Steering

Because of the growing demand for mobile broadband network evolution is taking place through migration towards multi-layer deployments. Operators are faced with challenges of managing traffic flow across multiple layers (different radio access technologies, multiple operating frequencies, varying cell sizes, etc.). The concept of traffic steering is introduced to control and direct data and voice to the best suitable cell layer and radio technology within any network [47]. It address the challenges of directing traffic to the best possible layer in a multi-layer deployment environment by finding ways to coordinate mobility configurations of different layers. Cell load balancing, UE speed, power consumption, UE capabilities and backhaul capacity are few principles which could be used for adaptive traffic steering decisions [48].

In our study, we identify three types of layers for the deployment scenario under investigation. These are, LTE macro layer, HSPA macro layer and HSPA small cell layer. Normal LTE-UEs will be able to connect to any of these layers while HSPA-UEs can migrate from HSPA macro to HSPA small cell or vice versa. Contrary to these users, small cell backhaul will only be served by LTE macro layer. Since our study uses static simulator, the traffic steering scheme considered is radio resource connection (RRC) idle traffic steering mechanism as described in [48]. RRC connected traffic steering mechanism is not considered. Hence, users will be able to choose which RAT (LTE or HSPA) or which cell (macro or small cell) to camp on during cell reselection period. In our study, the merits of two traffic steering alternatives will be discussed, LTE small cell backhaul prioritized and normal LTE-UE prioritized. The former involves providing LTE resources first to small cell backhaul based on demand and allowing LTE-UEs to migrate to LTE macro only when there is left over resource from the backhaul capacity demand and it is enough to support a minimum data rate for the migrating LTE-UEs. To that end, we assume all UEs to be camping on HSPA network initially for this case. The later requires LTE-UEs to camp on LTE macro cells and only after providing at least the minimum throughput (512 Kbps) that the small cell backhaul demands can be entertained.

4.1.3 Simulator and Simulation Parameter Descriptions

Two independent system level simulators (one based on HSPA technology and another based on LTE technology) and a common system which will coordinate the two simulators by setting common parameters and providing traffic steering functions where developed. We adopted the HSPA simulator from another work carried out earlier on HSPA small cell performance in densely populated informal settlement areas [43].

Throughput performance of UEs served by the HSPA heterogeneous network (macro and small cell) will be generated using the HSPA simulator. The aggregate traffic generated at each active small cell will then be collected to serve as an input to the LTE simulator for backhaul dimensioning purpose. The LTE simulator will then perform the small cell backhaul provisioning along with LTE-UEs that are camping on it based on the traffic steering policies as described before. These process is performed for all deployment scenarios and small cell backhaul enhancement mechanisms discussed before. Fig. 4.3 below show schematic block diagram representation of the LTE system simulator.

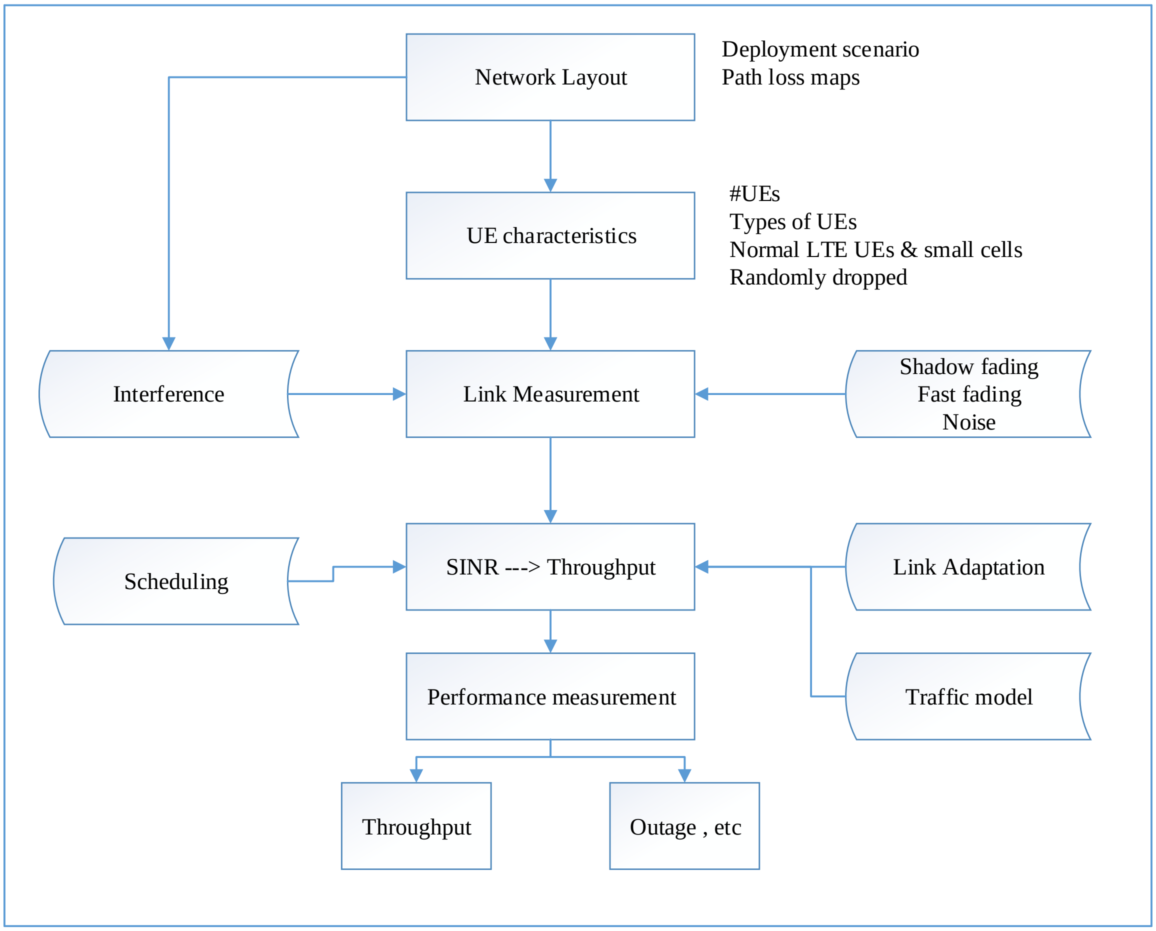


Figure 4.3 Schematic block diagram of LTE system level simulator

In total 45 LTE or HSPA capable UEs are dropped randomly in the service area and user throughput is collected at each snapshot. For small cell backhaul priority case all UEs are assumed camping on the HSPA network (macro or small cell) and after dimensioning the backhaul for aggregate traffic of each serving small cell, some of LTE-capable UEs will be pushed to the LTE network based on availability of resources to meet the minimum required throughput. In the case of LTE-UE priority, performance is evaluated for varying levels of LTE penetration (for LTE minority, equal number of HSPA/LTE UEs or LTE majority).

We selected downlink connection, which is usually the bottleneck in mobile broadband provision, to study the system level performance of our network. To adhere to realistic path loss model, we used the dominant path loss model of WinProb commercial tool to carry out the propagation prediction with realistic three dimensional building vectors and topographical data of the Hanna Nassif area.

The parameters specifications for both technologies (HSPA and LTE) follows commonly used recommendations of 3GPP and are listed in Table 4.1 below.

Table 4.1 HSPA Simulator parameter and assumptions

Parameter	**Values/Assumptions**			
Air Interface	HSPA FDD, LTE FDD			
Carrier Freq./ Bandwidths	LTE: 2600/800 MHz / 10 MHz and 2 x 10 MHz HSPA: 2112.5 MHz / 5 MHz			
Simulation	Radio propagation modeling (WinProp) **Error! Reference source not found.**, Static system level simultion (Matlab), 2.5 m resolution			
SINR-throughput mapping		2x2 MIMO	4x4 MIMO	8x8 MIMO
	SINR_{min} (dB)	-10	-10	-10
	BW_{eff}	0.42	0.40	0.33
	SINR_{eff}	1.1	1.5	2.1
	S_{max} (b/s/Hz)	7.67	14.5	25.6
Macro Paramaeters				
Macro Sites	Site1 (3 cells)	Site2 (3 cells)	Site3 (1 cells)	
Transmit Power	LTE: 46 dBm, HSPA: 37.8 dBm (10% for CPICH)			
Antenna Height	10 m	15 m	10 m	
Antenna Patterns	Kathrein 741984			
Sector Azimuths	20°,140°,260°	0°, 120°, 240°	250°	
Intersite distance	Site 1-2: 955 m, Site 2-3: 880 m, Site 3-1: 585 m			
Small Cells Parameters				
SC number	Three cases considered: 10, 30 and 60 small cells			

Parameter	Values/Assumptions
Location/Height	Randomly deployed, Indoor:1.5 m, Rooftop: 4 m or 7 m
LTE backhaul	Antenna Gain: 0 dBi, Noise Figure: 9 dB, Antenna config: 2x2, 4x4, 8x8 MIMO
HSPA access	Tx power 20 dBm (10% for common pilot channel), Omni, 0 dBi antenna gain, 3 dB cell selection bias
UE Parameters	
UE height/location	1.5 height, 50% HSPA-UEs/LTE-UEs dropped randomly in whole area, 50% HSPA-UEs/LTE-UEs cluster-dropped within 40m radius of small cells
UE number	45 HSPA-UEs or LTE-UEs in service area
LTE-UEs	Noise Figure: 9 dB, 2 × 2 MIMO, Ant. Gain: 0 dBi
HSPA-UEs	Omni.; 0 dBi gain, -99dBm noise; 15Code HSDPA
Buildings and Fading Characteristics	
Shadow Fading	Shadow fading: WinProp ray tracing
Fast fading	Rician (for small cell-eNB, K=2), Rayleigh (for UEs)
Buildings	Variable dimensions, heights 3-6 m, penet. loss: 10 dB

A. HSPA SINR to Throughput Mapping

Evaluation of SINR in the simulation is carried out by taking into account own cell interferences, which comes due to multipath effect on the channelization codes, and interference from other cells. SINR for each randomly distributed active UEs in the service area is calculated and SINR to throughput mapping is done using curve fitting algorithm.

B. LTE SINR to Throughput Mapping

LTE FDD with 10 MHz bandwidth at two operating frequencies, 800 MHz and 2600 MHz, is studied in the simulation. The small cell backhaul is dimensioned by scaling the small cell served capacity by 1.26 to account for control overheads (Iu-h interface between the HSPA small cell and core network) which follows the recommendation by NGMN [49] [50].

Modified Shannon's formula for LTE capacity equation as suggested in [51] is employed for SINR to throughput mapping. It provides throughput per user obtained using a single LTE resource block.

$$TP_{ue} = BW_{prb} * BW_{eff} * \log_2\left(1 + \frac{SINR}{SINR_{eff}}\right) \qquad (4.1)$$

BW_{eff} and $SINR_{eff}$ are correction factors for the modified formula with values as given in the parameters table above. They are selected such that equation 3.1 better approximates LTE link level throughput effectively and they depend on antenna configurations, network implementation and signal processing. The parameter BW_{prb} represents bandwidth of a single LTE PRB, which we selected 180 kHz value among the alternatives. Equation 4.1 provides user throughput values which increases logarithmically with SINR value. Practically throughput cannot increase indefinitely, pertaining to physical limitations on the maximum number of bits we can pack in a symbol (maximum modulation scheme). A maximum spectral efficiency values are set depending on the MIMO configuration and modulation schemes used as provided in Table 3.1.

4.2 Simulation Results and Discussions

As pointed out earlier, two operating frequencies are considered in our simulation, 800 and 2600 MHz frequencies. LTE is a multi-radio technology and as such it operates in a range of frequencies. The selection of these two operating frequencies serves as representative of this range. However, for the deployment scenario we considered, the significance of choosing one over the other brings very little difference in terms of throughput gain. This observation is attributed to the fact that the deployment scenario we considered is interference limited network. Performance difference due to difference in operating frequency starts to shrink with decreasing inter-site distance as the system becomes interference limited [52].

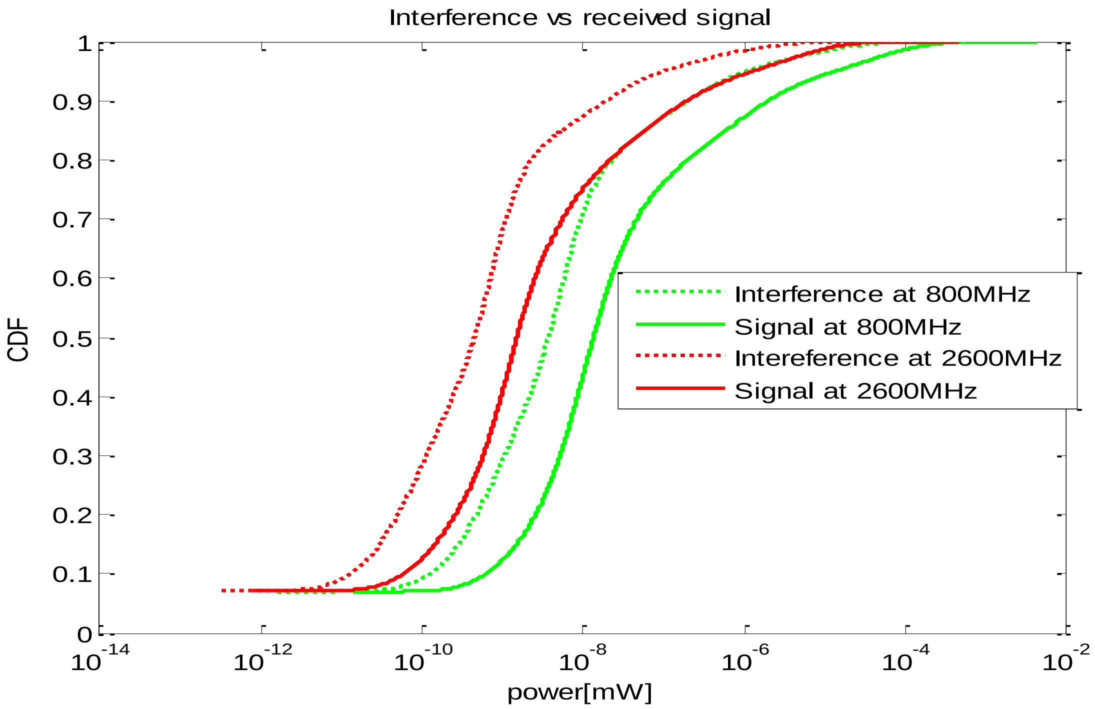


Figure 4.4 CDF plot of signal versus interference levels received at 800 and 2600 MHz frequencies

Fig.4.4. shows typical signal and interference levels received at the two frequencies. The received signal level and interference level at 800 MHz is significantly higher compared to the received signal level and interference level at 2600 MHz, respectively. The SINR at the two frequencies shows no significant difference as can be observed from cumulative distribution functions (CDFs) of SINR per PRB plot in Fig.4.5. Hence, expected throughput gain due to lower operating frequency than relatively higher operating frequency is insignificant without employing interference mitigation technique, which is out of the scope of this thesis. Hence, hereafter, our discussion will concentrate on 2600 MHz and the observations will similarly apply to the 800 MHz as well.

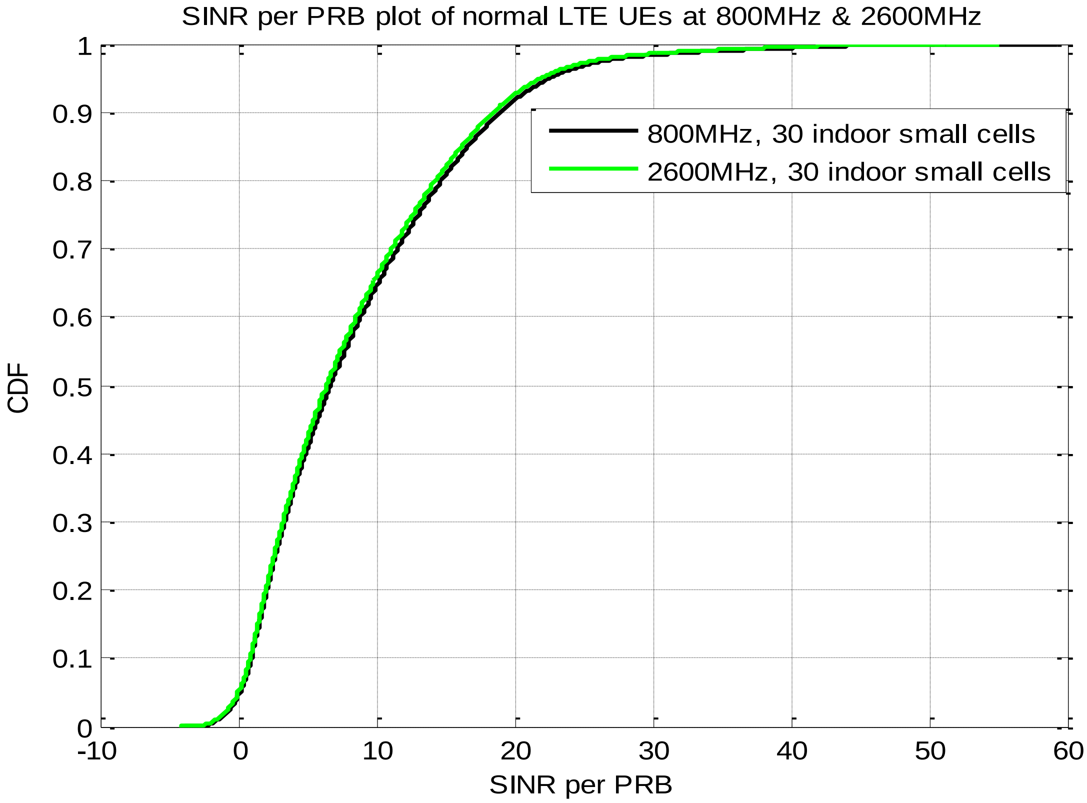


Figure 4.5 CDF plot of SINR per PRB at 800 and 2600 MHz frequencies

Fig.4.6. shows aggregate (sum of user throughputs served by an HSPA small cell) access capacity generated by HSPA small cells when independently running the HSPA simulator. Increased user offloading to outdoor deployed HSPA small cells, due to improved coverage area of rooftop deployment, results to relatively high access capacity. Indoor small cells are rarely active as their coverage is limited by building penetration loss. But when active they provide high SINR link level connection due to proximity to users, which is the reason for indoor small cells relatively high performance at the high end of the CDF plot. The LTE small cell backhaul is expected to provide enough capacity for occasionally active but relatively high capacity generating indoor small cells and frequently active but relatively lower capacity generating outdoor small cells. With increasing small cell density per LTE macro, the aggregate capacity from multiple outdoor deployed small cells will bring a challenge on the LTE macro resource allocation.

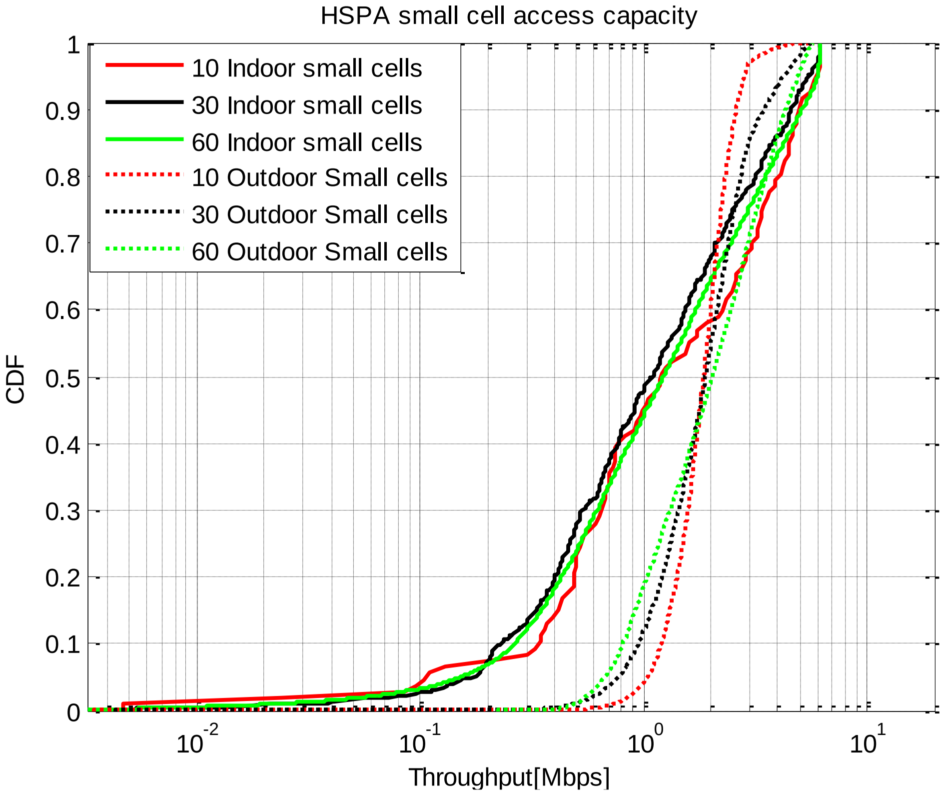


Figure 4.6 Throughput CDF of aggregate HSPA Small cells access capacity

Individual UEs throughput served by rooftop deployed small cells tend to be lower relative to those served by indoor small cells. But when it comes to the frequency of being active, rooftop small cells top because of higher offloading opportunity in the relatively larger area they serve. For 60 small cells, for instance, outdoor deployed small cells are active 16.25% more than indoor deployed small cells. In addition, outdoor deployment provides the opportunity to use off-grid powering options (such as solar cell) and the study of throughput fairness for HSPA-UEs in the presence of small cells shows that outdoor deployment provides the most equitable user throughput distribution [43].

The rest of this chapter is dedicated to small cell LTE backhaul performance results discussion and analysis along with the implications on LTE-UEs served by LTE macros. Our discussion focuses on outdoor small cells for the performance reasons outlined above and because collectively they present high backhaul capacity demand. We present first results for HSPA small cell backhaul prioritized followed by results for LTE-UEs prioritized traffic steering cases. In both cases, the discussion includes the performance gains obtained when different small cell LTE backhaul enhancement mechanisms that where presented earlier (e.g. higher order MIMO and bandwidth scaling) are considered. Some of the terminologies used in the plots are presented in Table 3.3 below.

Table 4.2 Terminologies used in performance results

Terminologies	Comments
SC-LTE-BH	Small cell LTE Backhaul
LTE connected UEs	LTE-capable UEs served by LTE macro
HSPA connected UEs	UEs served by HSPA macro or HSPA small cells

4.2.1 HSPA Small cell Backhaul Prioritized

Here, much of the LTE macro resource is allotted to serve small cell backhaul capacity. To that effect, all users are initially assumed camping on the HSPA heterogeneous network (HSPA macro and small cell). Then, small cell backhaul dimensioning is conducted based on small cell served UEs aggregate throughput plus control overhead estimation. Some LTE UEs are allowed to establish LTE cell connection if the selected cell has enough resource to support a minimum throughput of 512 kbps.

The ratio of provided small cell LTE backhaul capacity to requested small cell backhaul capacity is chosen as performance metrics to study the performance of LTE/LTE-advanced as small cell backhauling option. Fig.4.7 shows this ratio for three different backhaul performance indicators (perfect backhaul, more than 50% backhaul capacity demand addressed and less than 50% backhaul need addressed). It can be clearly observed that the majority of small cells backhaul demand is fully addressed. With increasing small cells, though, the challenge to provide enough LTE resources also becomes difficult, as can be observed for 60 small cells for which only 87% are getting full backhaul resources.

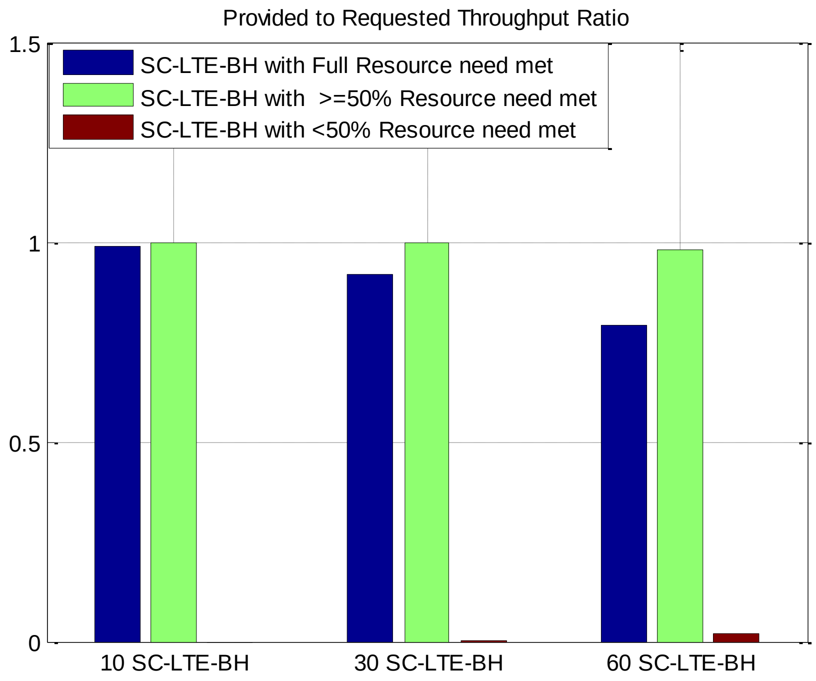


Figure 4.7 Outdoor SC-LTE-BH (2x2 MIMO) provided to requested capacity ratios

Fig. 4.8, Fig. 4.9 and Fig. 4.10 show performance results when the different small cell backhaul performance enhancement mechanisms (4x4 MIMO, 8x8 MIMO and Dual Carrier, respectively) are applied. We can clearly observe the performance improvements that comes with increasing order of MIMO configurations (improved spectral efficiency). The highest improvement happens with 8x8 MIMO and increased spectrum (2x10 MHz), where almost all backhaul capacity requirements are fully addressed.

Table 4.3 Percentage of fully satisfied SC-LTE-BH

# Small cells	2x2 MIMO	4x4 MIMO	8x8 MIMO	2x10 MHz
10	99.98	100	100	100
30	96.11	99.87	99.99	99.99
60	87.39	99.12	99.93	99.91

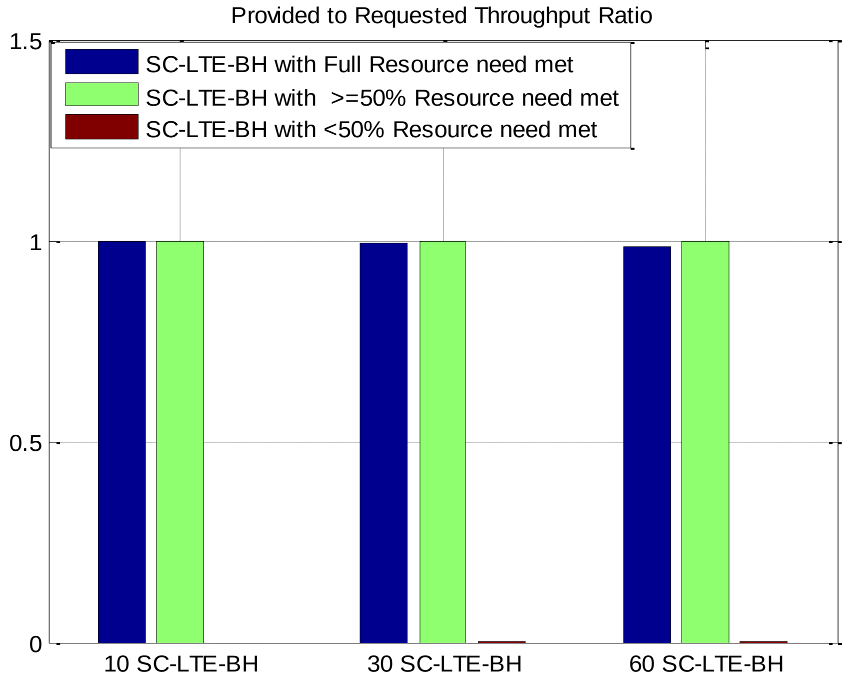


Figure 4.8 Outdoor SC-LTE-BH (4x4 MIMO) provided to requested capacity ratios

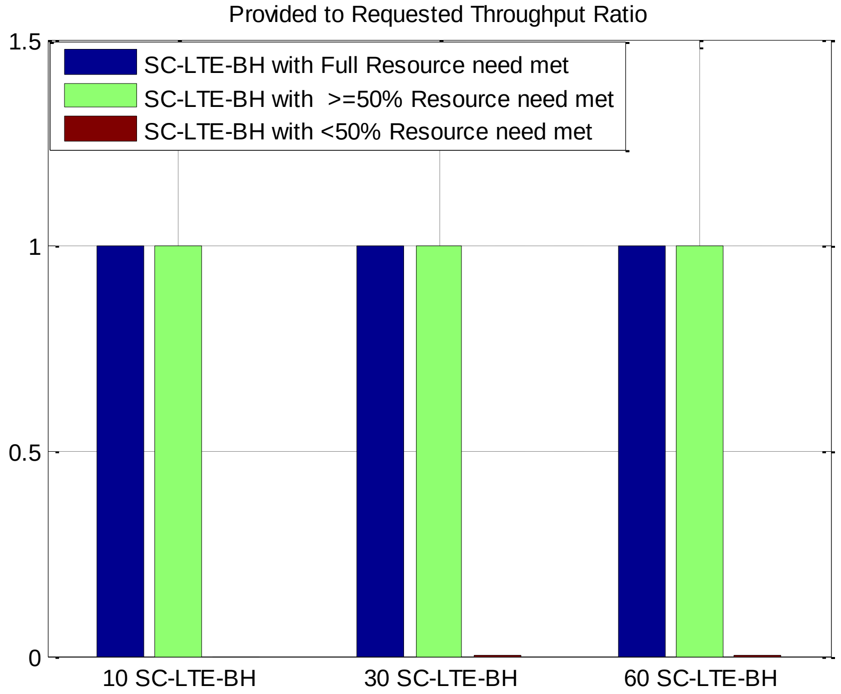


Figure 4.9 Outdoor SC-LTE-BH (8x8 MIMO) provided to requested capacity ratios

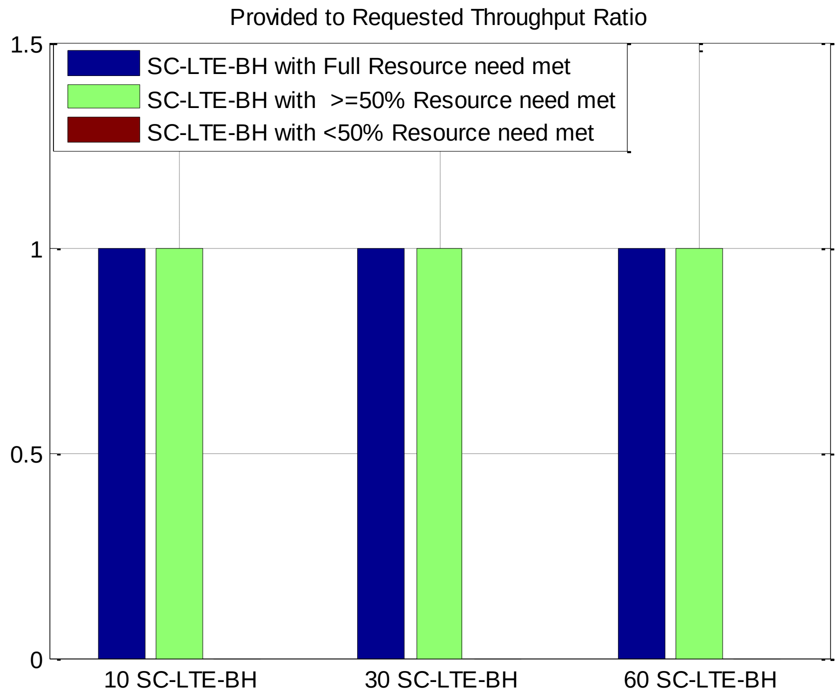


Figure 4.10 Outdoor SC-LTE-BH (Dual Carrier) provided to requested throughput ratios

We can also observe the performance from the perspective of normal LTE-UEs. Fig. 4.11 shows the throughput CDFs for UEs (both LTE and HSPA) with 2x2 MIMO configuration for small cells backhaul and single 10 MHz carrier. Improved performance is observed for UEs connected to LTE cells compared to those served by HSPA cells (macro or small cell). Performance also improves for HSPA-UEs with increasing number of small cells presence in the service area.

LTE-UEs throughput gains are also observed when higher order MIMO and carrier bandwidth scaling are applied to small cell backhaul. Using 2x2 MIMO and single carrier as a base line we evaluated the three enhancement mechanisms (4x4 MIMO, 8x8 MIMO and 2x10 MHz bandwidth scaling) as shown in Fig.4.12, Fig. 4.13 and Fig. 4.14. It can be noted that the highest throughput gain happens when additional carrier is provided.

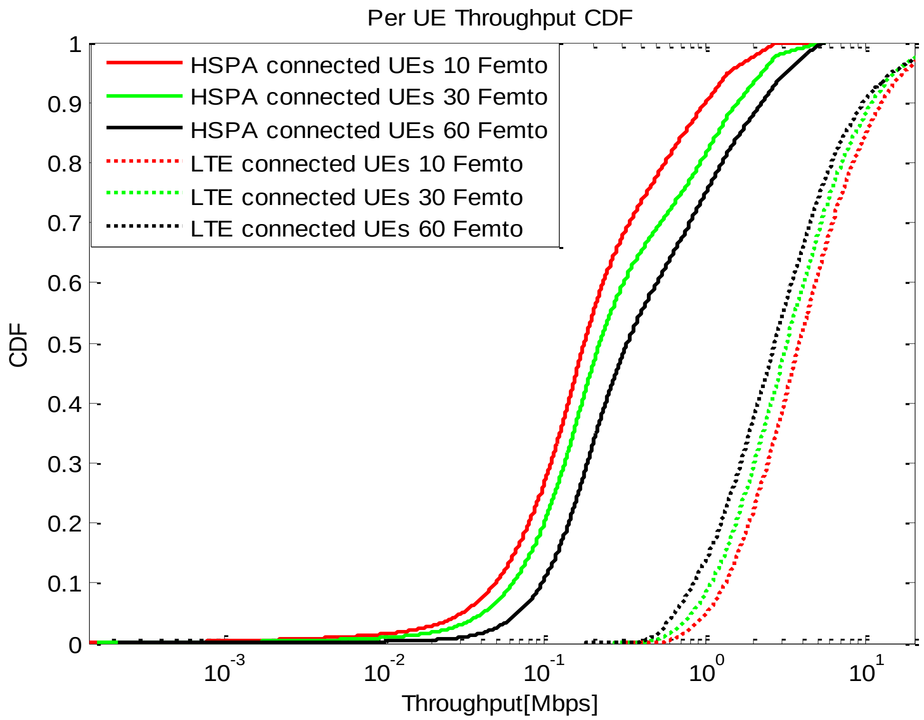


Figure 4.11 Throughput CDF of normal LTE UEs

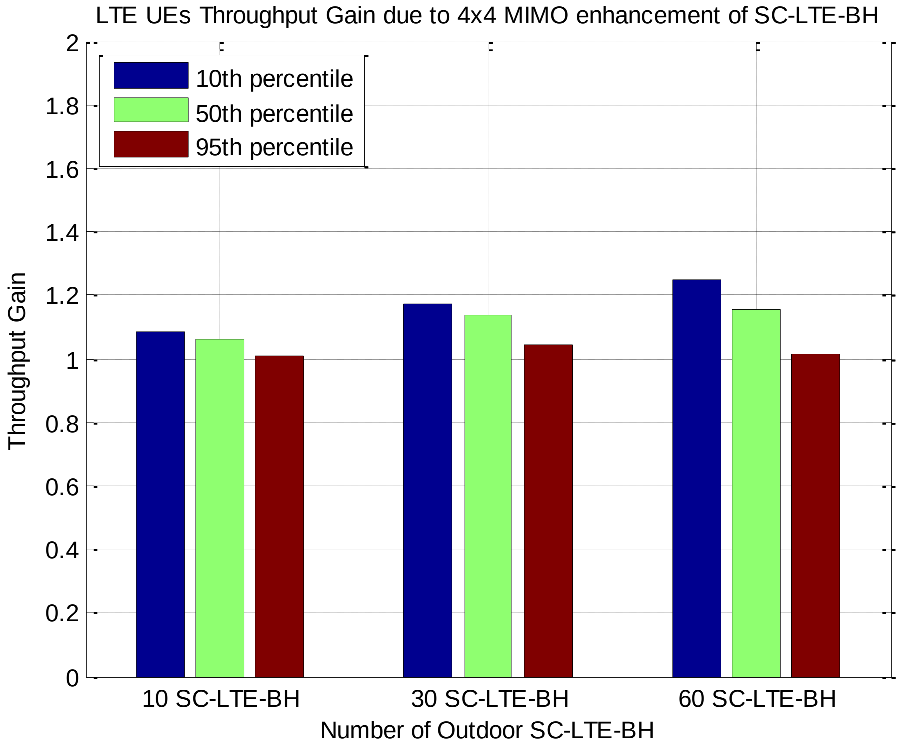


Figure 4.12 LTE UEs throughput gains for 4x4 MIMO

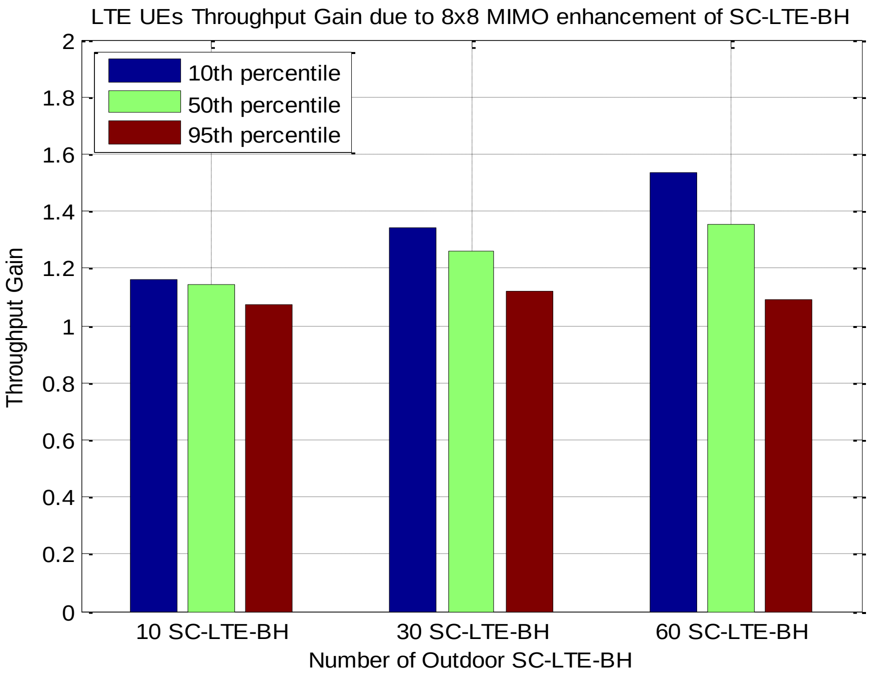


Figure 4.13 LTE UEs throughput gains for 8x8 MIMO

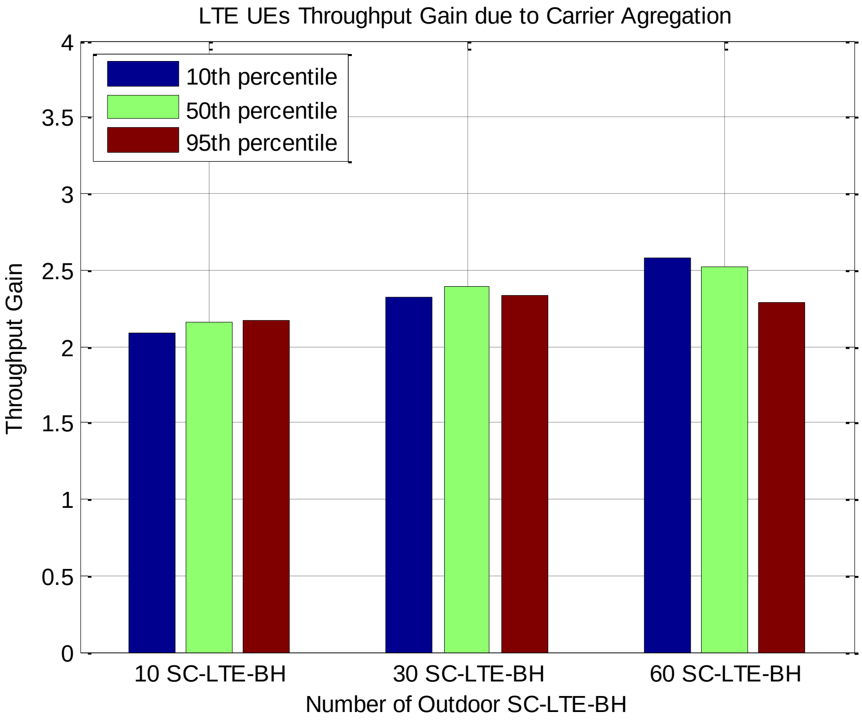


Figure 4.14 LTE UEs throughput gains for Dual Carrier (2x10 MHz)

4.2.2 LTE-UEs Prioritized

Three different LTE-UEs penetration levels where considered for LTE-UEs prioritized traffic steering policy. We considered 40:5 (HSPA-UEs: LTE-UEs ratio), 23:22 and 5:40 which represents minority LTE-UEs, similar LTE/HSPA-UEs level and majority LTE-UEs to understand how small cell backhaul performance is affected with increasing LTE-UEs penetration.

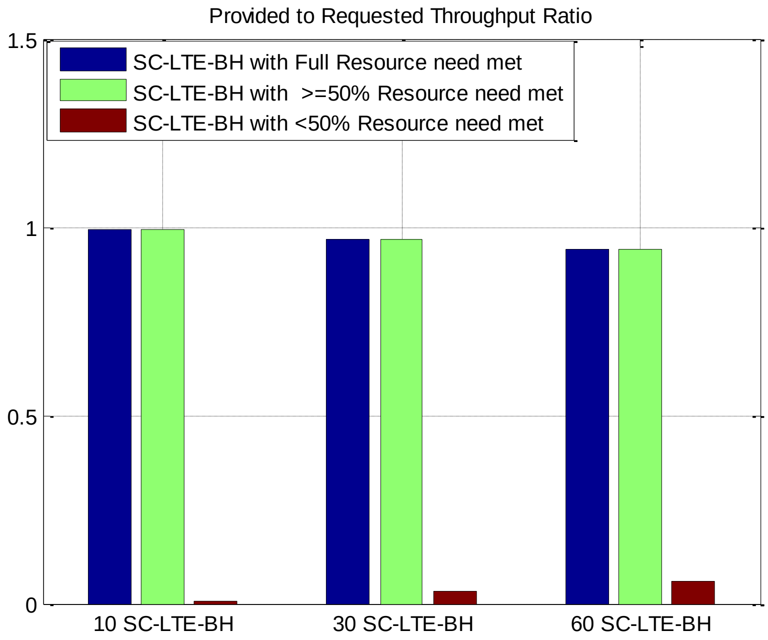


Figure 4.15 SC-LTE-BH (2x2 MIMO, 5-LTE-UEs) provided to requested capacity ratios

Fig. 4.15, Fig. 4.16 and Fig. 4.17 provide the performance results of small cell backhaul for the three LTE-UEs penetration levels. We can clearly observe the drop in performance (e.g. drop in percentage of fully satisfied small cells backhaul) as UEs connected to LTE macro cells increases. With majority LTE-UEs case small cell served UEs are small. But as can be observed from Fig. 4.17 the small cell backhaul performance is the worst compared to other cases. Since LTE-UEs are prioritized in resource scheduling there will be limited resource for backhauling.

In Table 4.4 we present backhaul performance improvements due to higher order MIMO and bandwidth scaling. It is noted that percentage of fully satisfied backhaul capacity improves significantly with 8x8 MIMO and it reaches near perfection when dual carrier is applied.

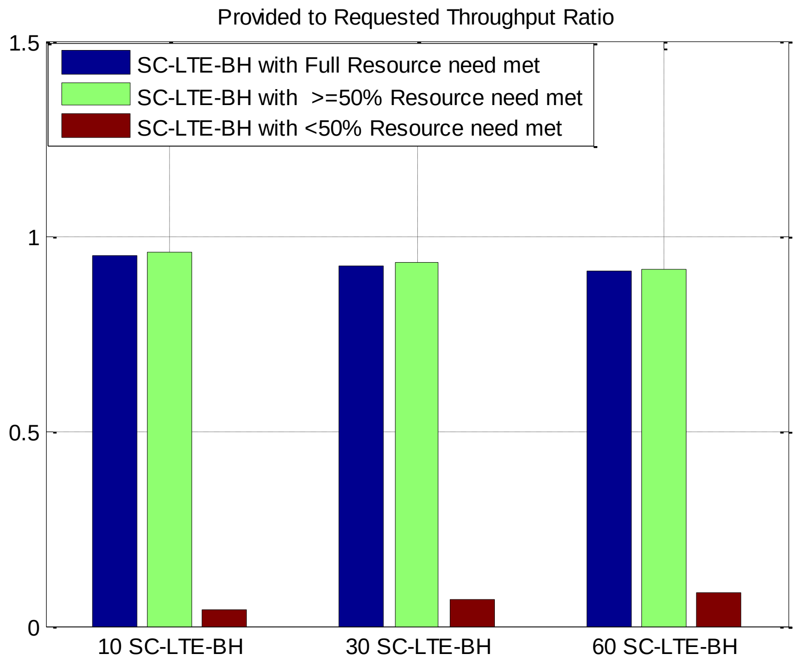


Figure 4.16 SC-LTE-BH (2x2 MIMO, 22-LTE-UEs) provided to requested capacity ratios

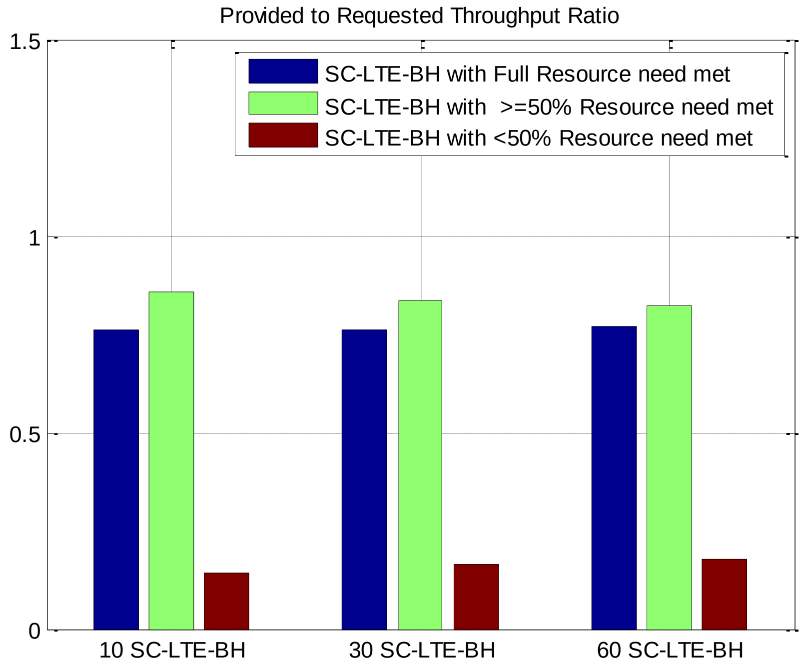


Figure 4.17 SC-LTE-BH (2x2 MIMO, 40-LTE-UEs) provided to requested capacity ratios

Table 4.4 Percentage of fully satisfied small cell backhaul

LTE-UEs: HSPA-UEs	#Small cells	2x2 MIMO	4x4 MIMO	8x8 MIMO	2x10 MHz
5:40	10	99.82	99.98	99.99	100
	30	98.32	99.86	99.98	100
	60	96.07	99.54	99.96	99.97
22:23	10	95.48	97.90	98.66	100
	30	92.84	96.91	98.59	99.97
	60	91.29	96.43	98.37	99.91
40:5	10	78.67	85.65	89.54	99.88
	30	78.67	85.75	89.16	99.70
	60	78.45	87.85	90.85	99.77

The performance results from the LTE-UEs perspective are presented in Fig. 4.18, Fig. 4.19 and Fig. 4.20 below for the three different levels of UE penetrations. It is clear that HSPA-UEs throughput improves as the fraction of LTE-UEs increases, and vice-versa. This is because of the strong dependency of resource allocation to fraction of users served by each technology (HSPA and LTE). The less fraction of users served by HSPA network the higher potential to provide large resources to a single user and vice-versa. Demand for LTE resources increases with increasing fraction of LTE-capable UEs resulting in reduced throughput performance for both small cell backhaul and LTE macro cell served UEs.

Table 4.5 presents throughput gains due to application of small cell backhaul enhancement mechanisms. By improving spectral efficiency of small cell backhaul, and hence, reducing LTE resource demand higher order MIMO configurations provide throughput gains for LTE-capable UEs. The highest throughput gain happens when bandwidth scaling is applied.

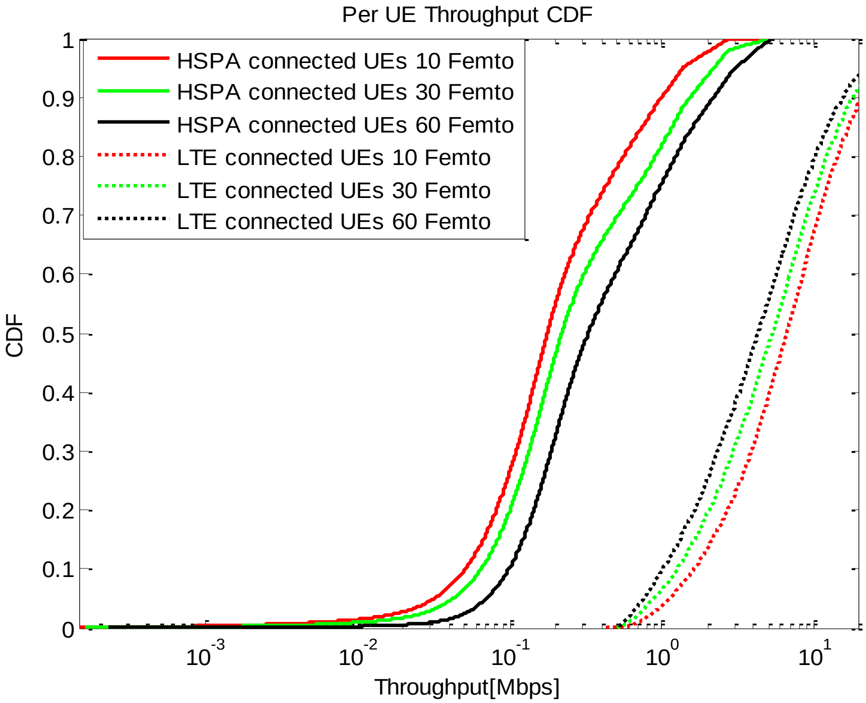


Figure 4.18 Throughput CDFs of normal LTE-UEs (2x2 MIMO, 5-LTE-UEs)

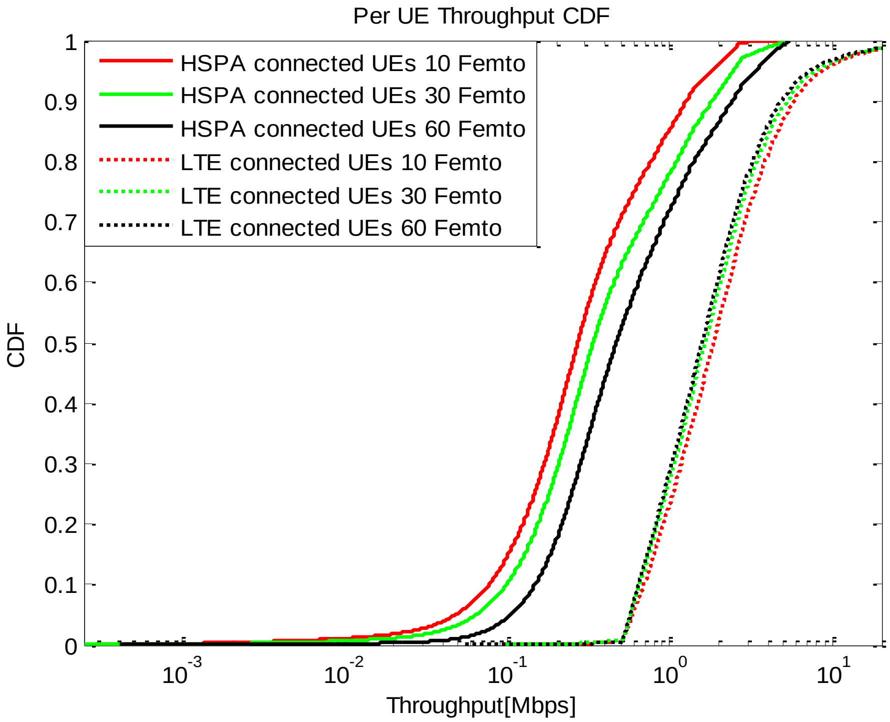


Figure 4.19 Throughput CDFs of normal LTE-UEs (2x2 MIMO, 22-LTE-UEs)

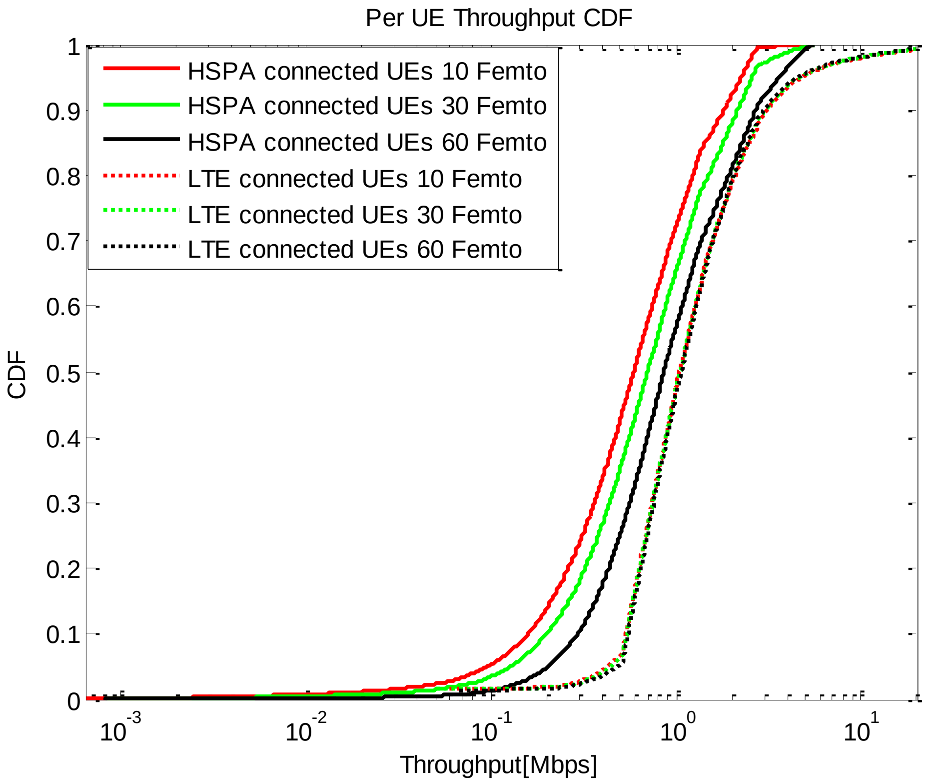


Figure 4.20 Throughput CDFs of normal LTE-UEs (2x2 MIMO, 40-LTE-UEs)

Table 4.5 LTE-UEs prioritized Throughput gains (compared to 2x2 MIMO, 1x10 MHz)

LTE-UEs: HSPA-UEs	# Small cell	Percentile	4x4 MIMO	8x8 MIMO	2x10 MHz
5:40	10	10th	1.13	1.21	2.48
		50th	1.13	1.17	2.38
		95th	1.07	1.1	2.3
	30	10th	1.23	1.38	2.72
		50th	1.22	1.32	2.71
		95th	1.09	1.15	2.34
	60	10th	1.39	1.64	3.14
		50th	1.42	1.64	3.20
		95th	1.20	1.28	2.47

22:23	10	10th	1.05	1.1	2.10
		50th	1.09	1.13	2.58
		95th	1.04	1.07	2.2
	30	10th	1.06	1.09	2.10
		50th	1.08	1.14	2.8
		95th	1.05	1.1	2.3
	60	10th	1.05	1.13	2.04
		50th	1.11	1.29	2.87
		95th	1.09	1.12	2.41
40:5	10	10th	1.01	1.01	1.75
		50th	1.01	1.01	2.59
		95th	1.02	1.03	2.28
	30	10th	1.01	1.01	1.73
		50th	1.02	1.01	2.51
		95th	1.03	1.02	2.28
	60	10th	1.01	1.02	1.83
		50th	1.04	1.07	2.68
		95th	1.02	1.08	2.24

5.0 Conclusion

In this work, we have studied the performance of LTE/LTE-advanced as a cost effective HSPA small cell backhauling alternative in densely populated sub-urban deployment. The study involved investigating how different LTE link capacity enhancement mechanisms and traffic steering policies can potentially address small cell backhaul needs, and also how these enhancements and LTE resource sharing between small cells backhaul and normal LTE-capable UEs affects the throughput performance of the later.

The extensive simulation study highlights the potential of cost effective self-backhauling for small cells through LTE macro resources without significantly harming normal LTE-capable users' throughput performance. It can also be concluded that the traffic steering policies (LTE-UEs prioritized or small cell backhaul prioritized) bring no significant performance difference as long as majority UEs are not LTE-capable. With majority LTE-capable UEs applying enhancement mechanisms (higher order MIMO or bandwidth scaling) is necessary to provide acceptable level of backhaul performance (e.g. 90% fully satisfied backhaul). Adding extra carrier (bandwidth scaling in LTE or carrier aggregation in LTE-advanced) is proved to be the best way to provide close to perfect small cell backhauling while at the same time improving LTE-capable UEs throughput.

We recommend investigating joint radio resource management across different layers and link segments (access and backhaul) as a future work. In addition, future work is required on SON algorithms for optimum load balancing across different layers.

REFERENCES

[1] "Heterogeneous Networks," Ericsson White Paper , Feb 2012.

[2] H. Holma and A. Toskala, WCDMA For UMTS - HSPA Evolution and LTE 4th Edition, John Wiley & Sons Ltd., 2007.

[3] "It All Comes Back to Backhaul," Ericsson White Paper, Feb 2012.

[4] J. Robson, "Small Cell Backhaul Requirements," Next Generation Mobile Networks (NGNM), Jun 2012.

[5] "Mobile Backhaul Evolution and Convergence," NEC Corporation, Jan 2010.

[6] J. Kolko, "Does Broadband Boost Local Economic Development," PPIC, Jan 2010.

[7] "Broadband Access," iDA, Nov 2002.

[8] "IIA 2013 BROADBAND GUIDE FOR THE 113TH CONGRESS," IIA Broadband, 2013.

[9] Paul Budde, Broadband: A platform for progress, A Report by the Broadband Commission for Digital Development, Jun 2011: ITU/UNESCO.

[10] J. Robson and L. Hiley, "Easy Small Cell Backhaul, An Analysis of Small Cell Backhaul Requirements and comparison of solutions," Cambridge Broadband Networks, Feb 2012.

[11] "DSL Technology Evolution," Broadband Forum.

[12] "Broadband Technology Overview," CORNING, Jun 2005.

[13] I. Cale, "Gigabit Passive Optical Network - GPON," Proceedings of the ITI 2007 29th Int. Conf. on Information Technology Interfaces, Jun 2007.

[14] "Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation," WiMAX Forum, Aug 22006.

[15] "Technology Synergies for Small-Cell Backhaul in 4G Networks," Intracom S.A. Telecom Solutions, 2012.

[16] M. Paolini, "Crucial economics for mobile data backhaul," SENZA FILI Consulting, 2011.

[17] J. Bright and D. Mavrakis, "Satellite backhaul for rural small cells," Informa Telecoms & Media, 2012.

[18] E. Kemppinen, "Prospects for Wireless Infrastructure in Emerging Telecom Markets," NSN, 2011.

[19] "Traffic and Market Report," Ericsson, Jun 2012.

[20] "Picocell Application Guide," ADC Telecommunications, 2008.

[21] "Small cells - What's the big ideal?," Small Cell Forum , Feb 2012.

[22] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariya, N. Johnson, B. Raghothaman and A. Richardson, "Interference Management and Performance Analysis of UMTS/HSPA+ Femtocells," *IEEE Communications Magazine*, Sep 2009.

[23] D. P. Agrawal, "Femtocells: Introduction and Research Issues," DMC.

[24] J. G. Andrews, H. Claussen, M. Dohler, S. Rangan and M. C. Reed, "Femtocells: Past, Present, and Future," *IEEE*, vol. 30, no. 3, Apr 2012.

[25] K. Elleithy and V. Rao, "Femto Cells: Current Status and Future Directions," International Journal of Next-Generation Networks (IJNGN), Mar 2011.

[26] "Universal Mobile Telecommunications System (UMTS);UTRAN architecture for 3G Home Node B (HNB);Stage 2," ETSI, 2013.

[27] J. Peisa, S. Wager, M. Sågfors, J. Torsner,, B. Göransson, T. Fulghum, C. Cozzo and S. Grant, "High Speed Packet Access Evolution – Concept and Technologies," *IEEE*, 2007.

[28] "The Evolution of HSPA, The 3GPP Standards Progress for fast mobile broadband using HSPA+," 4G Americas, Oct 2011.

[29] "Dual-Carrier HSPA: A Growth Opportunity," Ericsson, Dec 2012.

[30] V. Chandrasekhar and J. G. Andrews, "Femtocell Networks: A Survey," Texas Instruments, Jun 2008.

[31] K. Elleithy and V. Rao, "Femtocells: Current Status and Future Directions," *International Journal of Next-Generation Networks*, vol. 3, no. 1, Mar 2011.

[32] D. N. Knisely, T. Yoshizawa and F. Favichia, "Standardization of Femtocells in 3GPP," *IEEE Communications Magazine*, Sep 2009.

[33] [Online]. Available: http://www.telecomseurope.net.

[34] "Universal Mobile Telecommunications System (UMTS); UTRAN Overall Description," ETSI TS 125 401 V3.4.0, 2000-09.

[35] G. Horn, "3GPP Femtocells: Architecture and Protocols," QUALCOMM Incorporated, Sep 2010.

[36] D. De, R. R. Bhat and V. S. Rao, "Iuh: A Protocol Solution for Scaling Femtocells," Radysis Corp., Sep 2011.

[37] M. Olsson, S. Sultana, S. Rommer, L. Frid and C. Mulligan, SAE and the Evolved Packet Core - Driving The Mobile Broadband Revolution, Elsevier Ltd., 2009.

[38] Harri Holma and Antti Toskala, LTE for UMTS OFDMA and SC-FDMA Based Radio Access, Wiley, 2009.

[39] C. Gessner, A. Roessler and M. Kottkamp, UMTS Long Term Evolution (LTE) - Technology Introduction, Rohde and Schwarz, July 2012.

[40] Srikanth S., Kumaran V., Manikandan C. and Murugesapandian, "Orthogonal Frequency Division Multiple Access: Is it the Multiple Access System of the Future?," AU-KBC Research center.

[41] "4G Mobile Broadband Evolution: Release 10, Release 11 and Beyond HSPA+, SAE/LTE and LTE-Advanced," 4G Americas, Oct 2012.

[42] "Documentation of Regularization of Experience in Informal Settlement in Kinondoni Municipality, Dar es Salam, Experience of Hanna Nassif 2010," WAT Human Settlements Trust, 2010.

[43] E. Mutafungwa, R. Rakibul, B. B. Haile and J. Hämäläinen, "Performance Study for Small Cell Deployments in Densely Populated Informal Settlements".

[44] PCTEL, Simplifying Wireless, "Maximizing LTE Performance Through MIMO Optimization," PCTEL, simplifying wireless, 2011.

[45] J. Zyren, "Overview of the 3GPP Long Term Evolution Physical Layer," freescale semiconductor, 07/2007.

[46] G. Yuan, Xiang Zhang, Wenbo Wang and Yang Yang, "Carrier Aggregation for LTE-Advanced Mobile Communication Systems," IEEE Communications Magazine, February 2010.

[47] Seppo Hämäläinen, Henning Sanneck and Cinzia Sartori, LTE Self-Organizing Networks (SON): Network Management Automation for Operational Efficiency, Wiley, 2012.

[48] Panagiotis Fotiadis, Michele Polignano, Lucas Chavarria, Ingo Viering, Cinzia Sartori, Andreas Lobinger and Klaus Pedersen, Multi-Layer Traffic Steering: RRC Idle Absolute Priorities & Potential Enhancements, IEEE Vehicular Technology Conference, 2013.

[49] J. Robson, "Guidelines for LTE Backhaul Traffic Estimation," NGNM, Jul 2011.

[50] J. Robson, "NGMN Requirements for Small Cell Backhaul," NGNM, Oct 2012.

[51] P. Mogensen, W. Na, I. Z. Kovács, F. Frederiksen, A. Pokhariyal, K. I. Pedersen, T. Kolding, K. Hugl and M. Kuusela, "LTE Capacity compared to the Shannon Bound," *IEEE*, 2007.

[52] O. N. C. Yilmaz, E. Mutafungwa and J. Hämäläinen, "Performance of Relay Enhanced LTE-Advanced Networks for Selected Suburban Scenarios in Emerging Market Environments," *IEEE*, 2012.

[53] E. 1. 4. "Universal Mobile Telecommunications Systems (UMTS); UTRAN Architecture for 3G Home Node B (HNB); Stage 2," ETSI, Jan 2013.

[54] "Dynamic Bandwidth Throttling," 17 05 2005. [Online]. Available: www.iAnywhere.com.

[55] I. Ullah, "Performance Analysis of LTE-Advanced Relay Node in Public Safety Communication," Aalto University, Aug 2012.

[56] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariyal, N. Johnson, B. Raghothaman and A. Richardson, "Interference Management and Performance Analysis of UMTS/HSPA+ Femtocells," *IEEE*, Sep 2009.

[57] W. BOLD and W. DAVIDSON, "Mobile Broadband: Redefining Internet Access and Empowering Individuals," Word Economic Forum, 2012.

[58] M. Singer, "Economic and Social Benefits of Broadband," ITU SPU Broadband Workshop, Apr 2003.

[59] "The LTE Network Architecture," Alcatel-Lucent.