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ADDIS ABABA INSTITUTE OF TECHNOLOGY

ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

Spectrum Refarming in LTE Network Planning: the Case of Addis Ababa

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Place: Addis Ababa

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This thesis has been submitted for examination with my approval as a university advisor.

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Advisor's Name Signature

Abstract

The deployment of Long Term Evolution (LTE) provides a better way to meet the increasing user demand for high rate mobile data. However, obtaining spectrum resource needed and deployment band selection are among the challenges to meet the demand. Spectrum already in possession by older technologies can be divided and granted to deploy new technologies. Such a technique of clearing frequencies from low-value (by economic and/or social criteria) and reassignment to high-value applications is called *Spectrum Refarming*.

In the case of Ethiopia, a 20 MHz bandwidth is statically refarmed to LTE from Global System for Mobile Communications (GSM) 1800 band, which has propagation advantages over the main stream 2600 MHz band while maintaining the remaining spectrum for legacy users. But static spectrum refarming (SSR) does not respond to the changing traffic conditions and the refarmed spectrum remains underutilized.

In this thesis, dynamic spectrum refarming (DSR) approach is proposed for possible use in Ethiopia's LTE deployment. The refarming intends to use LTE's flexible bandwidth deployment opportunity to refarm the available spectrum and insure smooth transition from GSM to LTE, which eventually be the case. To this end, a case study area of $5.88\,km^2$ around Gerji area is considered in Addis Ababa containing 5 GSM base stations and still co–sited with LTE.

Different user equipment distribution scenarios are generated for 200 mobile users in the covered area via simulation and results for the cases of static and dynamic spectral allocations are obtained. The results show that DSR can save 42 % of spectrum refarmed by SSR and possibly reallocates the physical resource blocks (PRBs) for about 155 GSM users in particular need that would rather be wasted in vain. Beside the efficient spectrum usage that can be achieved by employing dynamic spectrum refarming scheme, the aggregate throughput of the network is improved by 7.5 % for uniform User Equipment (UE) distribution case while 13.4 % improvement is achieved in the non-uniform UE distribution case as compared with static refarming.

Key Words: LTE; GSM; Static Spectrum Refarming; Dynamic Spectrum Refarming;

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Abbreviations

2G	Second Generation
3GPP	Third Generation Partnership Project
BCCH	Broadcast Control Channel
CCI	Co-Channel Interference
CCU	Cell Center User
CDF	Cumulative Distribution Function
CEU	Cell Edge User
DSR	Dynamic Spectrum Refarming
E-NodeB	Evolved NodeB
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplexing
FFR	Fractional Frequency Reuse
FRF	Frequency Reuse Factor
GSM	Global System for Mobile communication
HARQ	Hybrid Automatic repeat Request
HSPA	High Speed Packet Access
ICI	Inter-Carrier Interference
ICIC	Inter Cell Interference Coordination
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
LTE	Long-Term Evolution
MIMO	Multiple Input Multiple Output

MME	Mobility Management Entity
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Pick-to-Average Power Ratio
PCFICH	Physical Control Format Indicator Channel
PDCCH	Downlink Control Channel
PHICH	Physical Hybrid-ARQ Indicator Channel
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RF	Radio Frequency
RLB	Radio Link Budget
RSRP	Reference Signal Received Power
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFR	Soft Frequency Reuse
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
SSR	Static Spectrum Refarming
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TFR	Tight Frequency Reuse
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband Code Division Multiple Access

1. Introduction

1.1 Introduction

The cellular wireless communications industry witnessed tremendous growth in the past with regards to data traffic demands. The widely deployed second-generation (2G) cellular system is the Global System for Mobile Communications (GSM), which is mainly for voice service. In later releases, capabilities were introduced to support data transmission. The 3G standard is developed in 3G partnership project (3GPP) which is referred to as Wideband Code Division Multiple Access (WCDMA). A serious effort was then made to enhance the 3G systems for efficient data support requirements which has led to the introduction of High Speed Packet Access (HSPA), an enhancement to the WCDMA system [1].

The rising demand for data services has initiated the development of new mobile network technologies to satisfy the customer needs. This condition has led 3GPP to develop its own version of beyond 3G systems based on the Orthogonal Frequency Division Multiple Access (OFDMA) technology and network architecture. The beyond 3G system in 3GPP is called evolved Universal Terrestrial Radio Access (evolved UTRA) and is also widely referred to as Long Term Evolution (LTE) [1].

LTE is a key technology that provides higher data rates, packet-switched technology, lower latency and improved system design. Hence, the evolution to LTE is becoming critical for mobile network operators to deliver high speed data services for their customers. The capital city of Ethiopia, Addis Ababa, is becoming a center of vibrant economy with business activities enormously expanding throughout. The city requires a telecom infrastructure which is able to uphold and speed up the modernization process. In order to address these requirements, Ethio Telecom, the sole provider of telecom services in Ethiopia, launched the recent LTE technology with the capacity of serving about 400,000 inhabitants of the city. This, in turn, necessitated a spectrum allocation to be made; a new allocation or some portion of the spectrum from existing radio systems such as GSM. Particularly, the later allocation approach allows the co-existence of GSM and LTE through refarming the legacy GSM spectrum without the need for a new spectral allocation. The refarming technique can be implemented in either static or dynamic manner.

In the case of Addis Ababa, rich spectral resource is available in the telecom sector as the spectrum utilized by different technologies; hence, imminent need for advanced refarming techniques may not be huge. However, new digital transmission technologies that are being deployed added with the increase in number of users will definitely necessitate the refarming need sooner than later. Spectrum refarming is a good candidate to deploy LTE in the existing 3G and 2G networks and, hence, effect a smooth transition. Particularly, the GSM 1800 band which has propagation advantages over the main stream 2600 MHz LTE band has been statically refarmed for LTE in Addis Ababa recently. Besides, the wider spectrum available in this band and less traffic it bear makes it a good alternative than GSM 900 band.

In this thesis, spectrum refarming on the GSM 1800 band is studied. Static and dynamic spectrum refarming techniques are investigated for the refarming. Moreover, the dynamic refarming technique is proposed for efficient use of the spectrum over the existing static refarming that has already been implemented for LTE deployment. Besides, the impact on GSM band with respect to spectrum usage is analyzed.

1.2 Problem Statement

Mobile broadband is ushering in a brand-new era of communications, in which wireless network traffic is growing explosively in recent years. Traditional GSM voice subscribers are no longer satisfied with low-speed data access and new spectrum resource is needed to deploy advanced networks like LTE. Deploying LTE in GSM spectrum allows reusing highly valuable spectrum which is inefficiently used by an old technology for a highly spectrally-efficient solution while still maintaining the old technology for legacy devices. Spectrum refarming is an important candidate to realize these requirements.

The next important question is; which band to refarm? The GSM 1800 band and GSM 900 are the potential candidates. In the case of Ethiopia, spectrum refarming is carried out by statically partitioning the spectrum resource on the GSM 1800 band for LTE while providing the main voice service on the GSM 900 band. In spite of the simplicity of adopting the static spectrum refarming technique, the spectrum dedicated for LTE would be permanently possessed regardless of the changing traffic conditions in actual circumstances which cause a less efficient usage of spectrum resource.

However, as it is proposed in this thesis, the dynamic spectrum refarming technique is a better refarming technique in that it allows the efficient usage of the spectrum based on the dynamic demand and improves network capacity and performance. The implementation of this technique requires the study of the traffic trends in the co-existing GSM and LTE systems which would not make it an easy task to accomplish. Additionally, how to mitigate the impact on the mobile users that exist within the band selected for refarming need due to the new adopted technology, LTE, need to be carefully assessed.

1.3 Objectives

This thesis work, generally, investigates the performance improvement by using dynamic spectrum refarming techniques for the LTE mobile network deployed in Addis Ababa; the GSM 1800 frequency band, in the candidate spectrum for refarming.

Specifically, this thesis focuses on: -

- Studying the basic components of LTE network planning process;
- Assessing the general frequency allocation plan done by Ethio Telecom for the deployment of LTE network in Addis Ababa;

- Studying the GSM/LTE spectrum re-farming techniques and the steps involved in the process;
- Carrying out a case study on the application of the GSM/LTE spectrum re-farming techniques using the MATLAB simulation tool. The case study area contains 5 base stations around Gerji in Bole subcity covering an area of 5.88 km^2;
- Analyzing the effects of spectrum re-farming on GSM network with respect to spectrum usage and capacity;
- Drawing possible recommendations on implementation of dynamic refarming technique over existing static spectrum refarming technique on GSM 1800 band for LTE deployment

1.4 Methodology

Spectrum refarming is a very recent subject of interest which exists largely on research level. The implementation cases are few to mention that even vary from case to case. So, much of the work still remain in the state of standardization. Therefore, this thesis is mainly relied on the books on LTE, IEEE articles and journals on spectrum refarming and refarming techniques. Some practical spectrum refarming examples from different vendors like Huawei are considered.

This thesis starts with preliminary study on LTE, network planning and more importantly the spectrum refarming concept. The need for and the challenges of implementing spectrum refarming in the case of Ethiopia is then raised as a topic of interest. Available input data for the case study area including GSM and LTE co-site locations and the general frequency allocation ranges for both technologies have been gathered. Following, theoretical spectrum allocations are then made for all sites and parameters like SINR and throughput results are generated using MATLAB simulation tool for different mobile user distribution scenarios. The efficiency of spectrum usage in static and dynamic spectrum refarming cases is analyzed. The impacts on the GSM band is also assessed and compared in terms of spectrum usage and capacity in each deployment sites in both refarming techniques.

1.5 Literature Review

LTE started as a project in 2004 by telecommunication body known as 3GPP [1]. LTE is a pure packet system, with no support for legacy circuit switched voice or data. Harri Holma and Antti Toskala [2] described the details of LTE technology; system features and attributes and importantly the possibility of its co-existence with legacy technologies like GSM. As spectrum refarming is a recent concept, its development and standardization will remain an important research subject. Spectrum to be refarmed can be obtained from previous technologies on the ground by dividing a certain portion for initial deployment or the whole needed amount if enough spectrum is available [2].

Spectrum possessed by technologies like GSM and UMTS can be refarmed for new technologies like LTE. Particularly, there are some GSM refarming projects undertaken globally that consider refarming either on GSM 1800 or GSM 900. Different vendors or telecom operators like Huawei have witnessed refarming the GSM 1800 band as an ideal option for LTE deployment [3]. This is due to the large spectrum available and the relatively low traffic available on GSM 1800 which might be migrated to GSM 900 band.

X. Lin et al. [8] proposed an LTE/GSM spectrum re-farming to re-farm the GSM band by utilizing the sub bands that are not occupied by the GSM system. Accordingly, the spectrum refarming types can be either static or dynamic. In addition, the authors proposed a novel solution to provide GSM connectivity within an LTE carrier through an efficient, dynamic overlay by reserving a few physical resource blocks for GSM. With this approach, operators can migrate their 2G spectrum to LTE while still providing reduced capacity for GSM connectivity to their low data rate customers. To address the reduction in capacity, frequency reuse schemes and intelligent scheduling are proposed. The impact on GSM beside the reduction in capacity include the obvious inter technology interference between LTE and GSM. Since the signals of both technologies are transmitted in the same band, there is GSM adjacent channel interference leakage on LTE user equipments and vice versa. To mitigate interference from LTE physical resource blocks (PRBs) to GSM, transmit power on the PRBs close to GSM PRBs can be reduced. This approach also helps mitigate the impact of GSM on LTE since other non-adjacent PRBs can be allocated more power and partially recover the LTE capacity loss because of GSM overlay.

Furthermore, dynamic resource allocations and the static allocations are compared with respect to efficient use of spectrum by X. Lin et al. Their study shows that the loss of LTE capacity caused by GSM overlay or vice versa can be significantly reduced with the assessment of the negative impacts and proposed enhancements. In spite of the real and difficult challenges of implementing the dynamic spectrum allocation scheme, the efficient use of the spectrum and possibility of mitigating techniques overweigh the negative impacts and even improve the network performance.

In LTE deployment, different frequency planning schemes can be used. As explained by F. B. Álvarez, among the planning strategies the partial or fractional reuse is worth mentioning. R. Ghaffar and R. Knopp [14] also explained that fractional frequency reuse (FFR) can be implemented for mitigating inter-cell interference in the co-existing GSM and LTE users. The impact on GSM users, especially those at the cell edge can thus be reduced by careful frequency planning.

Besides the researches on the spectrum refarming techniques, especially the DSR technique, implementation on the real deployment conditions needs further study and analysis of the traffic trends, spectrum resource allocations and planning in particular sites that need to be reconsidered and tuned for better results.

1.6 Scope and Limitation of the Thesis

This thesis is expected to indicate the efficient spectrum usage and performance improvement that can be achieved by adopting dynamic spectrum refarming technique over the existing static refarming of GSM 1800 band for LTE considering a case study area in Addis Ababa.

In this thesis, the data related to the number of mobile users and their distribution in the selected deployment area was not available to include it as an input for simulation that would, if available, be possibly used in analyzing the actual capacity served and spectrum usage by eNodeBs for a better result. So, the results obtained from the simulation are limited to fixed number of UEs and generated UE distribution scenario.

1.7 Thesis Layout

This thesis consists of six chapters. Chapter one consists of an introduction, problem statement, general and specific objectives, literature review and the methodologies used in this thesis. Chapter 2 introduces the basics of LTE technology and network planning aspects. The spectrum refarming concept, refarming techniques (SSR and DSR), and frequency planning and reuse schemes are dealt in depth in Chapter three. Chapter four deals with the system design which includes the simulation set up for the case study area and the procedures followed. While Chapter five composes of the results obtained from the simulation and the further analysis based on the results. Finally, Chapter six contains the conclusions drawn from the result analysis and some recommendations for future work.

2. Overview of LTE and Radio Network Planning

2.1 Introduction

This chapter intends to give an overview of LTE technology and the procedures involved in its radio network planning process. In the introductory part, LTE's main system features, multiple access technologies and its network architecture is presented. In line with this, the steps in the LTE radio network planning; coverage and capacity planning are discussed in brief while the frequency planning step is discussed in chapter 3.

The goal of LTE is to provide a high-data-rate, low-latency and packet-optimized radio access technology supporting flexible bandwidth deployments. In parallel, new network architecture is designed to exploit these advantages. The goals of the LTE technology include the followings:

- Improved system capacity, high peak data rates and low latency;
- Multi-antenna support;
- Flexible bandwidth operations;
- Seamless integration with existing systems (GSM, UMTS, etc.).

LTE supports flexible bandwidths thanks to Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier - Frequency Division Multiple Access (SC-FDMA) access schemes. In addition to Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), half duplex FDD is allowed [1]. Unlike FDD, in half-duplex FDD operation user equipment (UE) is not required to transmit and receive at the same time. Table 2-1 shows the LTE system bandwidths; channel and transmission bandwidths. The flexible system bandwidths show the possible deployment alternatives for LTE from the minimum of 1.4 MHz to the maximum system bandwidth of 20 MHz.

This flexible deployment feature allows an operator with an opportunity of deploying LTE with initial small bandwidth that might be obtained from existing legacy technologies or new spectral allocation by a regulatory body. The former alternative allows smooth refarming of spectrum from previous technologies like GSM to the recent ones like LTE in process of time and hence a possibility of a co-existing network.

Table 2-1: LTE bandwidths [1]

Channels Bandwidth (MHz)	1.4	3	5	10	15	20
Transmission Bandwidth (MHz)	1.08	2.7	4.5	9	13.5	18
Transmission Bandwidth (Resource Blocks)	6	15	25	50	75	100

2.2 LTE Multiple Access Techniques

In LTE, the downlink multiple access scheme is based on the OFDMA and the uplink multiple access is based on the SC-FDMA [2]. Basically a Single Carrier (SC) transmission means that information is modulated only to one carrier, adjusting the phase or amplitude of the carrier or both. With the Frequency Division Multiple Access (FDMA) principle, different users would be using different carriers or sub-carriers, to access the system simultaneously having their data modulation around a different center frequency.

A low Peak-to-Average Power Ratio (PAPR) in SC-FDMA improves coverage and the cell edge performance. The reduced signal peakiness allows increasing UE transmission power providing larger range and coverage [1].

In the downlink, the principle of the OFDMA is based on the use of narrow, mutually orthogonal subcarriers. In LTE the sub-carrier spacing is typically 15 kHz regardless of the total transmission bandwidth. Different sub-carriers maintain orthogonality, as at the sampling instant of a single sub-carrier the other sub-carriers have a zero value, as shown in the Figure 2-1 for a 5 MHz bandwidth.

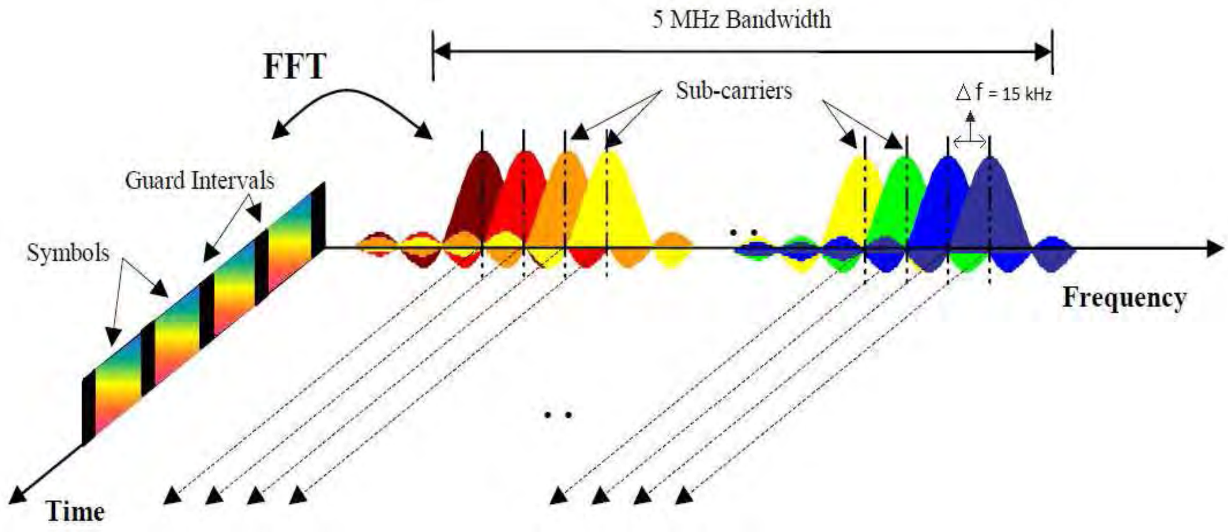


Figure 2-1: Frequency-time representation of an OFDM Signal [5]

The *Fast Fourier Transform (FFT)* is used to change the signal from time domain to frequency domain. However, the actual transmission is then done by transmitting a signal after the *Inverse Fast Fourier Transform (IFFT)* block, which is used to change from the frequency domain to the time domain representation of the signal. The IFFT block is followed by adding the cyclic extension, cyclic prefix.

We can see that in OFDMA, each sub-carrier only carries information related to one specific symbol, whereas in SC-FDMA, each sub-carrier contains information of all transmitted symbols. OFDMA transmits four Quadrature Phase Shift Keying (QPSK) data symbols in parallel, one per subcarrier, while SC-FDMA transmits the four QPSK data symbols in series at four times the rate, with each data symbol occupying Nx15 kHz bandwidth as shown in Figure 2-2.

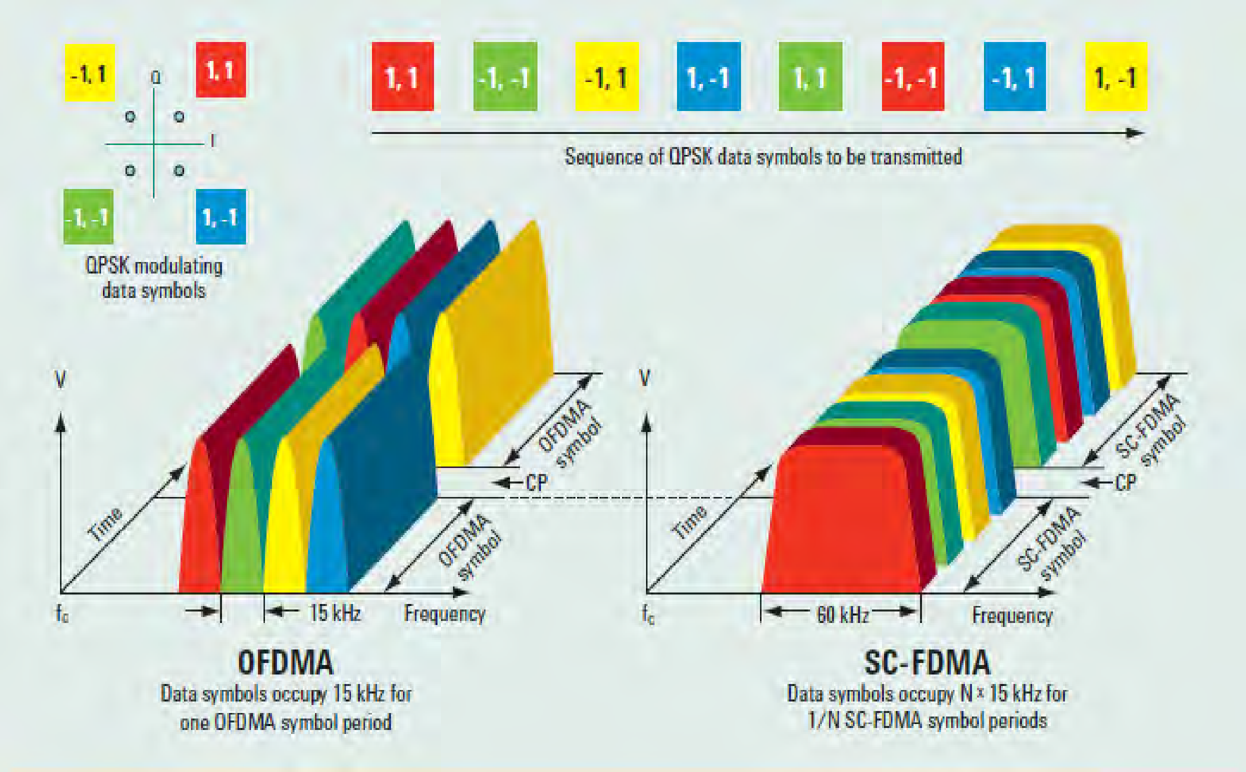


Figure 2-2: Comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols [5]

2.3 LTE Network Architecture

The network architecture has four main high level domains: UE, Evolved Universal Terrestrial Radio Access Network (E-UTRAN), Evolved Packet Core Network (EPC), and the Services domain. One major change is that the Radio Network Controller (RNC) is eliminated from the data path and its functions are now incorporated in evolved NodeB (eNodeB). Two logical gateway entities namely the serving gateway (S-GW) and the packet data network gateway (P-GW) are defined.

The S-GW acts as a local mobility anchor forwarding and receiving packets to and from the evolved NodeB (eNodeB) serving the UE. The P-GW interfaces with external packet data networks (PDNs) such as the Internet. The main functions of mobility management entity (MME) are idle-mode UE reachability including the control and execution of paging retransmission, tracking area list management, roaming, authentication, etc. The EPC contains Policy and Charging Resource Function (PCRF) and Home Subscription Server (HSS) is the subscription data repository for all permanent user data. Figure 2-3 shows the network architecture with the major components.

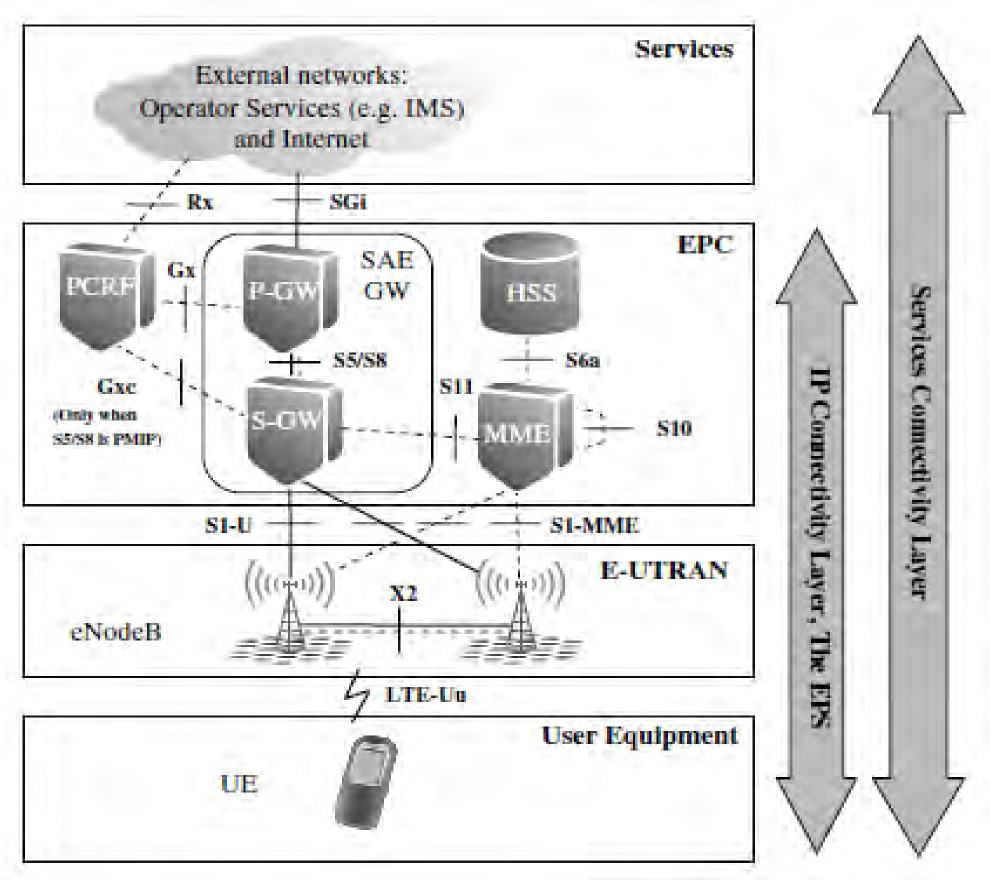


Figure 2-3: System architecture for e-UTRAN only network [2]

In LTE, the network architecture is designed with the goal of supporting packet-switched traffic which allows for the supporting of all services including voice through packet connections. This results in a highly simplified flatter architecture with only two types of nodes; eNodeB and MME/Gateway (GW). Some of the benefits of this simple architecture include reduced latency and the distribution of RNC processing load into multiple eNodeBs. In addition to this simple network architecture, having the Multiple Input and Multiple Output (MIMO) system feature, it is possible to support downlink and up link high peak data rates using 20 MHz LTE bandwidth. Since uplink MIMO is not employed in the first release of the LTE standard, the uplink peak data rates are limited to lesser amount. Table 2-2 shows the some of the main system attributes of LTE.

Table 2-2: LTE system attributes [1]

Bandwidth	1.4 – 20 MHz
Duplexing	FDD, TDD, half-duplex FDD
Mobility	~ 350Km/hr
Multiple access	Down link: OFDMA Up link: SC-FDMA
MIMO antenna	Down link: 2x2, 4x2, 4x4 Up link:1x2,1x4 Down link:173 and 326 Mb/s for 2x2 and 4x4 MIMO respectively
Peak data rate in 20 MHz	Up link:86 Mb/s with 1x2 antenna configuration
Modulation	QPSK,16-QAM and 64-QAM
Channel coding	Turbo code
Other techniques	Channel sensitive scheduling, Link adaptation, Power control, HARQ

2.4 LTE Radio Network Planning

In order to exploit the benefits of LTE's technology, a proper network planning need to be carefully designed in the particular deployment area of interest. This in turn needs to consider different factors including the targeted coverage area, capacity to be served and availability of the spectrum resource for the deployment of a new mobile network and frequency planning. These components are interrelated and demand detail analysis in planning process. In this section, the planning aspects of the coverage and capacity are dealt.

Radio access network (RAN) planning deals with planning the radio access part of a network. In the case of LTE, this covers the link between the UEs and base stations (eNodeBs). The RAN planning contains the phases of nominal planning, detailed planning and optimization. The nominal planning is the phase which estimates the required number of sites to provide sufficiently high quality of service (QoS) so that the end result is to deliver a lower bound on the number of network elements and their configurations required [25].

In detailed planning phase, the process begins with field surveys and tests where the actual site deployment is required [24]. The field test basics will help to verify the system behavior in a real environment, as assumption such as antenna direction, down tilting, power levels. This phase is aided with professional planning software that requires a proper propagation model with inclusion of the digital terrain map to take into account the topology of the environment. Finally, after the implementation of the proposed planning, the network performance should be analyzed and the system parameters are also tuned for optimized level of service.

At the beginning of RAN planning, a site survey which includes collection of pre-planning information that will be used in link budget preparation is carried out. Then coverage planning step is carried out which involves propagation model tuning, defining thresholds from link budget, creating detailed radio plan based on the thresholds. The next step planning network capacity against more detailed traffic estimates. At last, the frequency planning is done based on the requirements of the coverage and capacity of the network. Following, the two components of network planning: coverage and capacity planning [24] will be discussed in brief and whereas the frequency planning step is discussed in Chapter 3.

2.4.1 Coverage Planning

Coverage planning gives an assessment of the resources needed to cover the area under consideration. It consists of evaluation of downlink and uplink Radio Link Budgets (RLBs). The maximum path loss, which is the result of RLBs, is calculated based on the required Signal to Interference and Noise Ratio (SINR) level at the receiver, taking into account the extent of the interference and noise caused by traffic. The minimum of the maximum path losses in uplink and downlink directions is converted into cell radius, by using a propagation model such as Cost 231–Hata, Cost-231 Walfisch-Ikegami models appropriate to the deployment area [2].

The cell range gives the number of base station sites required to cover the targeted geographical area. The link budgets show that LTE can be deployed using existing GSM sites assuming that the same frequency is used for LTE as for GSM. LTE itself does not provide any major boost in the coverage. That is because the transmission power levels and the radio frequency (RF) noise figures are also similar in GSM. For LTE, the basic RLB equation can be written as follows (in units of dB):

$$P_L = P_{TX} + G_{TX} - \text{Losses}_{TX} - \text{SINR}_{REQ} + G_{RX} - \text{Losses}_{RX} - \text{Noise}_{RX} \text{ ---- } (2.1)$$

Where,

P_L = Total path loss encountered by the signal from transmitter to receiver (W)

P_{TX} = Power transmitted by the transmitter antenna (dBm)

G_{TX} = Gain of the transmitter antenna (dB)

$Losses_{TX}$ = Transmitter losses (dB)

$SINR_{REQ}$ = Minimum required SINR for the signal to be received at the receiver (dB)

G_{RX} = Gain of receiver antenna (dB)

$Losses_{RX}$ = receiver losses (dB)

$Noise_{RX}$= receiver noise (dBm)

In this thesis, the Cost–231 Hata propagation model which extends the Hata Model to cover a more elaborated range of frequencies: 1500 MHz to 2000 MHz is considered because the frequency used in the LTE deployment is at 1800 MHz (within the valid frequency range). Values valid for the model include:

- Mobile station antenna height: 1 up to 10 m,
- Base station antenna height: 30m to 200 m and

- Link distance: 1 up to 30 km.
- Mathematical formulation: The COST-231 Hata Model is formulated as,

Path Loss (L) = 46.3+ 33.9 $log_{10} f$ – 13.82 $log_{10} h_b$ – a(h_m) + [44.9 - 6.55 log(h_b)] log_{10} (d) + C [dB] --(2.2)

For suburban or rural environments: Where, L = Median path loss. Unit: Decibel (dB)

- f = frequency of transmission (MHz)
- h_b = base station antenna effective height in meter (m) (30m to 200 m)
- d = link distance (km)
- h_m = mobile station antenna effective height (m) (1m to 10m)
- a (h_m) = mobile station antenna height correction factor as described in the Hata model for urban areas.

  a(h_m) = (1.11 log f – 0.7) h_m – (1.56log f – 0.8)
- C = 3 dB and 0 dB for urban and for suburban and rural areas respectively.

Finally, in the coverage planning we have different site configuration for deployment. Figure 2-4 shows three different positions of the base station (eNodeB) creating a site. The coverage area A_{cell} of a base station is expressed by the following formula;

$$A_{cell} = (3\sqrt{3})\frac{d^2}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

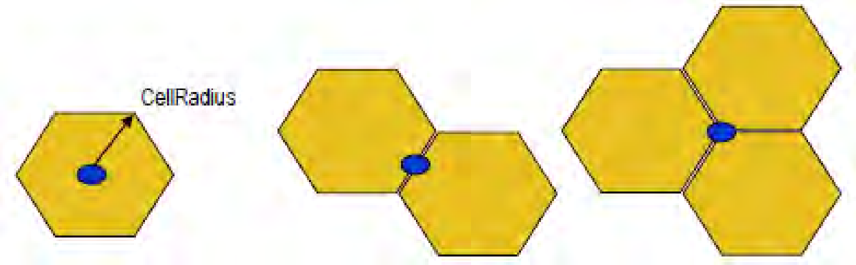


Figure 2-4: Three different types of sites (Omni-directional, bi-sector, tri-sector)

For three hexagonal cell models, site areas can be calculated as follows:

- Omni-directional site area = 2.6 * $CellRadius^2$
- Bi-sector site area = 1.3*2.6 * $CellRadius^2$
- Tri-sector site area = 1.95 * 2.6 * $CellRadius^2$

As it can be seen from the site areas calculations, using a tri-sector configuration help to attain the largest coverage area (3 cells) with 120 degree sector angles and hence widely used in deployments. The number of sites to be deployed can be easily calculated from the cell area and the input value of the deployment area (deployment area).

$$\text{Number of sites to be deployed} = \frac{\text{Deployment Area}}{\text{Site Area}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.4)$$

2.4.2 Capacity Planning

In the RAN planning the next step is capacity planning. Capacity planning gives us an estimate of the resources needed for supporting a specified offered traffic with a certain level of QoS (e.g. throughput or blocking probability). Theoretical capacity of the network is limited by the number of eNodeBs installed in the network and on the targeted coverage also. Cell capacity in LTE is impacted by several factors, which includes interference level, packet scheduler implementation and supported modulation and coding schemes.

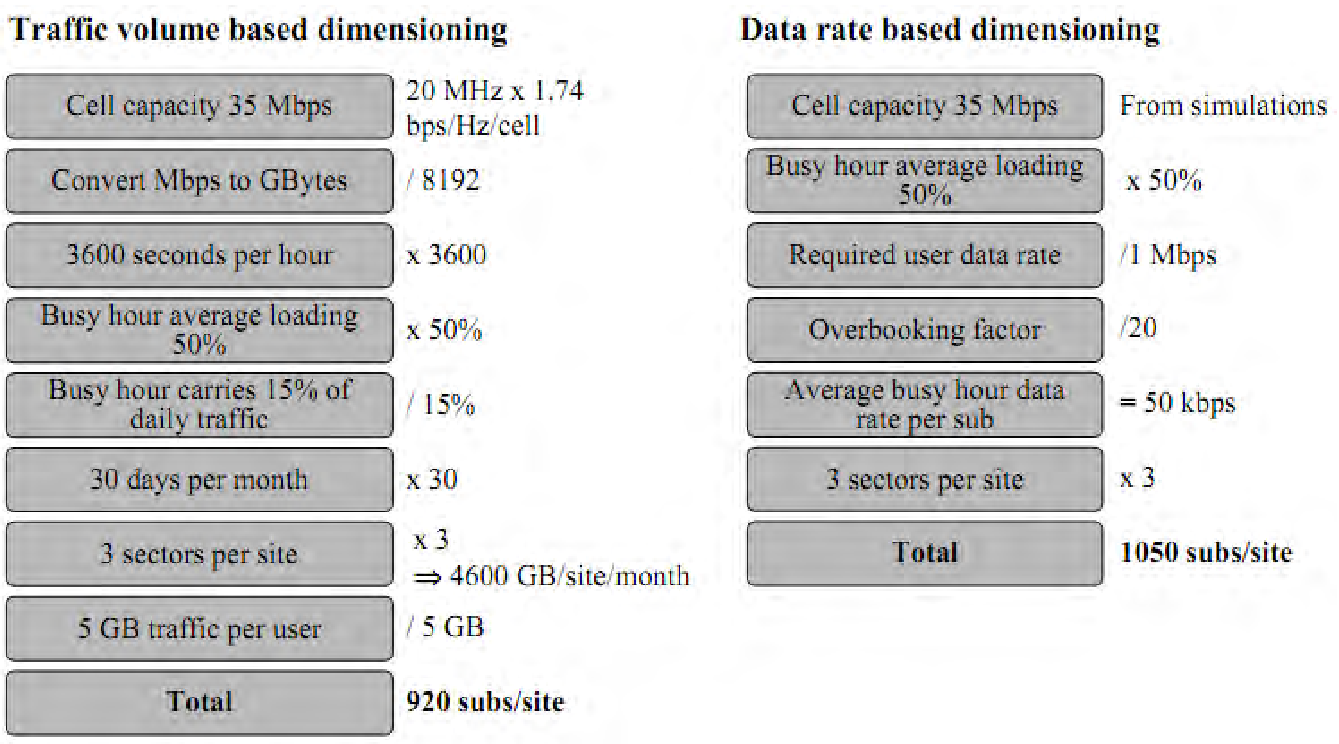
The evaluation of capacity needs the following two tasks to be completed [3]: being able to estimate the cell throughput corresponding to the settings used to derive the cell radius and analyzing the traffic inputs provided by the operator to derive the traffic demands, which includes the number of subscribers, the traffic mix and data about the geographical spread of subscribers in the deployment area.

Furthermore, the capacity calculation should consider different modulation schemes (QPSK, 16-QAM and 64-QAM) with combination of different coding rates are used based on customer demand. The higher code rate for the modulation schema, the higher data rate is achieved.

The capacity planning in LTE network planning can be done using different approaches. Figure 2-5 illustrates an example of the implementation of two methods: a traffic volume based approach and a data rate based approach [2]. The figure shows how to convert the cell throughput values to the maximum number of subscribers.

The traffic volume based approach estimates the maximum traffic volume in gigabytes that can be carried by LTE 20 MHz 3 sector in a site configuration. The spectral efficiency is assumed to be 1.74 bps/Hz/cell using 2 × 2 MIMO system. The calculation shows that the total site throughput per month is 4600 GB. To offer 5 GB data for every subscriber per month, the number of subscribers per site will be 920. Another approach assumes a target of 1 Mbps per subscriber.

Since only some of the subscribers are downloading data simultaneously, we can apply an overbooking factor, for example 20. This essentially means that the average busy hour data rate is 50 kbps per subscriber. The number of subscribers per site using this approach is 1050. As this example depicts, one of these approaches can be used in capacity planning giving priority to number of subscribers to be supported in a particular site or date rate service.



Traffic volume based dimensioning

Cell capacity 35 Mbps	20 MHz x 1.74 bps/Hz/cell
Convert Mbps to GBytes	/ 8192
3600 seconds per hour	x 3600
Busy hour average loading 50%	x 50%
Busy hour carries 15% of daily traffic	/ 15%
30 days per month	x 30
3 sectors per site	x 3 ⇒ 4600 GB/site/month
5 GB traffic per user	/ 5 GB
Total	**920 subs/site**

Data rate based dimensioning

Cell capacity 35 Mbps	From simulations
Busy hour average loading 50%	x 50%
Required user data rate	/1 Mbps
Overbooking factor	/20
Average busy hour data rate per sub	= 50 kbps
3 sectors per site	x 3
Total	**1050 subs/site**

Figure 2-5: LTE capacity dimensioning example for a 20 MHz LTE bandwidth [2]

3. Spectrum Refarming and Frequency Planning Techniques

3.1 Introduction

Radio Spectrum is a scarce resource as it is known and hence it must be managed to maximize the benefits from the activities realized by using it. At this time of rapid technological evolution and globalization, spectrum management must be carried out in a systematic way in order to satisfy the growing demand for frequencies in the emerging mobile communication technologies. A regulatory body might grant the available spectrum to operators or vendors that can be shared between them. Alternatively, the spectrum already in possession can be divided and granted for new operators or used for deploying new technology. The later approach is called as spectrum refarming.

Generally, spectrum refarming is a combination of present and future administrative, financial and technical measures within the limits of frequency regulation in order to make a specified frequency band available for a different kind of usage or technology [4]. Figure 3-1 shows a spectrum management cycle.

The figure illustrates that development of an existing radio system or conception of a new radio system or service can be managed on global level by organizations like International Telecommunication Union (ITU) or direct application for licensing at local level based on the demand identified. The requirements should then be set regarding the operational system, frequency range and amount of spectrum. After analyzing the feasibility of sharing the spectrum, decision is made.

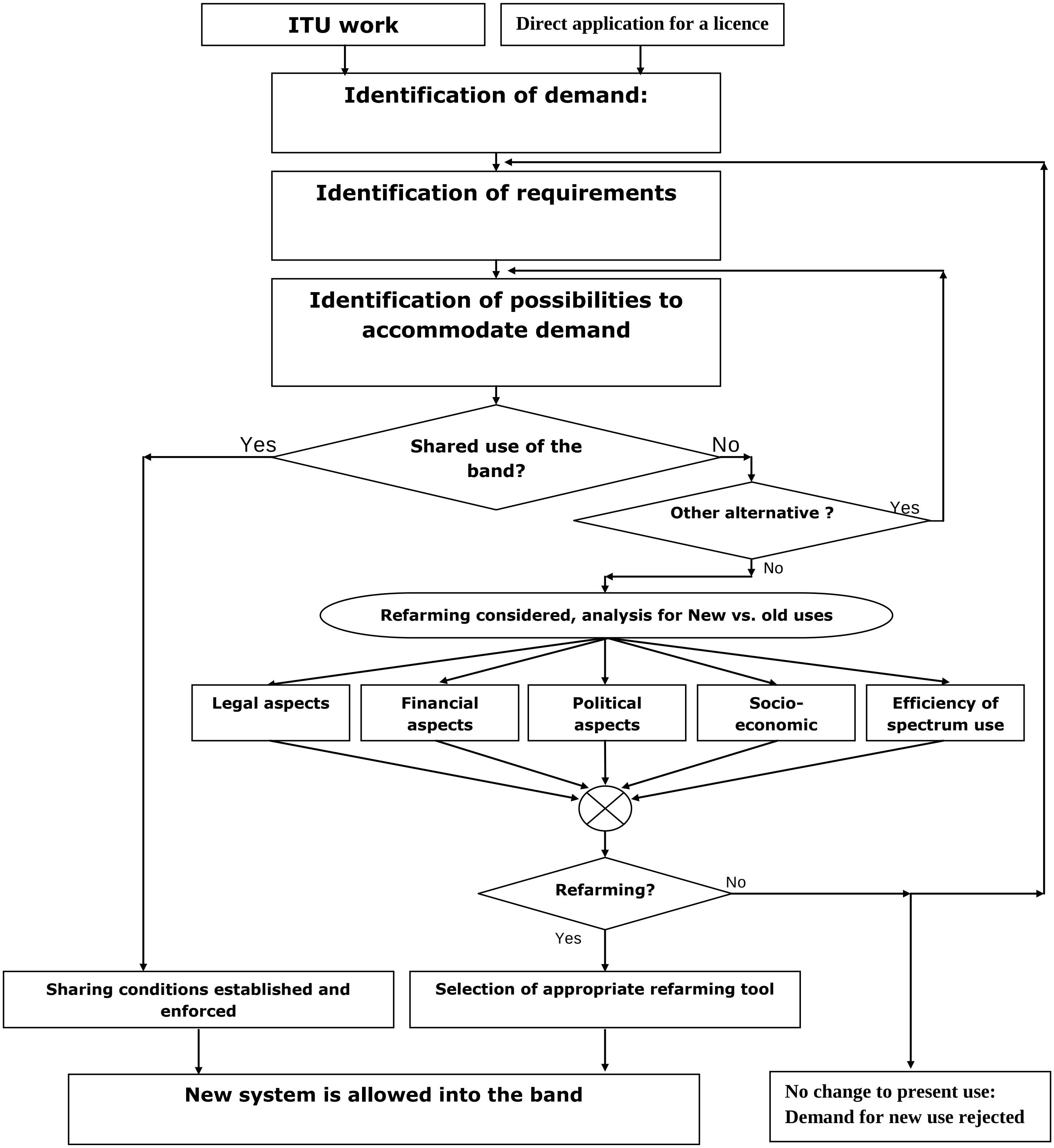


Figure 3-1: Refarming in a spectrum management cycle [4].

Sharing the spectrum imposes a new system to be allowed into the same band originally possessed by an operator. This needs an advanced coordination and monitoring system to be adopted between the parties since they will be using the same band based on a separate sharing mechanism in place. The other possible option is, spectrum refarming, where a distinct amount of spectrum is dedicated to each operator or technology at the ground. The selection of spectrum refarming option needs to take into account a variety of aspects like socio-economic and technical issues in comparison with the use of previous technologies. The selection of appropriate refarming tool to reuse either partially or fully the spectrum of an existing radio system is also an important step in the refarming process.

3.2 GSM/LTE (G/L) 1800 Refarming

The GSM refarming refers to smoothly phasing out currently used GSM services and reallocating the frequency bands to a more spectrum efficient and data optimized technology LTE. In spite of the need for GSM refarming, it is a time consuming process because it is difficult for a mobile operator to shut down its GSM network immediately due to the existing voice demand and global roaming capability [7].

A wider pair of 75 MHz available and the opportunity for a smooth transition makes the GSM1800 band an ideal candidate for refarming. More importantly, voice traffic carried over GSM1800 is decreasing due to the increasing penetration of 3G services, subscriber migration, and 3G traffic mostly carried over the 2,100MHz band. Frequencies in the 1800 MHz band can, therefore, be gradually refarmed to be used for more advanced LTE networks. The 1800 MHz band features lower propagation and penetration losses than the mainstream 2600MHz band for LTE [6].

The GL1800 Refarming solution results not only in significant savings on expenditure for new spectral resources but also faster LTE network deployment. In actual deployment, operators may also opt to reuse sites or even equipment based on the status of their existing network equipment, realizing smooth evolution to LTE from GSM.

3.3 Static Spectrum Refarming (SSR)

Static spectrum refarming refers to a static partitioning of the spectrum being utilized by a legacy network to a new technology (e.g., LTE). The bandwidth allocated for a new network is fixed and hence the changes in the traffic demand are not entertained. However, SSR is simple to implement and less complex as it does not take in to account the dynamics within the mobile networks in real circumstances.

Generally, to come up with an effective spectrum refarming, three critical techniques need to be taken into account. The first is about how to reallocate frequencies and control interferences between neighboring GSM and LTE frequencies. The second is about the method of migrating GSM voice service subscribers to release part of the spectrum. And the third is how different networks should be coordinated [6]. Similarly, the GSM 1800 band refarming can be implemented by following these generic steps.

3.3.1 Static Spectrum Refarming Methods: Full and Partial Refarming

In SSR, frequency reallocation, there are two mainstream methods commonly used in the industry, namely full refarming and partial refarming. In full refarming, the whole bandwidth of the legacy technology is refarmed for full LTE deployment while in partial refarming, a portion of the spectrum is refarmed for LTE on the possible deployment bandwidths. Full refarming is suitable for mobile operators with well developed GSM and UMTS networks and rich spectral resources. The number of GSM subscribers will be decreasing as 3G services are growing and these subscribers can be migrated to 3G networks, leading to fewer loads on the GSM network at 1800MHz. Therefore, the 1800MHz spectrum can be fully refarmed to be used for LTE networks, while all the voice services are borne by GSM 900.

Partial refarming is suitable for the operators with limited spectral resources who have no UMTS networks and have difficulty in subscriber migration or who have a large number of GSM subscribers that will remain stable in the short term. Partial refarming is done by two methods –

the *sandwich method* and the *edge allocation method* as shown in the Figure 3-2 and Figure 3-3. In the sandwich allocation mode, the LTE carrier can be arranged at any location (not necessarily at the center) in the spectrum resources of the operator, depending on the operator's strategies. Meanwhile, portions on both ends are still used by GSM. For later capacity expansion of the LTE, the operator might allocate more frequencies to LTE.

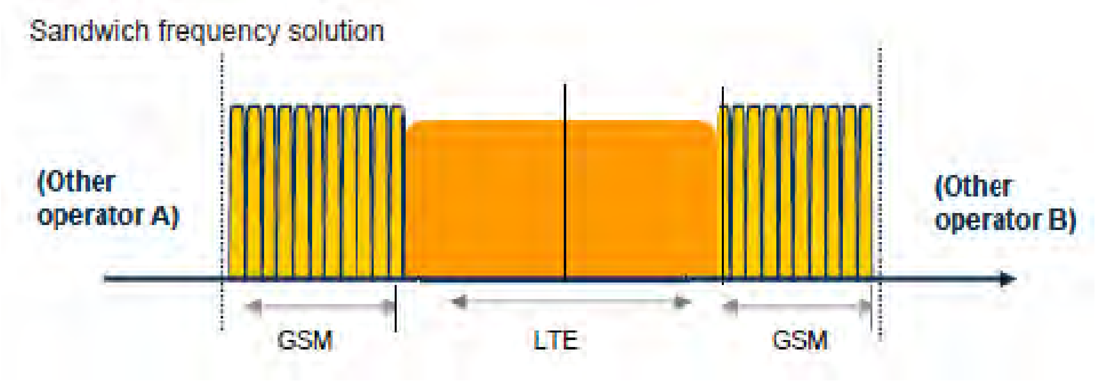


Figure 3-2: Sandwich frequency allocation [7]

In the edge allocation mode, the LTE carrier is allocated at the edge of the GSM spectrum. It has lower frequency utilization since a larger guard band is applied to reduce adjacent frequencies interference to other operators as shown in Figure 3-3.

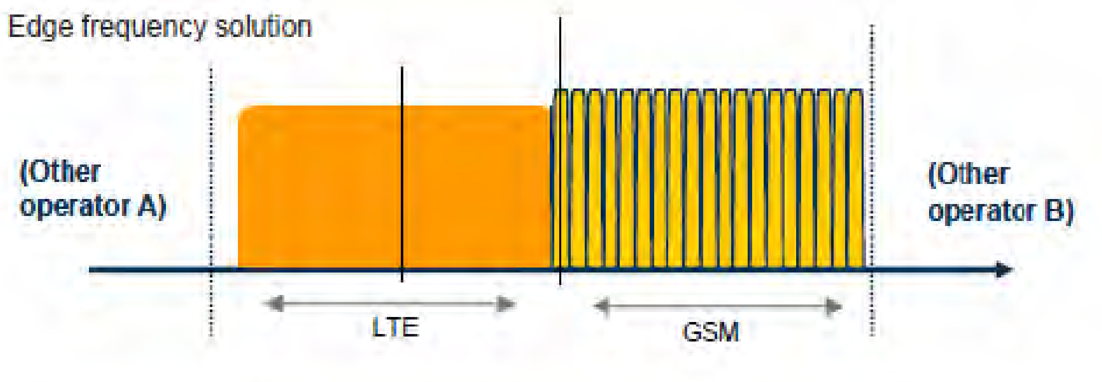


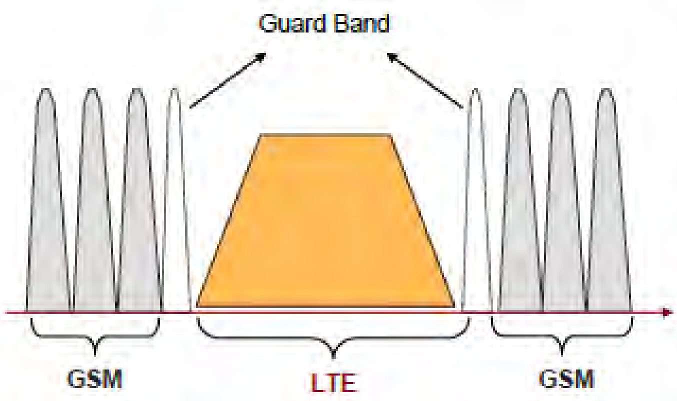
Figure 3-3: Edge frequency allocations [7]

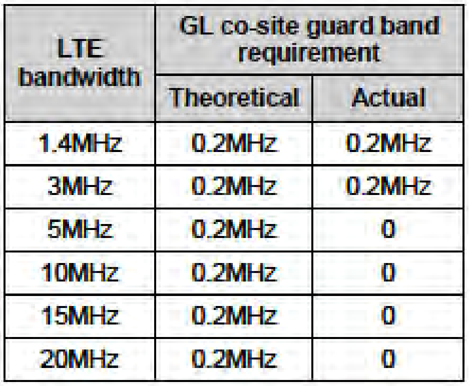
The sandwich method is recommended, given the GSM frequency reuse plan, interferences between frequencies and, in particular, interferences with other operators. Control over interferences between GSM and LTE can be done within the frequency band owned by an operator without needing to coordinate neighboring bands of other operators.

Also based on the preceding two frequency refarming methods, space division may be used to effectively reduce mutual frequency interferences between GSM and LTE. Operators may push refarming from cities to suburbs, from the perspectives of network loads and subscriber needs. They may first refarm some frequencies for LTE to satisfy the demand for mobile data in urban areas, for example. As for non-urban areas, they do not need to refarm frequencies and may instead keep using their own full-bandwidth GSM bands since there is no strong demand for high-speed mobile data services in these areas.

Mutual interferences of the same band between LTE and GSM should be avoided, as they often take place when this same band is used for LTE in urban areas and still for GSM in non-urban areas. Geographically, a transitional zone may be set between a city and its suburbs, where this band is left unused, to spatially prevent interferences caused by the use of the same band for both technologies.

In partial refarming, a guard band is needed to reduce the out-of-band spurious emissions which are inevitable. For narrow band LTE (1.4MHz - 3MHz), typically a 0.2MHz guard band is needed because 1.4MHz - 3MHz doesn’t have enough in-band guard bands [7]. For LTE with 5 MHz and above bandwidth, guard band is not necessarily required because there are enough in-band guard bands to avoid the spurious emission as shown in the Figure 3-4.





LTE bandwidth	GL co-site guard band requirement	
	Theoretical	Actual
1.4MHz	0.2MHz	0.2MHz
3MHz	0.2MHz	0.2MHz
5MHz	0.2MHz	0
10MHz	0.2MHz	0
15MHz	0.2MHz	0
20MHz	0.2MHz	0

Figure 3-4: Guard band between LTE and GSM

The flexible LTE bandwidth makes refarming easier because LTE can start with 1.4 MHz or 3.0 MHz bandwidths and then grow later when the GSM traffic has decreased. The required separation of the LTE carrier to the closest GSM carrier is shown in Table 3-1. The required total spectrum for LTE can be calculated based on the carrier spacing.

The coordinated case assumes that LTE and GSM use the same sites while the uncoordinated case assumes that different sites are used for LTE and GSM [2]. The uncoordinated case causes larger power differences between the systems and leads to a larger guard band requirement. The coordinated case values are based on the GSM UE emissions and the uncoordinated values on LTE UE blocking requirements.

It may be possible to push the LTE spectrum requirements down further for coordinated deployment depending on the GSM UE power levels and the allowed LTE uplink interference levels. The limiting factor is the maximum allowed interference to the PUCCH (Physical Uplink Control Channel) PRBs that are located at the edge of the carrier.

Table 3-1: Spectrum requirements for LTE refarming [2]

	LTE-GSM carrier spacing		LTE total spectrum requirement	
	Coordinated	Uncoordinated	Coordinated	Uncoordinated
5 MHz-LTE (25 RBs)	2.5 MHz	2.7 MHz	4.8 MHz	5.2 MHz
3 MHz- LTE (15 RBs)	1.6 MHz	1.7 MHz	3.0 MHz	3.2 MHz
1.4 MHz- LTE (6 RBs)	0.8 MHz	0.9 MHz	1.4 MHz	1.6 MHz

The carrier spacing definition is illustrated in Figure 3-5 and Figure 3-6 shows the expansion of the LTE carrier bandwidth when the GSM traffic decreases. In Figure 3-5 we can see that there is a 2.5 MHz carrier spacing for a 5 MHz LTE bandwidth from an adjacent GSM carrier. This is resulted from a deduction of 0.1 MHz guard band from both ends of LTE carrier.

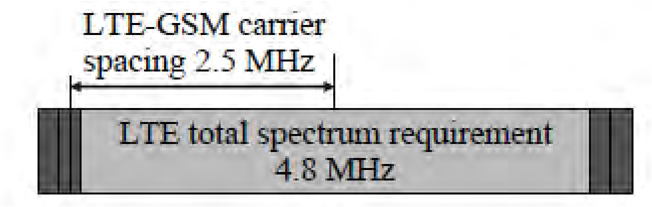


Figure 3-5: LTE 5-MHz refarming example

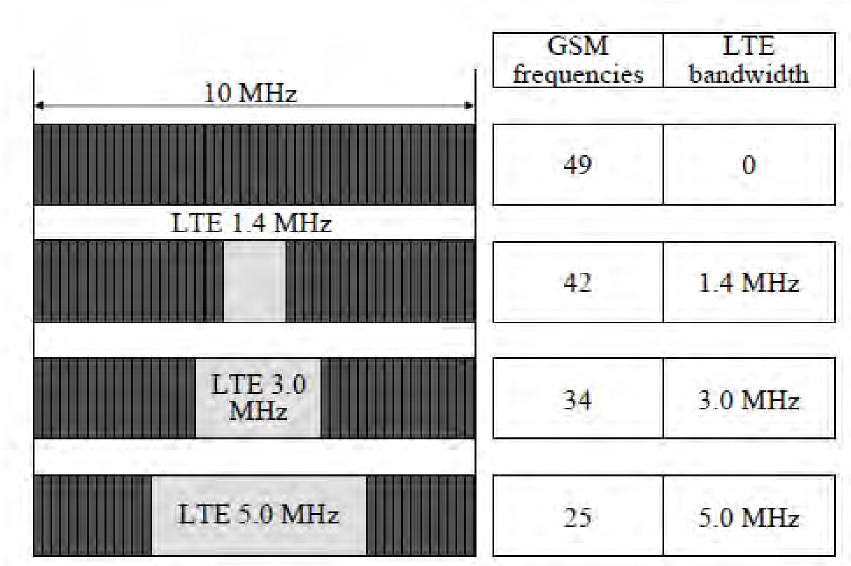


Figure 3-6: LTE refarming to GSM spectrum

Hence, there will be 0.2 MHz spacing between adjacent GSM and LTE carriers. In the expansion of LTE carrier as shown in Figure 3-6, only seven GSM carriers need to be removed to make room for LTE 1.4 MHz and 15 GSM carriers for LTE 3.0 MHz refarming and so on.

3.4 Dynamic Spectrum Refarming

Static refarming of the available spectrum for LTE network does not make room for the dynamic mobile network demand requirements which is clearly visible in real circumstances. On the other hand, mobile network operators may have to keep providing GSM service for legacy devices, although they would like to refarm their GSM spectrum for LTE.

Dynamic spectrum refarming (DSR) approach allows for the coexistence of GSM and LTE in a flexible way. Some LTE physical resource blocks (PRBs) will be reserved for GSM transmission, i.e., LTE eNodeB will not schedule those reserved PRBs for any User Equipment (UE) and accordingly suppress the reference signals. With this approach, operators can migrate their GSM spectrum to LTE while still providing GSM connectivity to their low data rate customers. This approach is advantageous compared to static partitioning of the legacy spectrum since LTE itself forges more efficient use of spectrum.

3.4.1 The Technique of Bandwidth Utilization

The basic idea of DSR is to exploit the flexibility of OFDM used in LTE to embed GSM transmissions within a portion of LTE transmissions. PRBs that are reserved for GSM need to be carefully picked so that the critical LTE PRBs used for synchronization, control signaling and other signaling such as Hybrid Automatic repeat Request (HARQ) feedback are not allowed for use by GSM. With this approach, LTE UEs are not significantly impacted by GSM transmissions [8]. Finally, GSM requires frequency reuse. Spectral efficiency can be improved by allowing low power LTE transmissions to LTE UEs close to the base station on the GSM PRBs of the neighboring cells/sectors. With this fractional reuse approach between LTE and GSM, the amount of spectrum needed to support GSM can be minimized.

Let’s consider an exemplar allocation of GSM spectrum with in 10 MHz LTE in Fig 3-7. Each block in the figure represents 200 KHz, the width of a GSM carrier. A total of 12 200 KHz blocks or about 2.4MHz of spectrum can be assigned as default GSM spectrum. This represents about 25% of the LTE spectrum. Each sector can have a GSM Broadcast Control Channel (BCCH) carrier and a traffic carrier. A frequency reuse of 3/9 can be supported for BCCH and 1/3 for traffic channel.

The diagram also shows that some of the GSM blocks meant for use in other cells can be used in this cell for LTE with low power so that they do not cause interference to other cells. The grey blocks cannot be assigned to GSM since they need to be protected for LTE control signaling. The spectrum sharing can be dynamic in the sense that when there is no GSM traffic in a given sector, the GSM blocks can be used for LTE transmission.

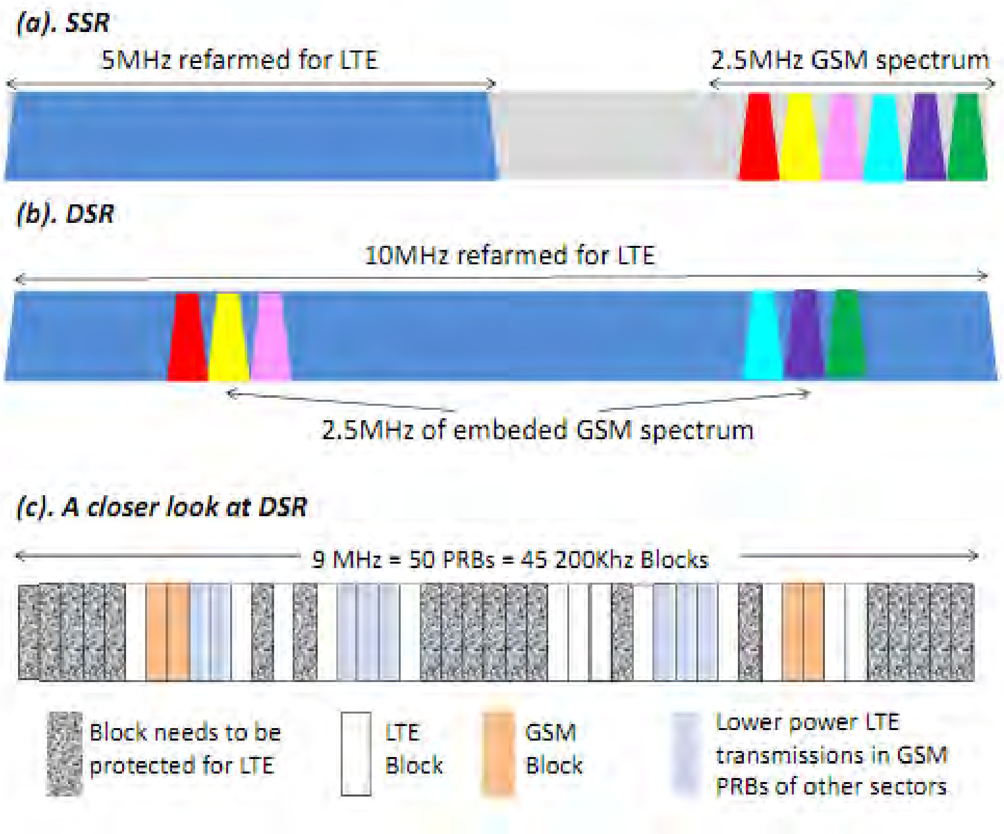


Figure 3-7: SSR and DSR [8]

It should also be noted from Figure 3.7 (c) plot that 45 200 KHz blocks rather than 50 180KHz LTE PRBs. As GSM center frequency must be an integer multiple of 200 KHz, GSM channel edges may not be always aligned with LTE PRB edges. It should be noted that the number of PRBs that are reserved for GSM should be appropriately determined: there would be inefficiency or loss if either excess or too few PRBs are reserved.

In DSR, the number of reserved PRBs is based on relatively long term statistics such as hours. In contrast, the durations of GSM sessions are at the time scale of seconds or at most minutes. Thus, on a short time scale the reserved PRBs may be underutilized or over loaded. The reserved PRBs utilization can be made efficiently even though the number of reserved PRBs is determined based on long term average GSM traffic trends.

3.4.2 Reserving Physical Resource Blocks (PRBs) for GSM

The reservation scheme in DSR changes the channel structure of LTE. In order to ensure normal operation of LTE, it is needed to carefully select the positions of those reserved PRBs out of the LTE channel. Taking the 10MHz LTE channel as an example, shown in Figure 3-8, we are going to see how the system should reserve PRBs to minimize the potential impact of LTE puncturing on the broadcast and synchronization channels, reference symbols, and other control signaling channels including Physical Control Format Indicator Channel (PCFICH), Physical Downlink Control Channel (PDCCH) and Physical Hybrid-ARQ Indicator Channel (PHICH).

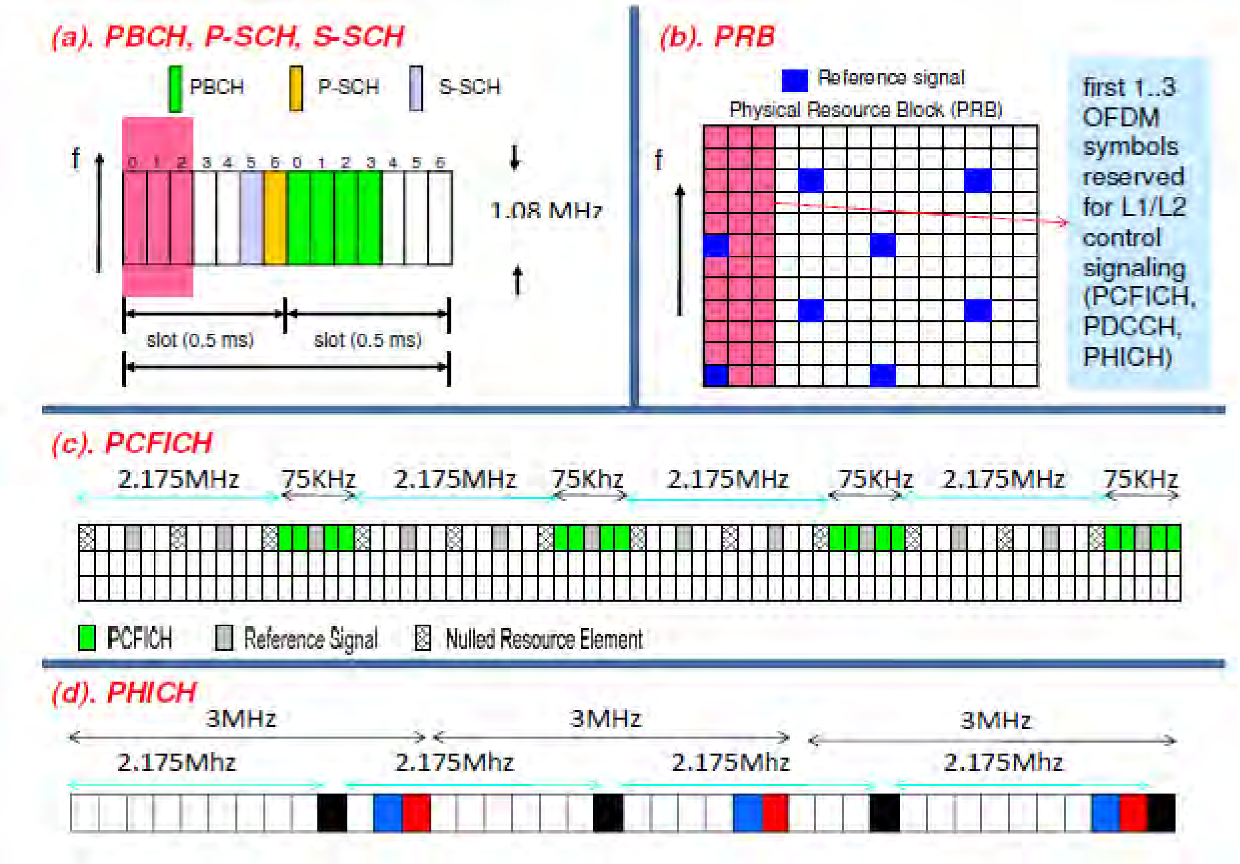


Figure 3-8: LTE downlink channel structure (10MHz example) [8]

The impact of puncturing on broadcast and control channels can be described as follows.

a) The impact on broadcast and synchronization channels

LTE broadcast and synchronization channels are located within the central 1.08MHz of the 10MHz LTE channel, as shown in Figure 3-8 (a). So we can avoid reserving the PRBs used by the LTE broadcast and synchronization channels.

b) The impact on reference signals

The impact of puncturing on reference symbols is not an issue because the reserved PRBs will not be scheduled for any user.

c) The impact on PCFICH and PHICH

The PCFICH occupies four 75 KHz chunks within the 10MHz LTE channel, as shown in Figure 3-8 (c). As for PHICH, multiple PHICHs are mapped to the same set of resource elements and these PHICHs constitute a PHICH group. The positions of PCFICH and PHICH are not fixed and vary with the physical cell ID. They would spread out and occupy all the PRBs if the entire cell IDs were used and we would not be able to reserve PRBs without affecting them. To overcome this issue, we can only use a small subset of the cell IDs. Then PCFICH and PHICH will only occupy certain part of the LTE transmission bandwidth, which can be avoided by the reserved PRBs.

d) The impact on PDCCH

The real challenge comes from the PDCCH which occupies all the PRBs. This implies that a certain number of resource element groups carrying the PDCCH have to be wiped out with LTE puncturing. Fortunately, LTE multiplexes and interleaves several PDCCHs within one LTE sub-frame. This helps to spread the impact of puncturing over all the PDCCHs and each PDCCH only needs to tolerate a certain level of the errors. Moreover, LTE allows the system to increase the aggregation level of the control channel elements, which can make PDCCHs more robust against errors. Given limited resource of the control channel elements, increasing its aggregation level reduces the number of PDCCHs that can be simultaneously used.

Finally, since LTE signal and GSM signal are transmitted in the same band, there is GSM adjacent channel interference leakage on LTE UE and vice versa. To mitigate interference from LTE PRBs to GSM, transmit power on the PRBs close to GSM PRBs can be reduced. This also helps mitigate the impact of GSM on LTE since other non-adjacent PRBs can be allocated more power and partially recover the LTE capacity loss because of GSM overlay.

3.5 Comparison between DSR and SSR

We can compare DSR to static spectrum refarming (SSR) to highlight the key advantages of DSR using the same example depicted above. SSR completely separates GSM and LTE within the band, i.e., part of the GSM spectrum is kept for legacy devices while the remaining GSM spectrum is refarmed for LTE.

As a specific example, consider the scenario shown in Figure 3-7. Because LTE transmission bandwidth can only be 1.4, 3, 5, 10, 15, or 20 MHz wide, the operator will be restricted to refarming 5 MHz of the spectrum for LTE and the remaining 2.5MHz will be underutilized. Even if LTE can simultaneously support a 5MHz channel and a 1.4MHz channel by e.g. carrier aggregation, the remaining 1.1MHz spectrum is underutilized. In contrast, DSR allows the deployment of 10MHz LTE channel with 2.5MHz of GSM embedded. Thus, compared to SSR, DSR can minimize the wastage of spectrum.

The second advantage of DSR is its flexible spectrum reuse capability. In SSR, the LTE bandwidth is fixed (5 MHz in Figure 3.7). The system cannot reassign bandwidth between GSM and LTE with changing traffic demand. In contrast with DSR, LTE in a given sector can utilize the GSM carriers of the neighboring sector with low transmit power. Low power LTE transmissions targeting good geometry users can provide significant spectral efficiency. Since transmissions are of low power, GSM transmissions in the neighboring cell are (nearly) not affected. This idea can be viewed as a form of fractional frequency reuse (FFR) for inter-technology inter-cell interference coordination (ICIC).

Besides, if immediate transmission is not strictly required for low data rate users, then the traffic on GSM can be scheduled to avoid the busy hour and DSR allows more spectrum to be used for LTE to accommodate the needs. Finally, DSR provides GSM connectivity within an LTE carrier through an efficient, dynamic overlay by reserving a few PRBs for GSM.

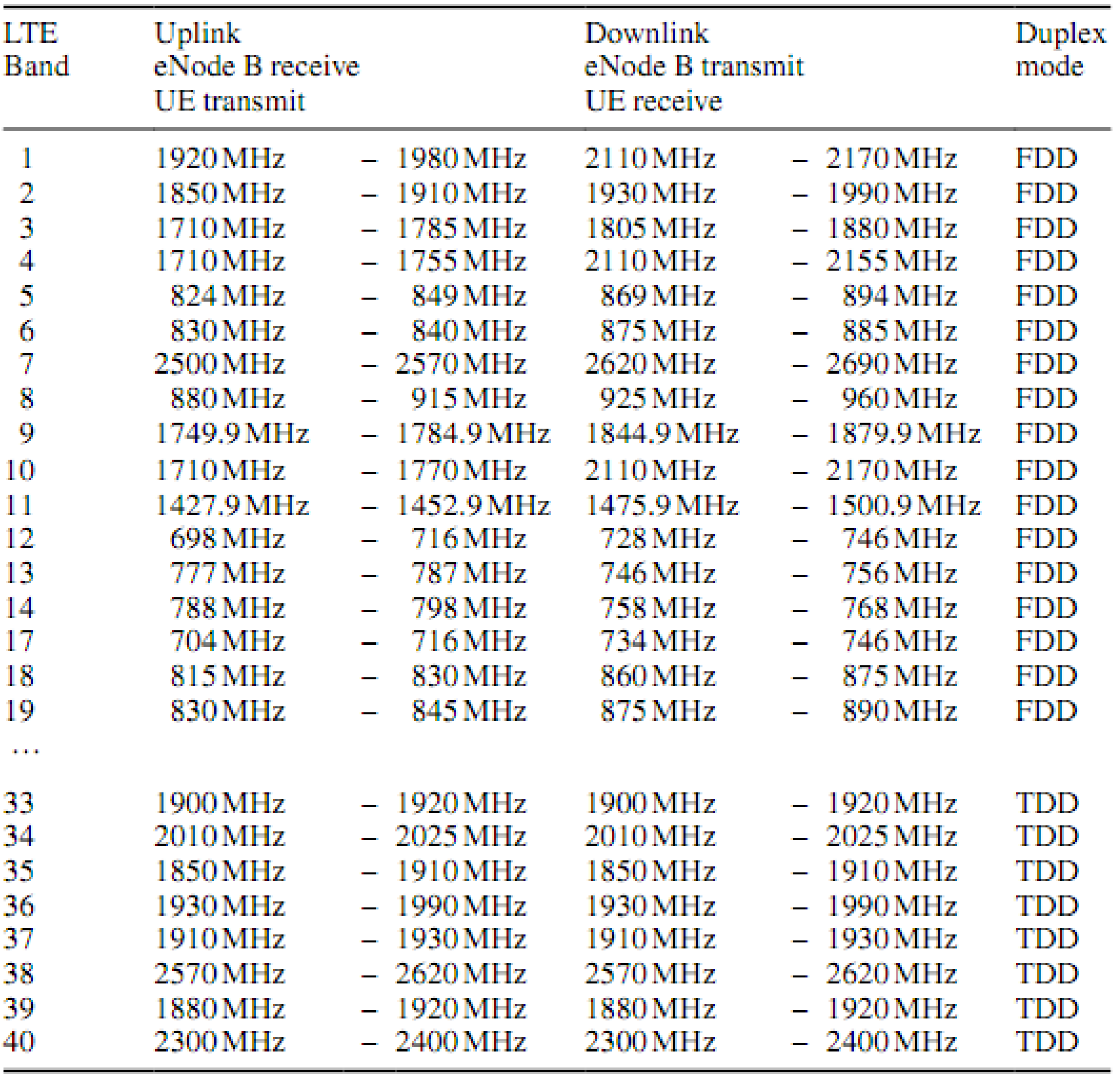
3.6 Frequency Planning and Frequency Reuse Schemes

3GPP defines minimum Radio Frequency (RF) performance requirements for terminals (UE) and for base stations (eNodeBs). LTE is defined for a wide range of different frequency bands, in each of which one or more independent carriers may be operated. Table 3-2 gives details of the frequency bands for FDD and TDD operation in LTE respectively. Several frequency planning schemes and inter cell interference mitigation have been envisaged for multi-cell OFDMA networks. Due to excessive inter cell interference, especially from adjacent cells; some users at the edge could not be served.

Thus, Frequency Reuse Factor (FRF) concept was introduced leading to frequency planning schemes where inter cell interference is highly reduced, because orthogonal subsets of sub-channels are distributed among cells. Figure 3-9 illustrates different frequency planning schemes for FRF of 3.

In OFDMA, the system bandwidth is split into a number of sub-carriers, each featuring a bandwidth smaller than the systems coherence bandwidth, on which data of different users is transmitted in parallel. While the sub-carrier thinness and the resulting large OFDM symbol time reduce the effect of Inter-Symbol Interference (ISI), the orthogonality among them mitigates inter-carrier interference (ICI). By using appropriate cyclic prefixes, ICI and ISI can almost completely be avoided [14]. However, a key issue with OFDMA is the co-channel interference (CCI) or inter-cell interference: especially terminals located at the cell border largely suffer from the power radiated by the base station of neighboring cells in their communication band.

Table 3-2: LTE frequency bands [5]



LTE Band	Uplink eNode B receive UE transmit	Downlink eNode B transmit UE receive	Duplex mode
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD
5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
6	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD
11	1427.9 MHz – 1452.9 MHz	1475.9 MHz – 1500.9 MHz	FDD
12	698 MHz – 716 MHz	728 MHz – 746 MHz	FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	FDD
…			
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD

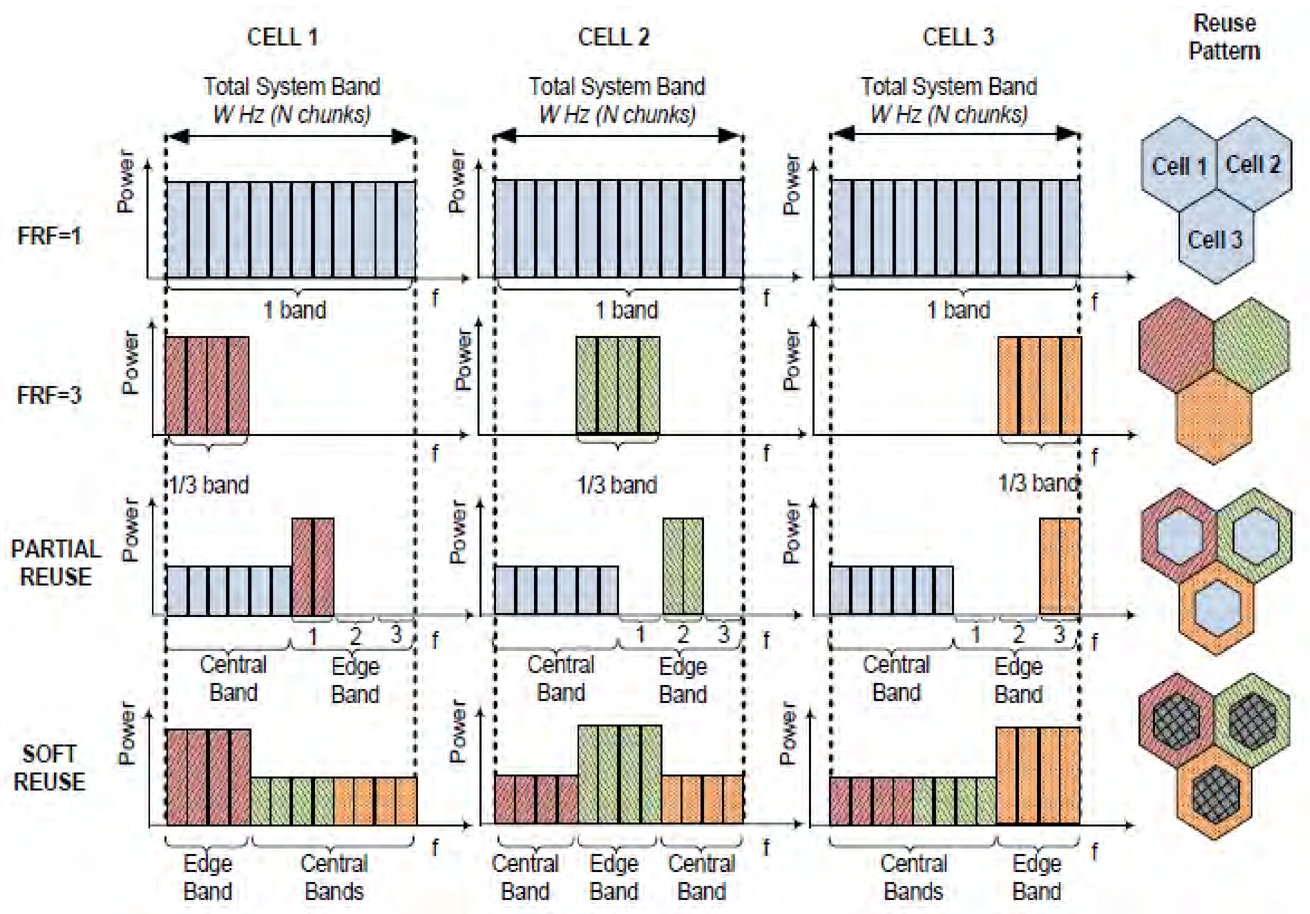


Figure 3-9: Frequency planning schemes for OFDMA radio interfaces [13]

There are three major frequency reuse patterns for mitigating inter-cell interference: Hard Frequency Reuse, Soft Frequency Reuse and Fractional Frequency Reuse (FFR) [14]. Hard frequency reuse splits the system bandwidth into a number of distinct sub-bands according to a chosen reuse factor and lets neighboring cells transmit on different sub bands. Hard frequency reuse though simple in implementation suffers from quite reduced spectral efficiency. Following, Soft frequency reuse and fractional frequency reuse schemes will be discussed in some detail.

3.6.1 Soft Frequency Reuse Scheme (SFR)

The basic idea of the SFR scheme is to apply Frequency Reuse Factor (FRF) of one to the cell center user (CCU) and FRF of three to the cell edge user (CEU). As illustrated in Figure 3-10, simply one third of the whole available bandwidth named Major Sub-channel can be used by cell edge users, and on these major sub-channels, packets are sent with higher power and the FRF is 3 for cell edge users [5].

The frequency assigned in the major sub-channel among directly neighboring cells should be orthogonal so that the ICI from the neighboring cells to those users can be alleviated. The cell center users can access the entire frequency resource with lower transmission power in the normal sub-channels.

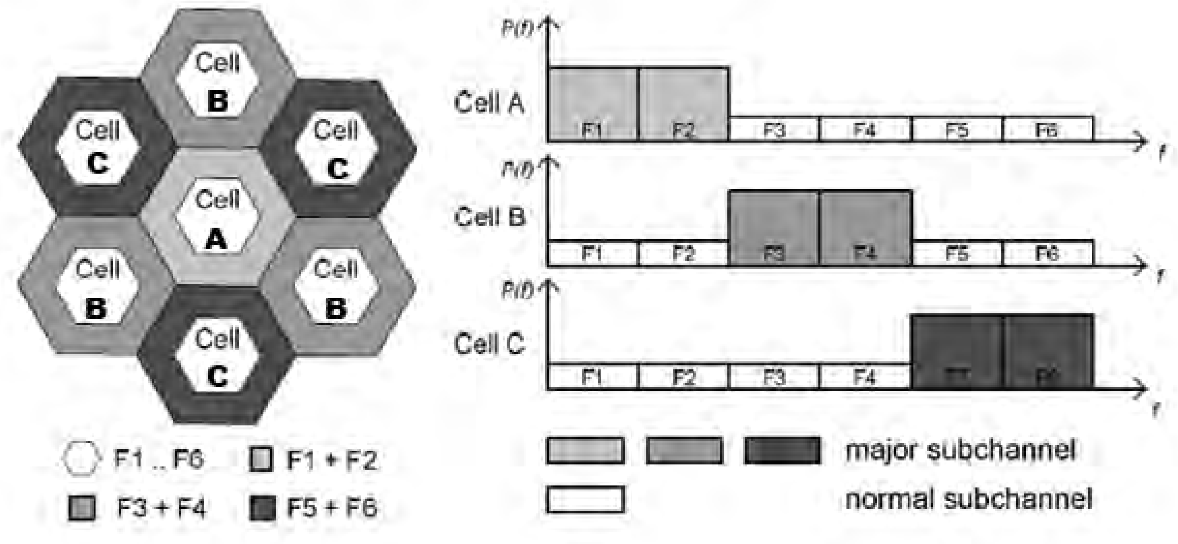


Figure 3-10: Soft Frequency Reuse scheme in a cellular system [5]

In a wireless cellular communication system, the signal to interference and noise ratio (SINR) can be generally described as

$$SINR = \frac{P_{rx}}{P_{intra-cell} + P_{inter-cell} + P_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where, P_{rx} is the received power of the expected user signal, $P_{intra-cell}$ is the inner cell interference power, $P_{inter-cell}$ is other cell interference power and P_n is the white noise power. If we assume that the intra-cell interference is eliminated, the SINR can be simplified as,

$$SINR = \frac{P_{rx}}{P_{inter-cell} + \frac{P_n}{Reuse\_factor}} \tag{3.2}$$

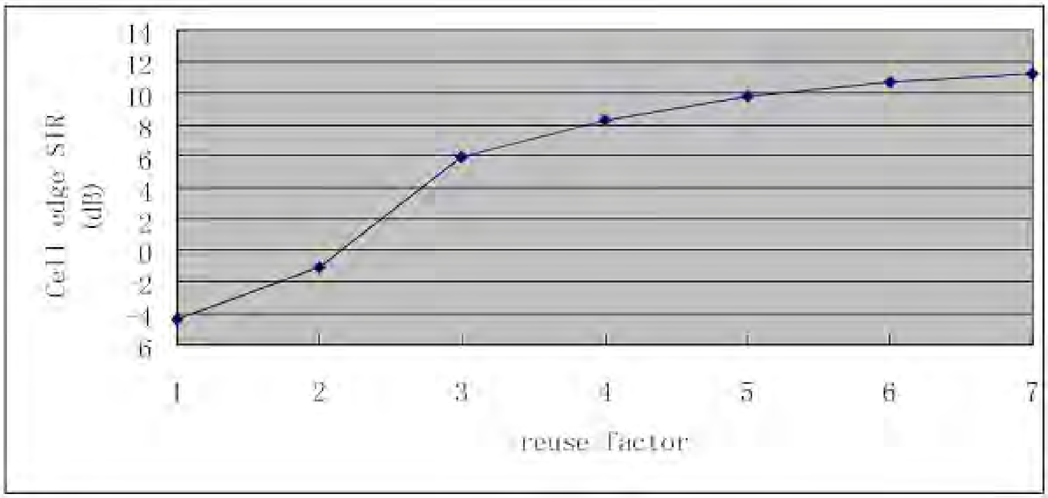
In case of flat fading channel, according to the Shannon's theorem, the channel capacity can be expressed as:

$$C = \frac{W}{reuse\_factor}\log_2(1 + SINR) \tag{3.3}$$

Where, W is the channel bandwidth

A simulation result of (3.2) above is illustrated in Figure 3-11. In Figure 3-11 (a), smaller reuse factor corresponds to larger available bandwidth for each cell and low signal to interference (SIR) due to co-channel interference. On the contrary, larger reuse factor corresponds to smaller available bandwidth and higher SIR.

After the reuse factor exceeds 3, the channel capacity at the cell edge decreases at a relatively slow rate and remains above the channel capacity of reuse factor 1 and 2 as shown in Figure 3-11 (b). This is the reason why the reuse factor is set 3 for the SFR.



(a)

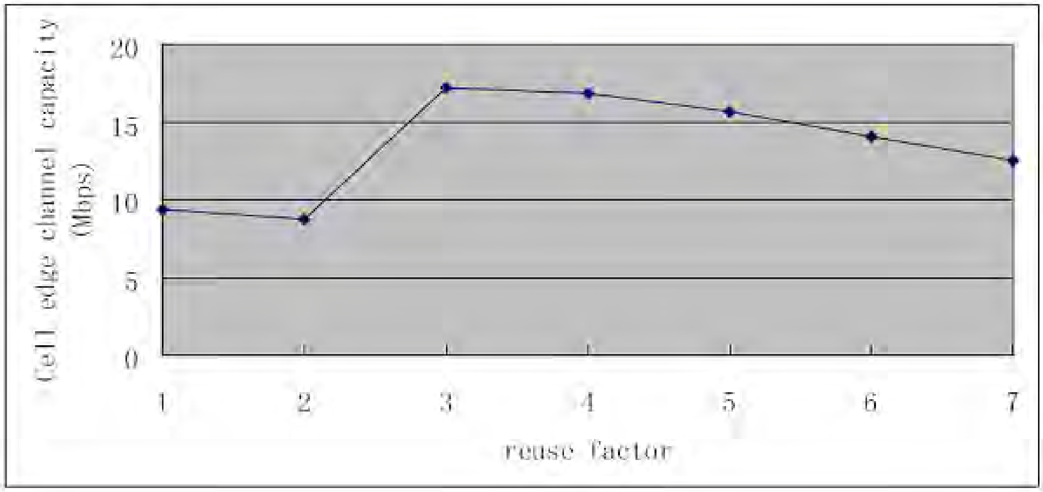


Figure 3-11: SIR at the cell edge (a) and Channel Capacity at the cell edge (b) [5].

Generally, Soft frequency reuse has full spectral efficiency and is a strong tool for inter-cell interference mitigation. But as it implies centralized, coordinated resource allocation, such a system can be impractical in realistic settings involving a large number of base stations, random traffic and realistic path-loss models.

3.6.2 Fractional Frequency Reuse (FFR)

FFR is considered as a compromise between hard and soft frequency reuse. It splits the given bandwidth into an inner and an outer part. It allocates the inner part to the near users (located close to the base station in terms of path loss) with reduced power applying a frequency reuse factor of one i.e. the inner part is completely reused by all base stations. For users closer to the cell edge (far users), a fraction of the outer part of bandwidth is dedicated with the frequency reuse factor greater than one. Figure 3-12 illustrates FFR scheme.

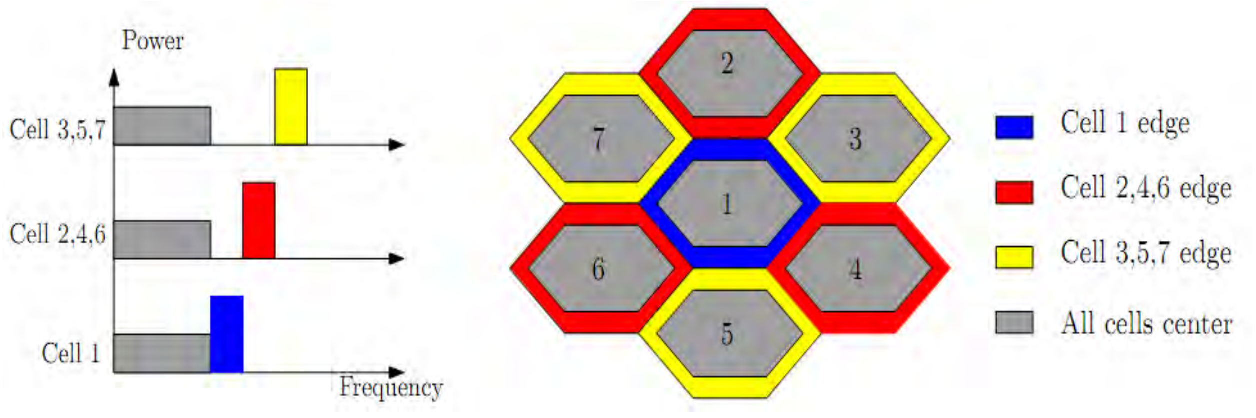


Figure 3-12: FFR in LTE (Frequency reuse factor for cell edge users is 3) [14]

Figure 3-12 shows the traditional FFR for LTE whereas Figure 3-13 shows the modified FFR. Here, we only focus on the outer part of spectrum which is reserved for the cell edge users. Traditional FFR ensures orthogonal allocation of sub bands in neighboring cells for cell edge users leading to zero interference for the cell edge users and the frequency reuse factor for cell edge users increases to 3. On the other hand, modified FFR ensures a maximum one interference for the cell edge users and the frequency reuse factor subsequently reduces to 1.5 leading from the calculation [14].

FRF= 1 / [(3(2/3) + 3(2/3) + 2/3) / 7] = 3/2 = 1.5. This leads to an improvement of spectral efficiency by 33% (i.e., by factor of 1/3).

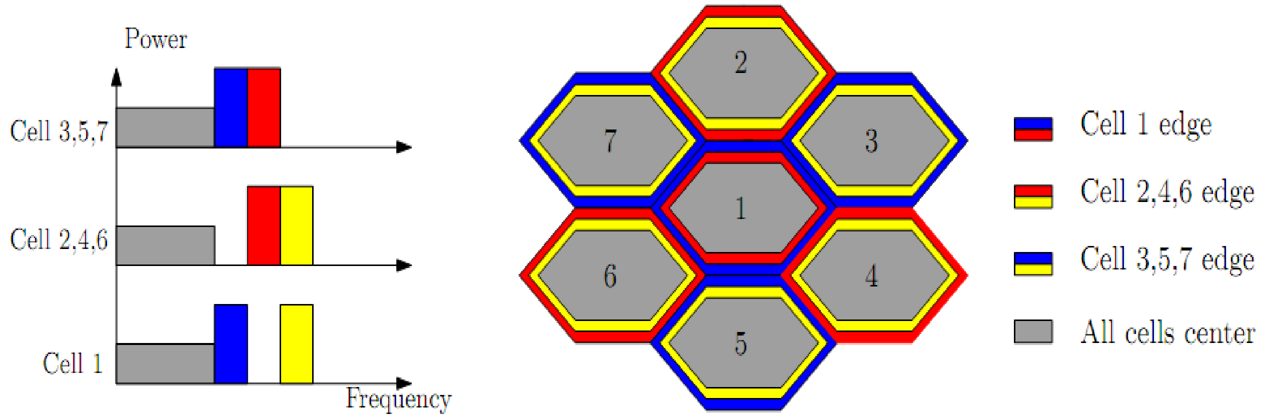


Figure 3-13: Modified FFR in LTE [14]

Finally, to improve cell edge performance and the overall throughput of a base station (eNodeB) and the radio network in general, a load indication message can be used for Inter-cell Interference Coordination (ICIC) [15]. As eNodeBs autonomously decide as to how they use their air interface, the X2 interface can be used to exchange interference-related information between neighboring eNodeBs, which can then be used to configure transmissions in such a way as to reduce the problem.

4. System Design

In this Chapter, a simulation set up is used in analyzing the GSM/LTE spectrum refarming techniques (SSR and DSR) and the frequency planning in deployment sites. For this purpose, MATLAB 2013a software is used for it is a conventional and flexible tool to embody the techniques of GSM spectrum refarming.

4.1 Simulation Procedure

The simulation is carried out considering the spectrum already possessed by GSM at 1800 MHz frequency which is refarmed for LTE deployment. To this end, site locations (eNodeBs) in the selected coverage area are taken as input and cell capacity (number of UEs served) is fixed. The refarming process is carried out assuming both static (fixed bandwidth allocations for every site) and dynamic refarming (different bandwidth allocations based on the demand conditions).

The bandwidth granted for LTE is planned in different site locations and the network performance is also evaluated using parameters like SINR, throughput obtained from simulation. The impact on the co-sited GSM network is also analyzed. The simulation procedure consists of deployment area selection and related input data gathering at the beginning. Following, the simulation parameters are set. Then, simulation for initial static spectrum allocation is carried out. Based on the bandwidth demand and usage, the spectrum is allocated dynamically. Finally, the impact on GSM is analyzed for both static and dynamic spectrum allocation cases. Figure 4.1 illustrates steps in the simulation procedure.

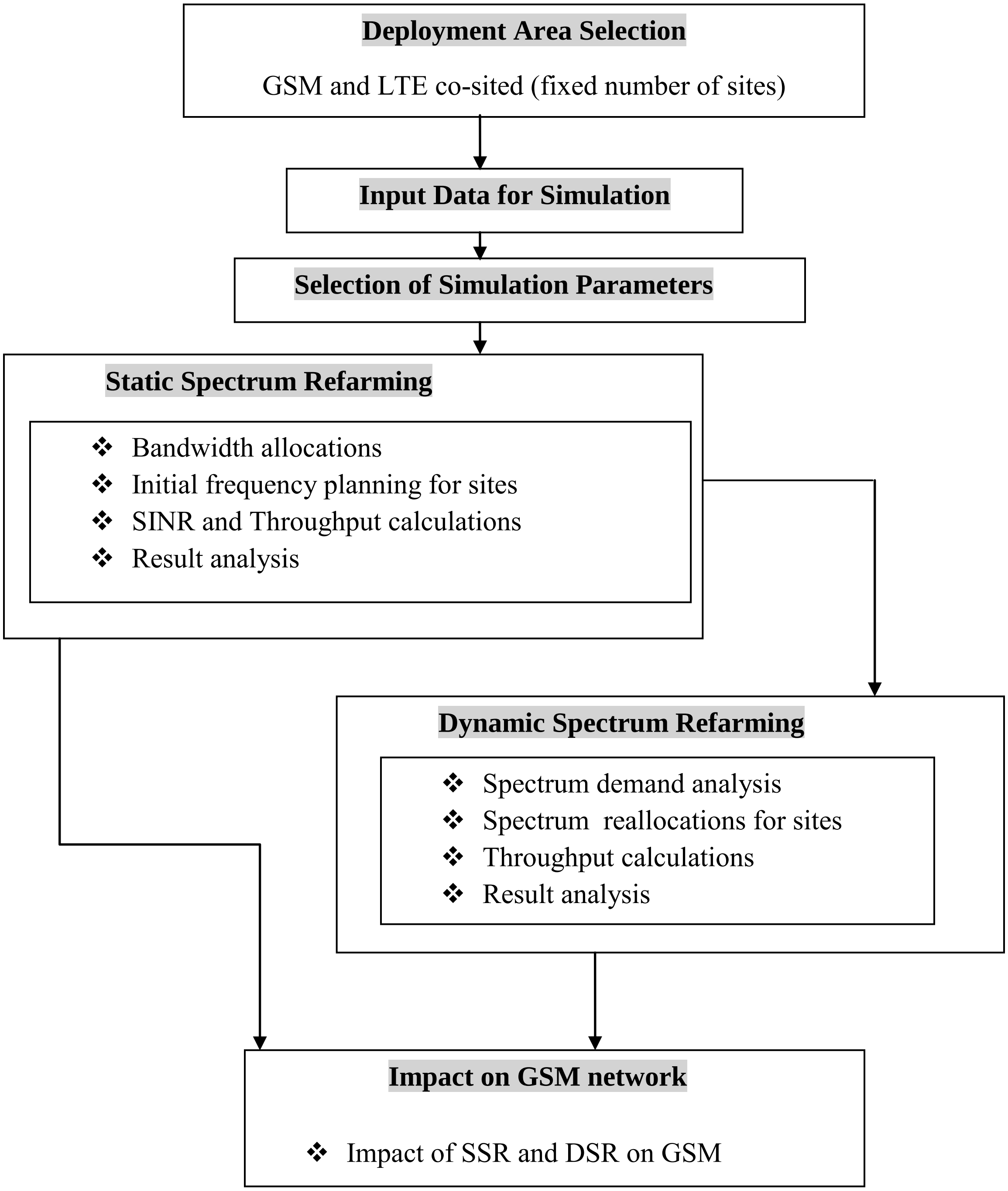


Figure 4-1: Simulation procedure

4.1.1 Deployment Area Selection

In this thesis, the area selected for study is located in Bole sub-city around Gerji with area covering about $5.88\ km^2$. The area stretches out from the end of Bole Air port area in the south west to the main residential area of Gerji in the east as shown in the Figure 4-2.

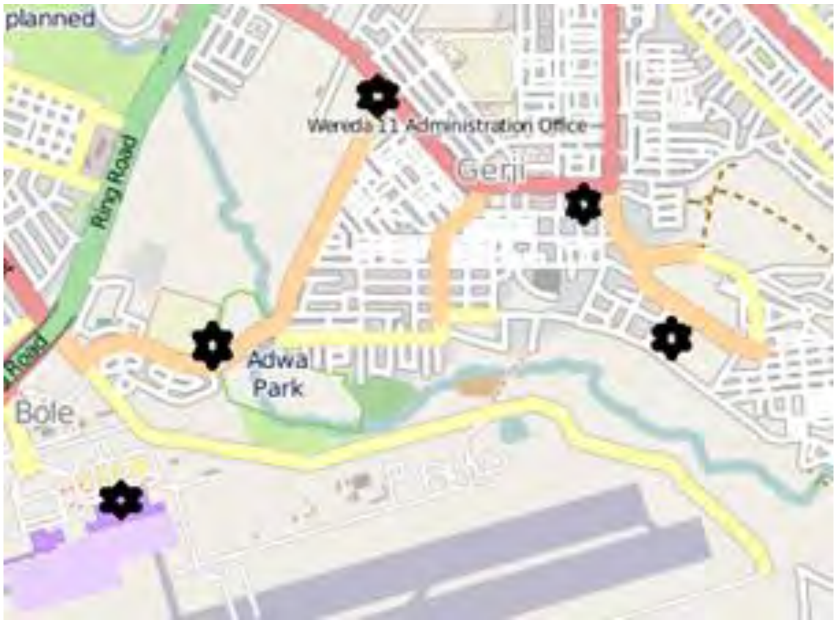


Figure 4-2: Selected deployment area (the stars indicate the site locations).

As shown in Figure 4-2, there are five sites selected in the focus area of interest. These base stations serve GSM and LTE network simultaneously hence a co-existing network.

4.1.2 Input Data for Simulation

The selected area contains five sites. Table 4.1 shows data regarding the base station locations.

Table 4.1 Base station locations in the case study area

No.	Longitude	Latitude	Sub City
1	38.8128	8.9938	Bole
2	38.7958	8.9831	Bole
3	38.7995	8.9885	Bole
4	38.8054	8.9977	Bole
5	38.8158	8.9890	Bole

The number of mobile users is fixed considering the maximum capacity of the base stations which is in turn derived from the specified bandwidth allocations by Ethio Telecom in the 1800 MHz frequency band and the frequency planning on the ground.

The LTE deployment project done by Ethio Telecom in Addis Ababa is based on classifying the city in to two morphologies based on the density of population: Dense urban and Urban. In this thesis, it is assumed that the case study area is classified as urban. The LTE frequency bandwidth is 20MHz, and the uplink is from 1727.5 MHz to 1747.5 MHz, the downlink is from 1822.5 MHz to 1842.5 MHz. Table 4-2 shows the frequency planning by Ethio Telecom.

Table 4-2: LTE frequency planning by Ethio Telecom

BANDWIDTH	**1800 MHz**			
	UPLINK		**DOWNLINK**	
1800 bandwidth	1710 ~1747.5		1805~1842.5	
GSM bandwidth	1710-1727.5		1805 –1822.5	
LTE bandwidth		1727.5–1747.5		1822.5–1842.5

The total bandwidth used for the uplink and downlink is 37.5 MHz each (GSM + LTE). There is a total of 2 x 0.1 = 0.2 MHz guard band between GSM and LTE bands.

4.2 Selection of Simulation Parameters

The base stations (eNodeBs) geographic location (latitudes and longitudes) is converted to distance metrics, using a standard conversion factor, which will be used as input. The mobile user number supported within the study area is fixed to be 200 (34 users/square kilometer). However, there should be cases of UE distribution that take in to account a non uniform mobile user distribution in real conditions.

The covered area is divided in to 4 equal square partitions with different user equipment distribution (hotspots) in order to analyze the changes that occur on the bandwidth usage consequently. Therefore, the spectrum usage is analyzed in the first case where all the subareas composing one fourth of the total number of UEs while in the second case, the same proportion is covered by the first two subareas and three fourth of the total UEs will be distributed in the rest two subareas. Figure 4-3 shows the whole coverage area and partitioning to four sub-areas in the deployment area.

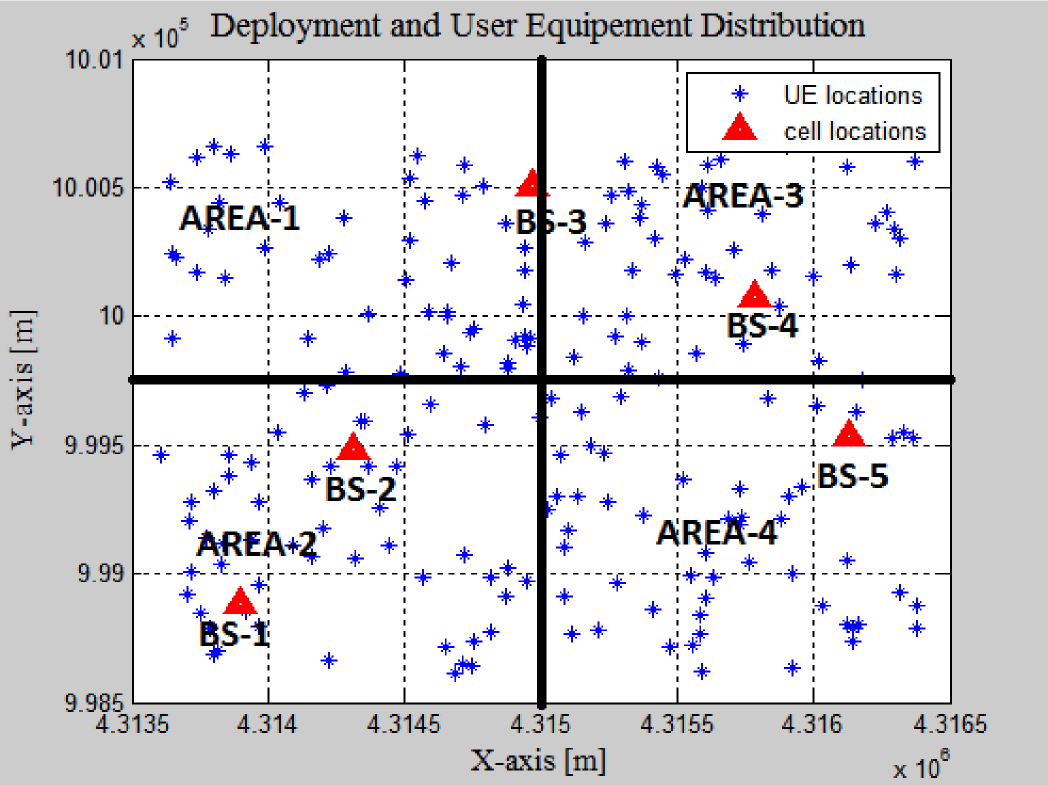


Figure 4-3: Coverage area partitions (Subareas).

The morphology of the selected area is categorized as urban which contains a less crowded and residential population (as being classified by Ethio Telecom). Table 4-3 shows the parameters for simulation as used in the selected area.

The COST 231-Hata propagation model is used in simulation for it is a valid and common model for 1800 MHz frequency band. In this respect, lower range values are selected for both the heights of UE and eNodeBs for chosen propagation model. For UE association with an eNodeB, a best RSRP value criterion is considered where the minimum RSRP is as low as -140 dBm.

Table 4-3: Selected parameters for simulation

No.	Parameter	Value/Remark
1	Morphology	Urban
2	Frequency (MHz)	1800
3	UE antenna height (m)	1.5
4	Base station (eNodeB) antenna height (m)	30
5	LTE system bandwidth (MHz)	20
6	LTE minimum frequency (MHz)	1822.5
7	LTE maximum frequency (MHz)	1842.5
8	Snapshots	500
9	Number of UE	200
10	Number of eNodeBs or Sites	5 x 3 (120^0 azimuth angle sectors)
11	Resolution (m)	1
12	Noise Floor (dBm/hz)	-173
13	Standard deviation of shadow fading (dB)	10
14	Path loss model	COST 231-Hata
15	Cell selection criteria for UE association	Best RSRP
16	Transmitter Antenna Gain (dBi)	18
17	Transmitter Power (W)	20
18	Minimum RSRP (dBm)	-140

5. Results and Analysis

As described in the previous chapter, the study area is categorized into four sub areas to separately analyze the effect of mobile user distribution on static and dynamic bandwidth allocation cases. To this end, results for uniform and non-uniform UE distribution cases are considered. Next, we will go through each case starting from the uniform distribution one.

5.1 The Case of Uniform UE Distribution

All partitioned sub areas in the deployment sites contain 50 UEs; each areas with uniform distribution. In this particular case, it is assumed that similar proportion of mobile users are available throughout the covered area which will be used to analyze its impact on the association with eNodeBs and, hence, the number of mobile users (UEs) to be served i.e., capacity and spectrum resource usage. Figure 5-1 shows the generated results for UE distribution in the deployment area.

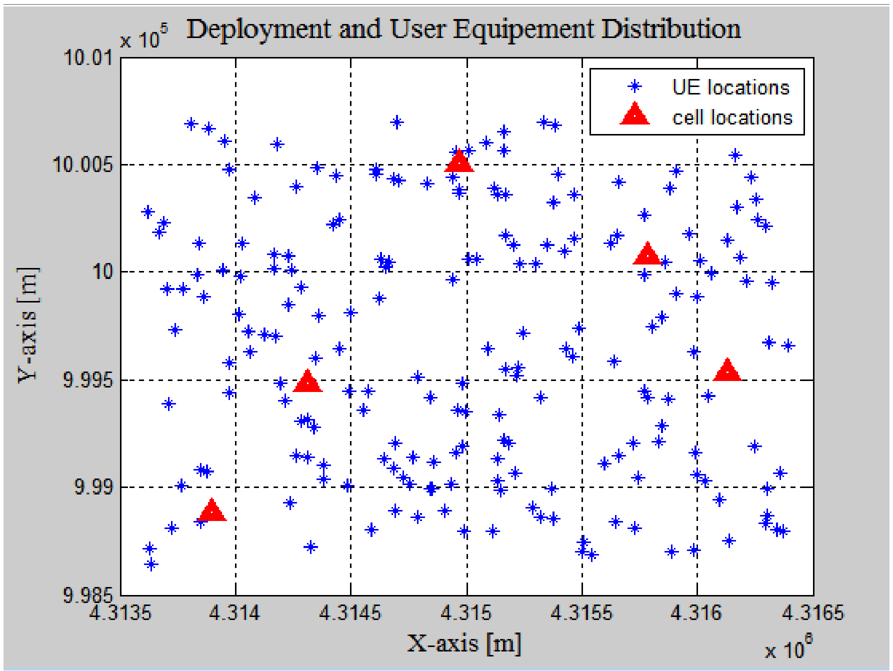


Figure 5-1: UE distributions in the deployment area for uniform distribution case.

5.1.1 Static Spectrum Allocation

Here in this particular case, static bandwidth allocations are made for all 5 sites (each site with 3 sectors) for uniform UE distribution case. The spectrum allocated for all sectors is 5 MHz and hence each site will be using 15 MHz out of the maximum 20 MHz for LTE. The bandwidth allocations are made in such a way that out of the selected 5 sites and a total of 0.2 MHz guard band removed from both ends of LTE band together, the individual sites will get a 6.6 MHz share for each sector.

Since LTE can be deployed on 1.4, 3, 5, 10, 15 or 20 MHz bandwidths, the usable bandwidth for each sector will then becomes 5 MHz (25 PRBs) and a total of 15 MHz per site (75 PRBs are available). So, the remaining 1.6 MHz is underutilized. As indicated in the previous procedure, all the sectors found in every site granted with 6.6 MHz bandwidth.

Therefore, frequency planning for the sectors starts from the LTE minimum frequency, 1822.5 MHz, and lasts to the maximum 1842.5MHz. The frequency reuse factor is 3, as the whole spectrum resource has been divided to three parts among the sectors in a site. Hence, in this particular case, all the corresponding sectors in each site use the spectrum range repeatedly as shown below.

- Site1_sector1:
  (1822.5 MHz + 0.1MHz guard band) + 6.6 MHz = 1829.2 MHz
  Bandwidth range: [1822.6 MHz to 1829.2 MHz]

- Site1_sector2:
  1829.2 + 6.6 MHz = 1835.8 MHz Bandwidth range: [1829.2 MHz to 1835.8 MHz]

- Site1_sector3:
  1835.8 + 6.6 MHz = 1842.4 MHz Bandwidth range: [1835.8 MHz to 1842.4 MHz]

Similarly, the following bandwidth allocations are made for the rest of the sectors in the remaining sites.

- Site2_sector1: Bandwidth range: [1822.6 MHz to 1829.2 MHz]
- Site2_sector2: Bandwidth range: [1829.2 MHz to 1835.8 MHz]
- Site2_sector3: Bandwidth range: [1835.8 MHz to 1842.4 MHz]
- Site3_sector1: Bandwidth range: [1822.6 MHz to 1829.2 MHz]
- Site3_sector2: Bandwidth range: [1829.2 MHz to 1835.8 MHz]
- Site3_sector3: Bandwidth range: [1835.8 MHz to 1842.4 MHz]
- Site4_sector1: Bandwidth range: [1822.6 MHz to 1829.2 MHz]
- Site4_sector2: Bandwidth range: [1829.2 MHz to 1835.8 MHz]
- Site4_sector3: Bandwidth range: [1835.8 MHz to 1842.4 MHz]
- Site5_sector1: Bandwidth range: [1822.6 MHz to 1829.2 MHz]
- Site5_sector2: Bandwidth range: [1829.2 MHz to 1835.8 MHz]
- Site5_sector3: Bandwidth range: [1835.8 MHz to 1842.4 MHz]

The average number of UE per Site-Sector (snapshot average) is shown in Table 5-1 where the maximum number of UEs to be associated with an eNodeB is limited to be 25 (equivalent to 25 PRBs in a 5 MHz LTE bandwidth assigned for each sector). Additionally, it can be observed from the result that the minimum number of UEs supported is 3 (Site 1– Sector 3) and the maximum is 25 which is supported by Site 5–Sector 3. The total number of UEs supported is 179 (21 UEs less than maximum 200 UEs supposed to be served) which refers to 89.5 % of the total traffic supported. From the Table 5-1 it can be observed that:

- Site 1 is serving 20 users
- Site 2 is serving 56 users
- Site 3 is serving 33 users
- Site 4 is serving 36 users
- Site 5 is serving 34 users

Table 5-1: Number of UEs in deployment sites for uniform UE distribution case

No. of Site	No. of eNodeB	Deployment Site	Number of UEs in each sector
1	1	Site 1- Sector 1	10
	2	Site 1- Sector 2	7
	3	Site 1- Sector 3	3
2	4	Site 2- Sector 1	24
	5	Site 2- Sector 2	24
	6	Site 2- Sector 3	8
3	7	Site 3- Sector 1	7
	8	Site 3- Sector 2	8
	9	Site 3- Sector 3	18
4	10	Site 4- Sector 1	12
	11	Site 4- Sector 2	11
	12	Site 4- Sector 3	13
5	13	Site 5- Sector 1	4
	14	Site 5- Sector 2	5
	15	Site 5- Sector 3	25

With the assumption that every site has been allocated with a 15 MHz bandwidth (75 PRBs), a single PRB is allocated for every UE which possesses 180 kHz bandwidth and the remaining frequency is reserved for the control and other channels; we have the following:-

- Site 1 uses 3.6 MHz bandwidth (24 % of the total allocated)
- Site 2 uses 10.08 MHz bandwidth (67.2% of the total allocated)
- Site 3 uses 5.94 MHz bandwidth (39.6 % of the total allocated)
- Site 4 uses 6.48 MHz bandwidth (43.2% of the total allocated)
- Site 5 uses 6.12 MHz bandwidth (40.8 % of the total allocated)

As the result shows Site 2 uses the largest amount of the resource allocated while in contrast Site 1 uses the least amount of spectrum allocated. The average percentage of bandwidth usage of all sites reaches about 42.96 %. The SINR cumulative distribution function (CDF) plot is shown in the Figure 5-2. The average SINR ranges from the minimum value of 13.89 dB to a maximum of 76.73 dB. It can be observed from the CDF plot that close to 70 % of the UEs have SINR values greater than 0 dB and less than a 10 % of the users have SINR values greater than 20 dB.

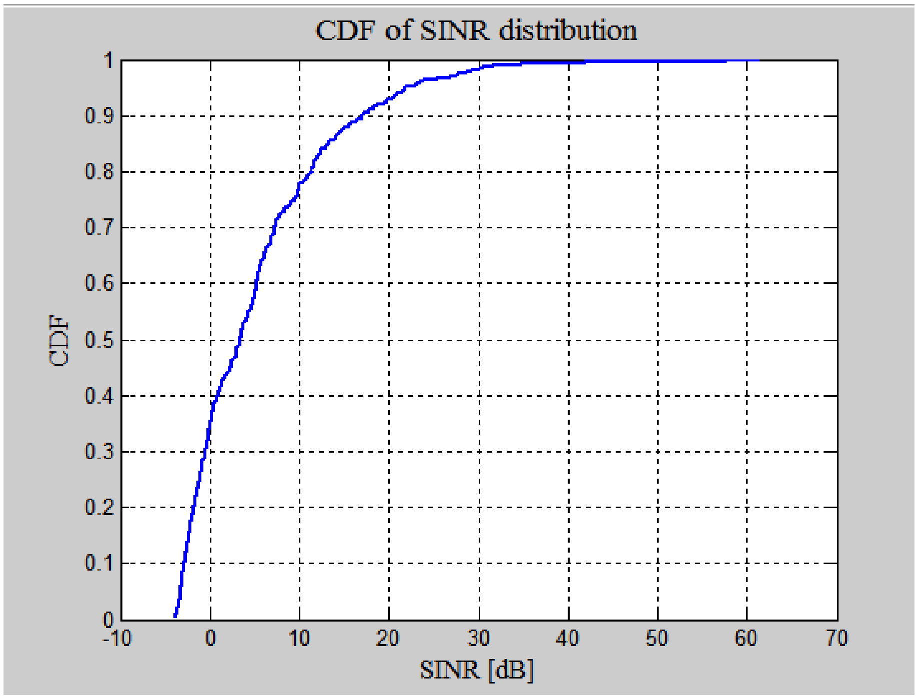


Figure 5-2: CDF plot for the SINR in uniform UE distribution case

The average throughput of the snapshots taken ranges from 0.54 Mbps to a maximum value of 3.01 Mbps while the average throughput per UE is 1.035 Mbps. In fact, the average cell throughput that can be achieved by using the maximum number of RBs, as in Site 5 (Sector 3), is 25.88 Mbps. The CDF plot for the throughput is shown in the Figure 5-3.

It can be noted that 40% of the users have a throughput greater than 1 Mbps and less than 5% of the total UEs has a throughput greater than 2 Mbps. In addition, with the maximum of 179 UEs served with static spectrum refarming, the aggregate throughput for the network is 185.27 Mbps.

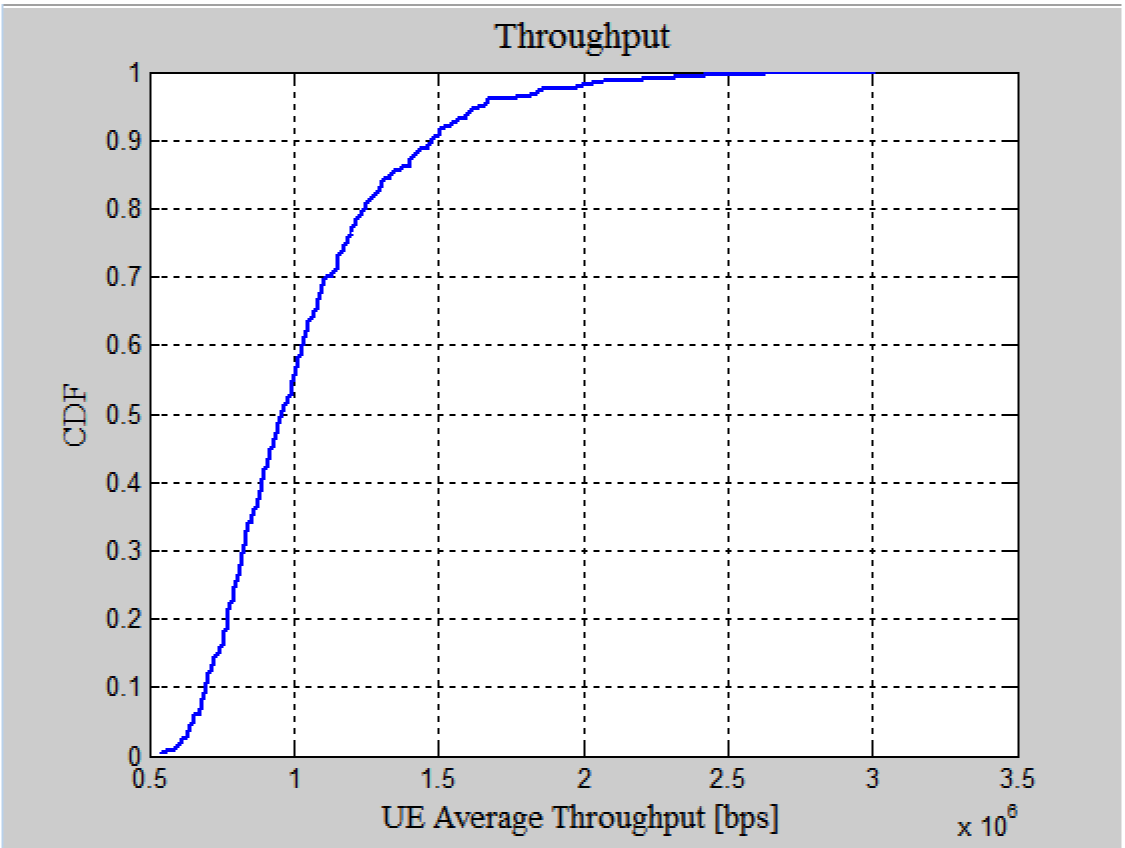


Figure 5-3: CDF plot for Throughput in uniform UE distribution case

5.1.2 Dynamic Spectrum Allocation

In DSR, the bandwidth allocations are dependent on the traffic conditions within the sites and hence all the available resource blocks (RBs) are not scheduled permanently for LTE or GSM. Initially, the same bandwidth allocation is assumed i.e., 5 MHz for each sector and a maximum of 75 PRBs per site. In this case, there will be dynamic RB allocations among the serving eNodeBs. Taking in to account the assumptions in Section 5.1.1 before, let's return back to the result obtained from the example used in the static bandwidth allocation case:

- Site1 needs to serve 20 UEs: 55 PRBs are unused

55*1PRB= 55 * 180 kHz = 9.9 MHz is left unused. This is roughly equal to 49 (200 kHz) carriers which might be reserved for GSM users.

- Site 2 needs to serve 56 UEs: 19 PRBs are unused. This equals to 3.42 MHz (roughly 17 GSM carriers).

- Site 3 needs to serve 33 UEs: 42 PRBs are unused. This equals 7.56 MHz unused. This roughly equals to 37 GSM carriers.

- Site 4 needs to serve 36 users: 39 PRBs are unused. This equals 7.02 MHz unused. This roughly equals to 35 GSM carriers.

- Site 5 needs to serve 34 users: 41 PRBs are unused. This equals to 7.38 MHz unused. This roughly equals to 36 GSM carriers.

But, the total number of UEs supposed to be served was 200 where the actual number of UEs supported is 179. The bandwidth underutilized is equivalent to about 174 GSM carriers which can be reserved for GSM users (per eNodeB bases). However, an additional amount of 21 PRBs (3.78 MHz) should be allocated to serve all users that will reduce the possible number of GSM carriers down to 155. Figure 5-4 shows the spectrum usage of the base stations (eNodeBs).

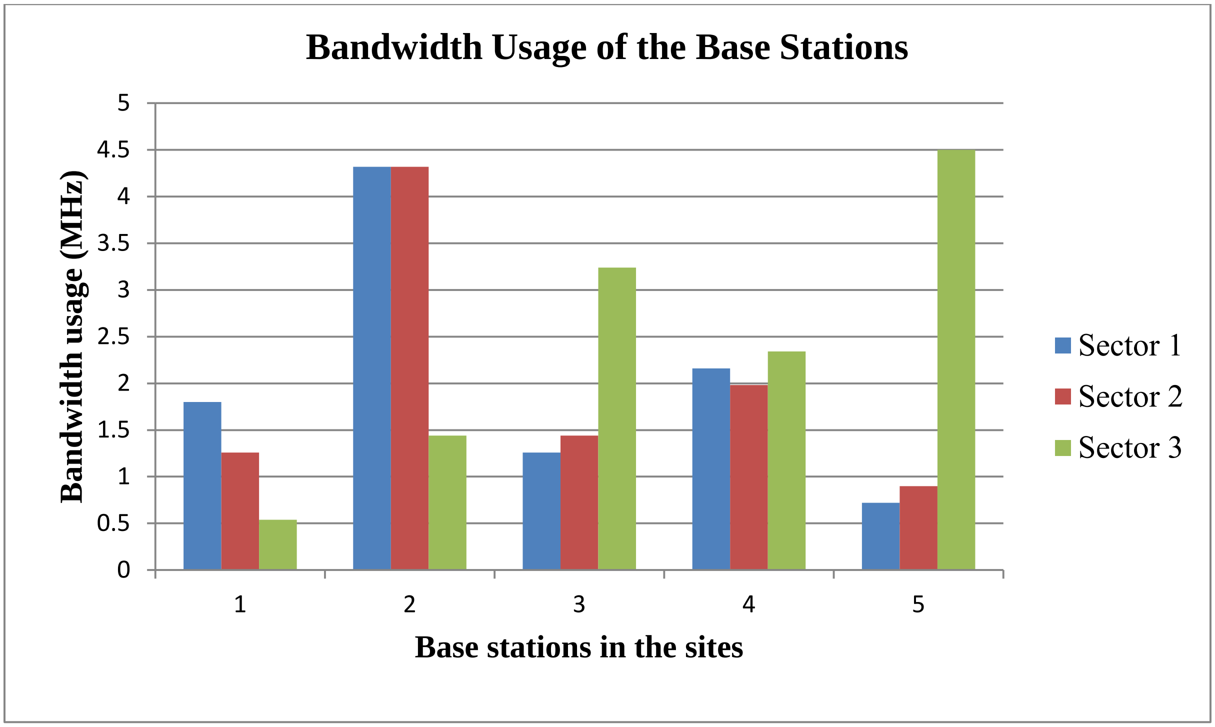


Figure 5-4: Bandwidth usage of the Base stations (eNodeBs) for uniform UE distribution

Among the 25 PRBs allocated for all sectors, Site 5 (sector 3) uses 25 PRBs while Site 1 sector 3 uses only 3 (which can be allocated for 3 UEs only). With a different load in all the base stations, the dynamic bandwidth allocation will help in supporting all users and hence efficiently use the spectral resource that is left unused in highly demanding places. The average percentage of bandwidth that is unused in this circumstance is 47.04 % of the 15 MHz allocated for each site. But including those UEs not served for full service (for 200 UEs now) the percentage drops to 42 %.

In the dynamic allocation of the refarmed spectrum, the bandwidth available for the mobile users is re-allocated based on the prevailing demand in the network. This in turn increases the cell throughput due to efficient allocation of frequency channels for demanding UEs in the mobile network. From the simulation results, we have the results for average number of UEs supported per cell shown in Table 5-2.

Table 5-2 Average Number of UEs supported for Uniform distribution case

No. of Site	No. of eNodeB	Deployment Site	Number of UEs in each sector
1	1	Site 1- Sector 1	10
	2	Site 1- Sector 2	7
	3	Site 1- Sector 3	3
2	4	Site 2- Sector 1	28
	5	Site 2- Sector 2	26
	6	Site 2- Sector 3	8
3	7	Site 3- Sector 1	7
	8	Site 3- Sector 2	8
	9	Site 3- Sector 3	18
4	10	Site 4- Sector 1	12
	11	Site 4- Sector 2	11
	12	Site 4- Sector 3	13
5	13	Site 5- Sector 1	4
	14	Site 5- Sector 2	5
	15	Site 5- Sector 3	34

The total number of UEs supported is 194 (97 % of total UE traffic). The snapshot average of throughput values for each cell is shown in Figure 5-5.

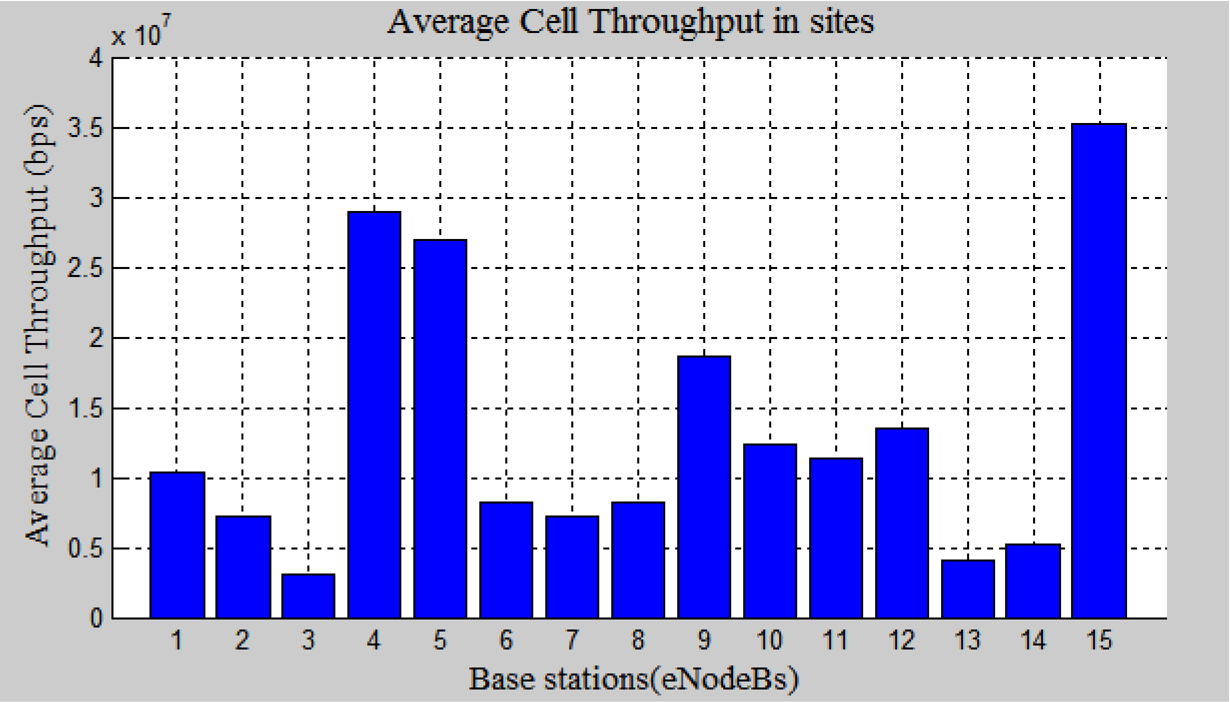


Figure 5-5: Average cell throughput for each cell (sector) for Uniform UE distribution

The average UE throughput is the same with the static refarming case because of the same prior assumption that a single RB has been allocated for every UE. The average cell throughput for Site 2 (Sector 1 and Sector 2) has improved from 24.84 Mbps for each sector to 28.98 and 26.91 Mbps respectively. Meanwhile, average throughput for Site 5 (Sector 3) has improved 25.88 Mbps to 35.19 Mbps. Finally, the aggregate throughput volume of the network improved from 185.27 Mbps to 200.19 Mbps which is about a 7.45 % percent rise compared to the static allocation case.

5.2 The Case of Non-uniform UE Distribution

Here, for this case of non-uniform UE distribution, the coverage area which was divided to four areas exhibit a different UE configuration, in order to see how the non-uniform UE distributions in practical cases would affect the capacity served by the mobile network and more importantly the changes that occur in spectrum usage. However, it is clear that the actual distribution pattern of the mobile users will be obviously different and is also affected by several environmental factors. In this particular case, the sub areas (Area 1 to Area 4) contain 25, 25, 75 and 75 number of UEs and their distributions respectively. This signifies that Area 1 and Area 2 together possess 25 % of the traffic, while Area 3 and Area 4 contain 75% of the total number of UEs.

In the actual case of the deployment area, Area 3 and Area 4 contain the region where a relatively high number of mobile users are concentrated whereas Area 1 and Area 2 are regions with less number of users. Figure 5-6 shows the generated result for UE distribution in the deployment area.

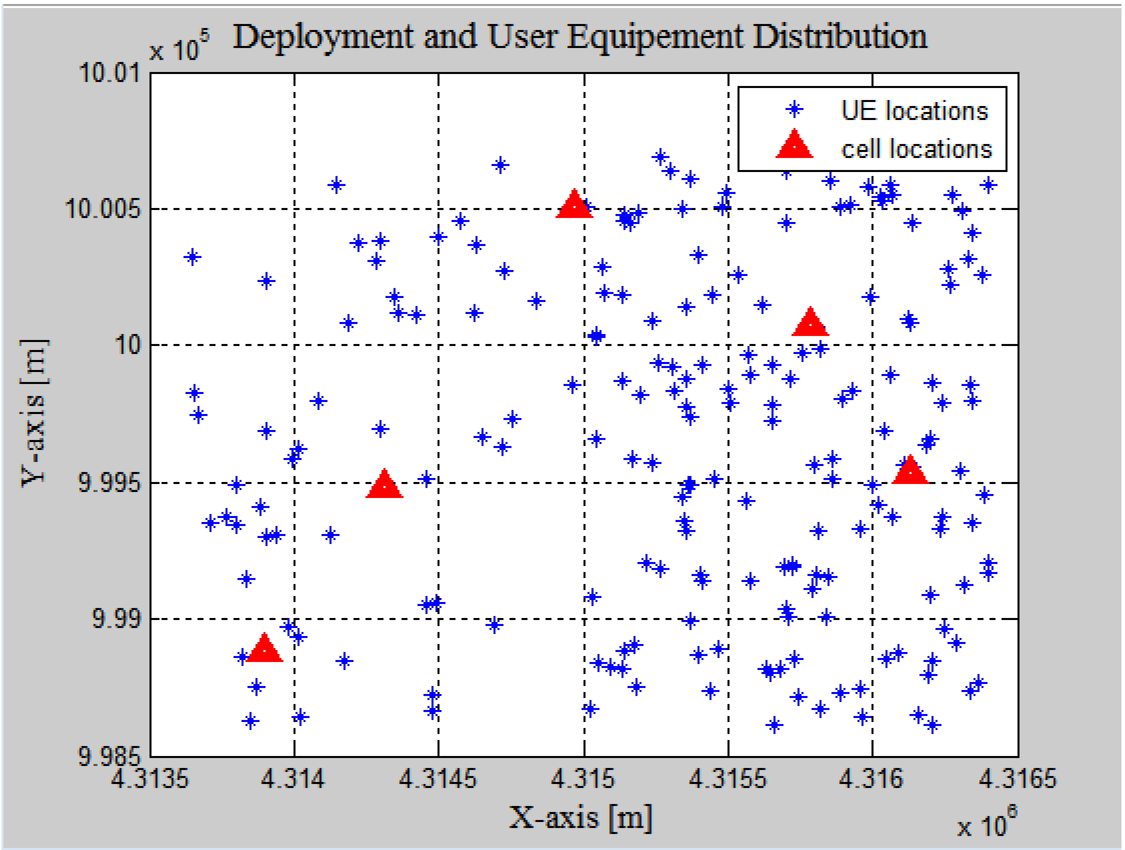


Figure 5-6: UE distributions in the deployment area for non-uniform distribution case

5.2.1 Static Spectrum Allocation

The result in this case is found for the same bandwidth allocation in the previous uniform user distribution case but for a different UE distribution condition. Table 5-3 shows the average number of UE per Site-Sector for this particular case. It can be observed from the result that the minimum number of UE supported is 1 (Site 1– Sector 3) and the maximum is 25 which is supported by Site 5–Sector 3. The total number of UEs supported is 168 (32 UEs less than maximum 200 UEs supposed to be served) which refers to 84% of the total traffic of the network.

From Table 5.3 it can be seen that:

- Site1 is serving 9 users
- Site2 is serving 38 users
- Site3 is serving 27 users
- Site4 is serving 54 users
- Site5 is serving 40 users

With the same assumption in Section 5.1.1; we have the following: results for the bandwidth usage in the sites:-

- Site 1 uses 1.62 MHz bandwidth (10.8% of the total)
- Site 2 uses 6.84 MHz bandwidth (45.6 % of the total)
- Site 3 uses 4.86 MHz bandwidth (32.4% of the total)
- Site 4 uses 9.72 MHz bandwidth (64.8% of the total)
- Site 5 uses 7.2 MHz bandwidth (48% of the total)

Table 5.3 Number of UEs in deployment sites for non-uniform UE distribution case

No. of Site	No. of eNodeB	Deployment Site	Number of UEs in each sector
1	1	Site 1- Sector 1	5
	2	Site 1- Sector 2	3
	3	Site 1- Sector 3	1
2	4	Site 2- Sector 1	21
	5	Site 2- Sector 2	13
	6	Site 2- Sector 3	4
3	7	Site 3- Sector 1	11
	8	Site 3- Sector 2	4
	9	Site 3- Sector 3	12
4	10	Site 4- Sector 1	18
	11	Site 4- Sector 2	17
	12	Site 4- Sector 3	19
5	13	Site 5- Sector 1	6
	14	Site 5- Sector 2	9
	15	Site 5- Sector 3	25

As the result shows Site 4 uses the largest amount of the resource allocated which was Site 2 in the uniform UE distribution case. Site 1 uses the least amount of spectrum which is even less than the result obtained in the uniform UE distribution scenario. The Subarea 3 and Subarea 4, which together cover 75 % of the UE traffic, are using more spectrum than uniform distribution case. This is the reverse for the remaining sub areas. In fact, the average percentage of bandwidth usage per site is about 40.32 %. As compared to the case of uniform UE distribution the average spectrum usage has dropped by over 2%. Therefore, it can be concluded that a more concentrated UEs in Site 4 and Site 5 has in turn necessitated more bandwidth usage to this particular sites while a lesser spectrum usage in the Sites 1,2 and 3 that cover only 25 % of the traffic altogether.

The SINR CDF plot is shown in Figure 5-7. The average SINR has the minimum value of 13.0411 dB and the maximum value dropped from 76.73 to 64.02 dB. The result resembles more or less with that obtained in the previous case with the significant difference here is that the maximum SINR value shows a decline of more than 12 dB.

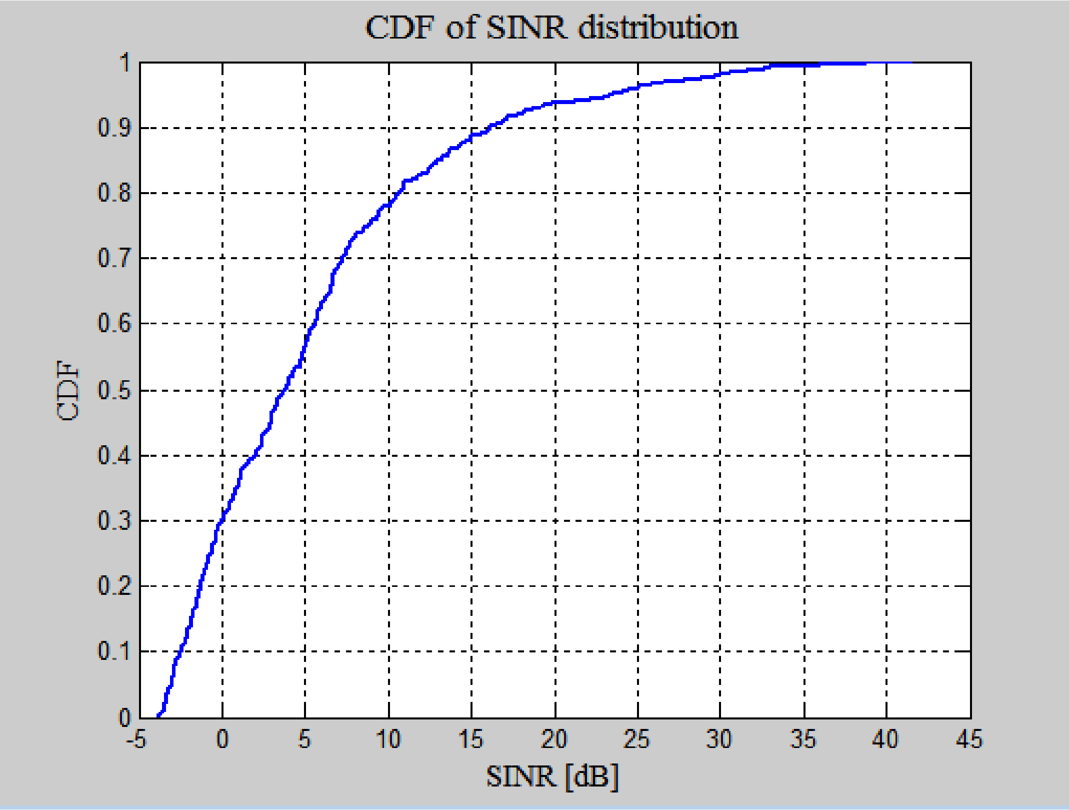


Figure 5-7: CDF plot for SINR in non-uniform UE distribution case

The average throughput of the snapshots taken changed from 0.527 to 0.506 Mbps and the maximum value from 3.01 to 2.51 Mbps while the average throughput per UE is 1.013 Mbps. In addition, the average cell throughput that can be achieved by using the maximum number of RBs, as in Site 5 (Sector 3), is 25.33 Mbps.

As it can be seen from the results, the peak data rate has declined for about 500 kbps which is caused by the changes in the UE traffic distribution that has in turn resulted in different demands of spectrum resource in the sites which has not been responded by the network. The CDF plot for the throughput is shown in the Figure 5-8. It can be noted that 40% of the users still have a throughput greater than 1Mbps and only a few percent of the total UEs obtain a throughput greater than 2 Mbps (lower than the previous result). In addition, with the maximum of 168 UEs served with static spectrum refarming, the aggregate throughput for the network in this particular case is 170.18 Mbps.

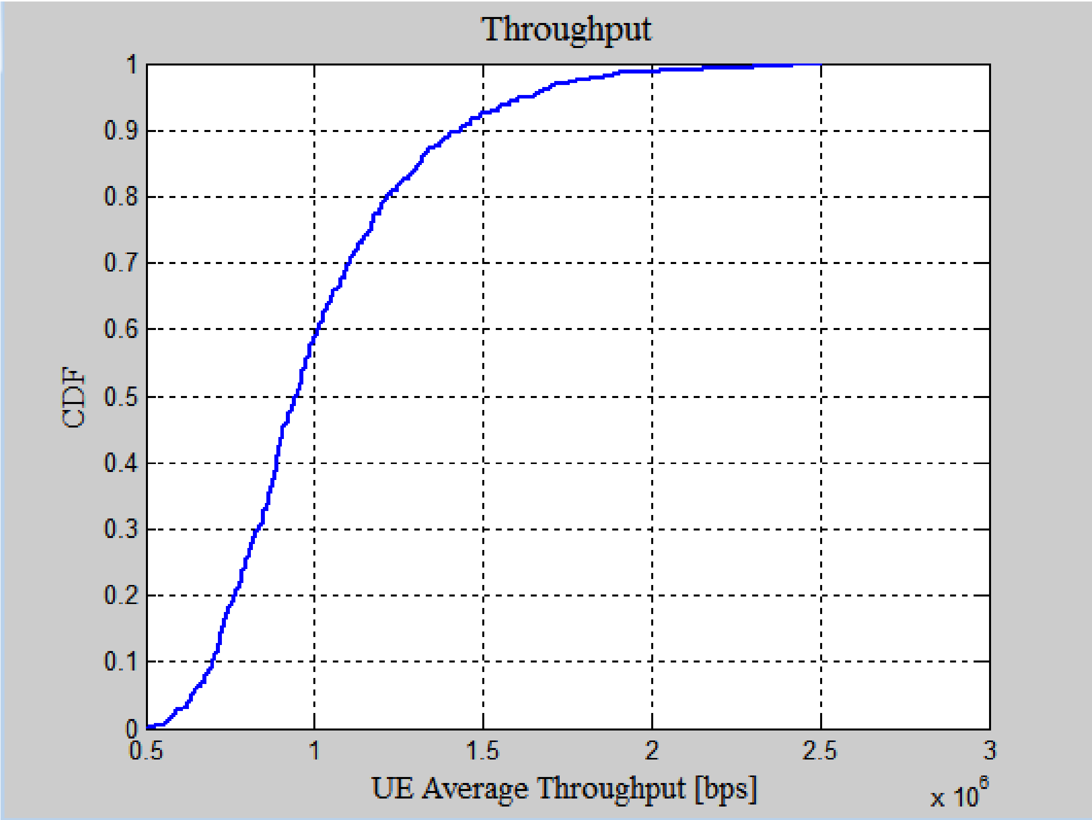


Figure 5-8: CDF plot for Throughput in non-uniform UE distribution case

5.2.2 Dynamic Spectrum Allocation

With the same assumptions taken as in Section 5.1.1 and returning back to the result obtained from the example used in the static bandwidth allocation case, we have the following results:-

- Site1 needs to serve 9 users
- Site2 needs to serve 38 users
- Site3 needs to serve 27 users
- Site4 needs to serve 54 users
- Site5 needs to serve 40 users

- Site1 needs to serve 9 UEs: 66 PRBs are unused

66*1PRB= 66 * 180 kHz = 11.88 MHz is left unused. This is roughly equal to 59 (200 kHz) carriers which might be reserved for GSM users.

- Site2 needs to serve 38 UEs: 37 PRBs are unused. This equals to 6.66 MHz (roughly 33 GSM carriers).

- Site3 needs to serve 27 UEs: 48 PRBs are unused. This equals 8.64 MHz unused. This roughly equals to 43 GSM carriers.

- Site4 needs to serve 54 users: 21 PRBs are unused. This equals 3.78 MHz unused. This roughly equals to 18 GSM carriers.

- Site5 needs to serve 40 users: 35 PRBs are unused. This equals to 6.3 MHz needed. This roughly equals to 31 GSM carriers.

But, the total number of UEs supposed to be served was 200 where the actual number of UEs supported is 168. The bandwidth not used is equivalent to about 184 GSM carriers which can be reserved for GSM users (per eNodeB basis).

But an additional amount of 32 PRBs (5.76 MHz) should be allocated to serve all UEs which lower the underutilized bandwidth to about 155 GSM carriers. Figure 5-9 below shows the spectrum usage of the base stations (eNodeBs).

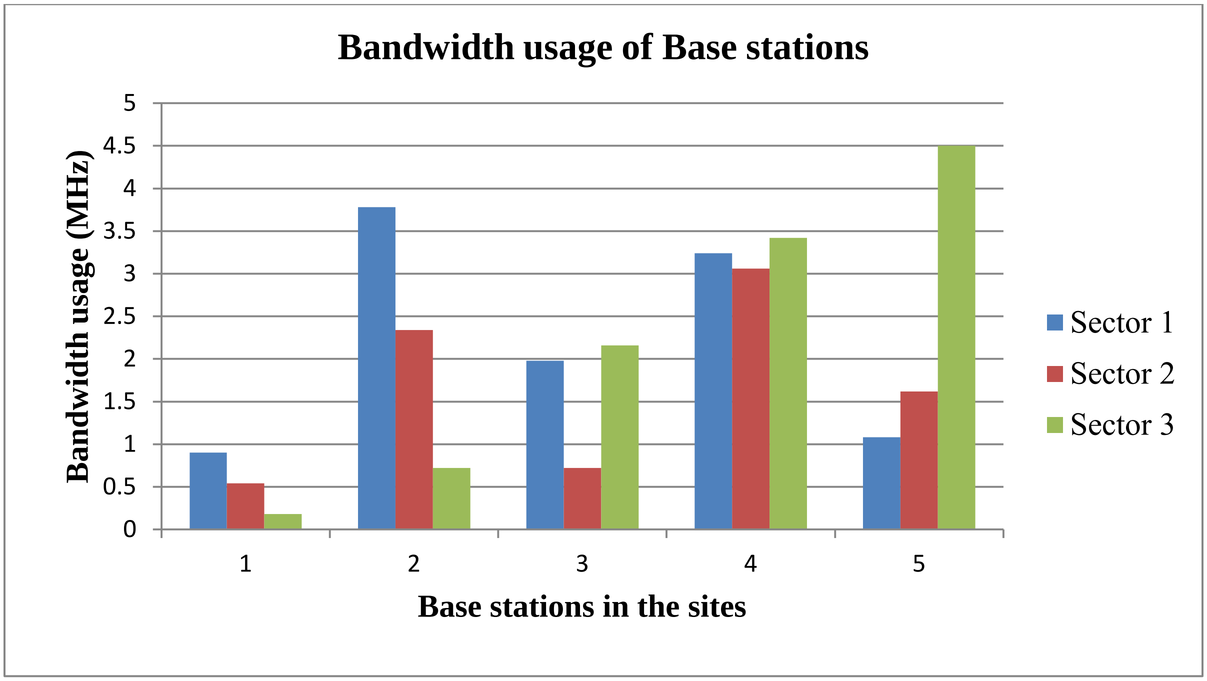


Figure 5-9: Bandwidth usage of Base stations (eNodeBs) for non-uniform UE distribution

Among the 25 PRBs allocated for all sectors, in Site 2-Sector 1(eNodeB 4) uses 21 PRBs and Site 5-Sector 3 (eNodeB 15) uses the maximum amount of 25 PRBs while Site 1-Sector 3 uses only a single PRB. In this condition, it can be observed that Site 2 and Site 5 still carry larger amount of traffic (but slightly lower than the result in uniform UE distribution case) and in contrast Site 1 supports less users which can be anticipated from the UE distribution. The average percentage of bandwidth that is unused in this circumstance is 49.68 % of the 15 MHz allocated for each site. If the network is serving the full capacity (number of users), the percentage drops to 42 % (the same with the previous result).

Following similar procedures as in the uniform UE distribution case, the bandwidth available for the mobile users is re-allocated by responding to the changes in spectrum demand in the network. Hence, efficient allocation of frequency resource for demanding UEs can be made in the mobile network. From the simulation results, we have the results for average number of UEs supported per cell shown in Table 5-4.

Table 5-4 Average Number of UEs supported for Non-uniform distribution case

No. of Site	No. of eNodeB	Deployment Site	Number of UEs in each sector
1	1	Site 1- Sector 1	5
	2	Site 1- Sector 2	3
	3	Site 1- Sector 3	1
2	4	Site 2- Sector 1	22
	5	Site 2- Sector 2	13
	6	Site 2- Sector 3	4
3	7	Site 3- Sector 1	11
	8	Site 3- Sector 2	4
	9	Site 3- Sector 3	12
4	10	Site 4- Sector 1	18
	11	Site 4- Sector 2	17
	12	Site 4- Sector 3	19
5	13	Site 5- Sector 1	6
	14	Site 5- Sector 2	9
	15	Site 5- Sector 3	50

The total number of UEs supported is 194 (97 % of total UE traffic) which is similar with the uniform UE distribution case. The snapshot average of throughput values for each cell is shown in Figure 5-10.

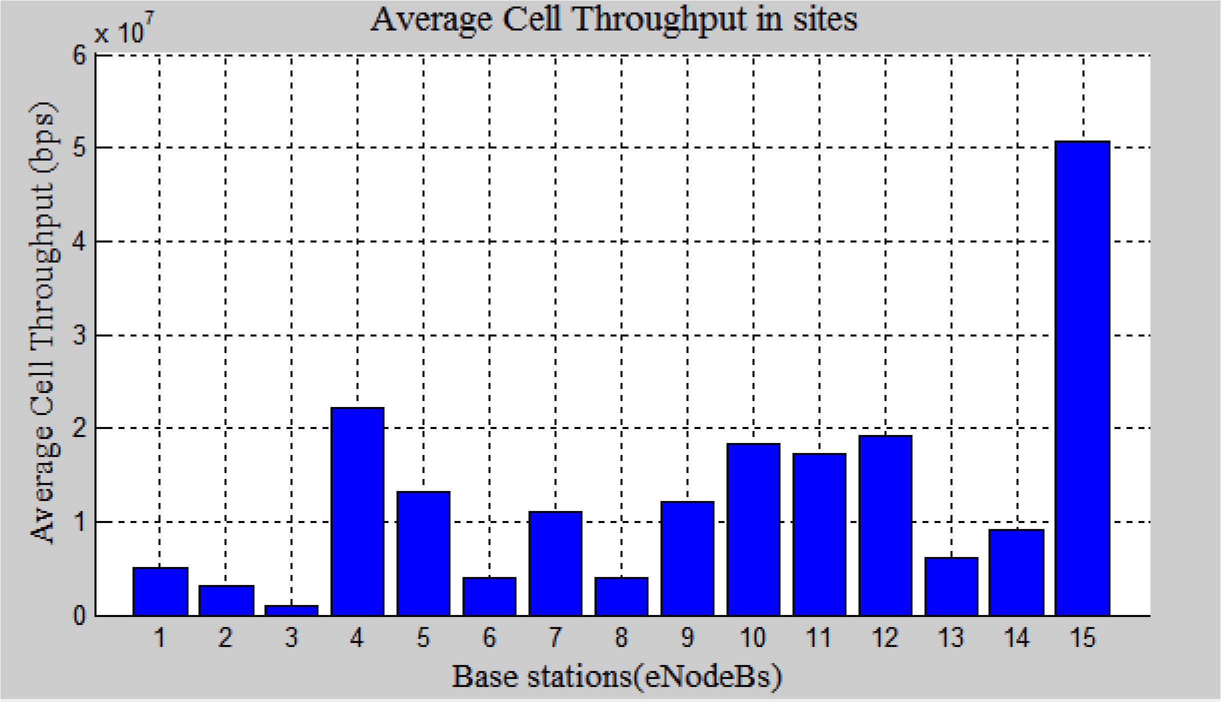


Figure 5-10: Average cell throughput for each cell (sector) for Non-uniform UE distribution

The average UE throughput is the same with the static refarming case because of the same prior assumption that a single RB has been allocated for every UE. The average cell throughput for Site 5 (Sector 3) has improved from 25.33 Mbps to 50.65 Mbps. Finally, the aggregate throughput volume of the network improved from 170.18 Mbps to 196.52 Mbps which about 13.4 % percent improvement as compared to the static allocation case.

5.3 Impact on the GSM 1800

As it has been indicated in the beginning, the 1800 MHz band containing a pair of 75 MHz bandwidth can be refarmed for LTE deployment. Initially before refarming, it can be assumed that the 20 MHz GSM bandwidth can theoretically support 100 users each with a 200 kHz carrier. However, applying frequency reuse factor 3 in a site and for all sites altogether, 500 UEs can be served.

Spectrum refarming will cause an inevitable reduction on GSM’s capacity. In static refarming, the fixed bandwidth allocation permanently utilizes the spectrum and leaves no room for GSM users. So, a priority can be set in comparison with a very high data rate service that LTE provides for its users. In fact, a large spectrum available in our case for Ethio Telecom and possibility of supporting the GSM users on the 900 MHz will help in reducing the negative impact.

On the other hand, dynamic allocation of spectral resource allows the reuse of the spectrum underutilized in LTE network. As shown in the results in the uniform UE distribution case, equivalent to 177, each with 200 kHz, GSM carriers can be assigned for GSM users. In the non-uniform UE distribution case, the number increases to 184 GSM carriers. But in the condition of serving all the 200 LTE mobile users, the number will be decreased to 155.

Therefore, the spectrum that would rather be wasted can be used effectively and the overall network performance can be improved in a co-existing GSM and LTE technologies. The negative impact on the GSM users can be well compensated by the systematic allocation of PRBs for GSM based on the traffic conditions in the network.

6. Conclusion and Recommendation

6.1 Conclusion

Spectrum refarming is an essential technique to use the spectral resource available efficiently. In this thesis, it is shown that refarming the GSM spectrum on the 1800 MHz which consists of a rich spectral resource can be used to deploy the new LTE mobile technology. LTE's flexible bandwidth deployment possibility (1.4, 3, 5, 10, 15 or 20 MHz) makes refarming even a more feasible option to take on. Among the possible set of LTE bandwidths, the maximum amount 20 MHz is considered for refarming in this study as it is being applied in deploying LTE in Addis Ababa by Ethio Telecom.

The results obtained from the simulation in static spectrum allocations for uniform UE distribution case show that a higher average SINR about 77 dB and an average throughput more than 3 Mbps is achieved with 5 MHz bandwidth refarmed for LTE. The different UE distribution pattern forced these parameters to change where the average SINR margin drops to 64 dB and the average throughput to about 2.5 Mbps because the UEs are more concentrated in some sites and the others are dispersed in the remaining ones.

Moreover, the actual UE traffic distribution and relative locations of the eNodeBs accounts for the static allocation to be less efficient due to the fact that the number of UEs to be associated with an eNodeB is affected by the distances and RSRP levels of UEs (in the first case only 176 UEs out of 200 UEs is served). This scenario resulted in underutilization of PRBs in some eNodeBs and higher loads on others which is even aggravated in non-uniform UE distribution case where 32 additional PRBs were required for full support of the traffic.

However, the dynamic spectrum allocations allows for bandwidth usage based on particular demand in a site and capacity of the eNodeBs. The PRBs enough to serve the UEs is granted and the remaining is allocated for GSM service. As it is shown in the uniform and non-uniform UE distribution case, an average of about 42 % of spectrum can be saved and reserved for GSM service. This spectrum can support 155 GSM users which will in turn help in trading off the reduction in GSM's capacity due to spectrum refarming for LTE deployment. Moreover, the aggregate throughputs are improved by 7.45 % and 13.4 % for uniform and non-uniform UE distribution cases respectively.

Finally, it can be concluded from the results that refarming the GSM spectrum for the co-existence with LTE, a new and advanced technology, by adopting a systematic and efficient dynamic bandwidth usage will greatly enhance the network performance and reduce the spectrum wastage.

6.2 Recommendation for future work

Spectrum refarming is a recent concept that is being imparted in the LTE network planning process. In the case of Ethiopia where the LTE technology itself is introduced in small scale in the capital very recently, the issue of spectrum refarming would be and remain an important area of research and study in the coming future.

In this thesis, main emphasis is given for spectrum refarming on the LTE network side with focus on the spectrum refarmed, frequency planning for deployment sites and some system performance analysis. The bandwidth usage is assumed for data use only in LTE while the voice service is assumed entirely to be carried by GSM 1800 band. Hence, the considerations on the refarmed GSM spectrum side with regards to capacity (voice and data), re-planning of the remaining frequency resource and other network planning related issues need to be further addressed separately.

Moreover, the proposed implementation of DSR technique in the current mobile network requires the assessment of real time data such as the traffic trends, patterns of spectrum allocation for mobile users and spectrum usage by the base stations (eNodBs) for a specified period of time. These factors can be further analyzed using enhanced and appropriate planning tools to set up a dynamic allocation scheme for more realistic and acceptable results. Following the same process for GSM network, the mutual impact can be further analyzed in LTE/GSM co-existing network.

In addition, the prevalence of a co-existing GSM and LTE network will inevitably create the problem of inter technology interference. This also needs further attention and measure in order to have a more robust co-existing system by adopting suitable interference mitigation techniques such as FFR in place. The theoretical models of the frequency reuse schemes proposed in this thesis for LTE frequency planning can be further developed and enhanced for inclusion in the network planning process.

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