Addis Ababa University

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School of Electrical and Computer Engineering

Telecommunication Engineering Graduate Program

Performance Analysis of Spectrum Scenarios for Outdoor LTE Small Cell Planning: The Case of Addis Ababa, Ethiopia

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Thesis Title

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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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Abstract

Due to the increasing penetration of smart devices and data intensive applications, mobile network operators are experiencing exponential data growth. In effect, network capacity limitation that leads to performance degradation is observed. To address this limitation, deployment of different types of small cells under umbrella macro network that results Heterogeneous Networks (HetNets) has been considered as one key capacity enhancement approach. In the introduction of HetNets, operator decision on spectrum allocation scheme significantly determines network performance.

The Ethiopian sole telecom operator, ethio telecom, has recently started the path to operate and manage HetNets by deploying small cells within its existing macro network. Nevertheless, there is no thorough performance study on potential spectrum scenarios considering Ethiopia's network environment so that an informed spectrum usage strategy is formulated. Spectrum scenarios can be cochannel, where small cells apply same frequency band used by macro cells, dedicated, where they apply different frequency bands or a hybrid of cochannel and dedicated. In this thesis, performance analysis is carried out for the spectrum scenarios formulated using 1800MHz and 2600MHz bands from network planning perspective while considering realistic network environment for selected area of Addis Ababa, Ethiopia. Multi-objective optimization based on Genetic Algorithm is applied for network planning. Network simulation is implemented using MatLab while propagation computation is performed using WinProp.

Performance results show that, allocating dedicated 20MHz band for small cell in 2600MHz band provides better aggregate capacity than allocating dedicated same amount of band in 1800MHz. For instance, dedicated 20MHz in 2600MHz band achieves 0.036Gbps per square km more capacity than in 1800MHz band for around three small cells per sector optimal deployment. On the other hand, dedicated 20MHz in 1800MHz achieves 2.3% less user outage rate than dedicated same amount of band in 2600MHz with around three small cells per sector optimal deployment. With regards to small cell distribution, planning results show that outdoor small cell deployment is needed more in locations other than main street.

Key words *–*HetNets, Small cells, Densification, Spectrum Scenario, Planning, Optimization, Capacity, Outage, Addis Ababa

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Table of Contents

Abstract……………………………………………………………………………… iii

Acknowledgment……………………………………………………………………...iv

List of Figures………………………………………………………………………vi

List of Tables……………………………………………………………………… ix

List of Acronyms……………………………………………………………………x

1 Introduction 1

1.1 Motivation and Background.. 1

1.2 Statement of the Problem 2

1.3 Objective 3

1.3.1 General Objective 3

1.3.2 Specific Objectives 3

1.4 Methodology 3

1.5 Related Work.. 4

1.6 Significance of the Study 6

1.7 Scope and Limitation 7

1.8 Outline of Thesis.. 7

2 Network Densification.. 8

2.1 Growth in Device connections.. 8

2.2 Network Upgrade Trends.. 9

2.3 Heterogeneous Networks 12

2.4 Deployment Considerations of Small Cells 15

3 HetNet Spectrum Scenarios in Addis Ababa 17

3.1 LTE Network in Addis Ababa 17

3.2 Densification Approaches 18

3.3 Outdoor LTE Small Cell for Addis Ababa 19

3.4 Spectrum Scenarios in HetNet 21
3.5 Spectrum Allocation Trend 22
3.5.1 Global LTE Spectrum Allocation 22
3.5.2 Sub Saharan African LTE Spectrum Allocation 24
3.6 Spectrum Scenarios for Addis Ababa 24
4 Network Modeling and Planning Approaches 28
4.1 Network Layout and Traffic Distribution 28
4.1.1 Macro Cells Network Layout 28
4.1.2 Small Cells Candidate Locations 28
4.1.3 Spatial Traffic Distribution 30
4.2 Propagation Model and Cell Association 31
4.3 Throughput Computation 33
4.4 Performance Metrics 34
4.5 Small cell Planning Approach 35
4.6 Optimization Methodology 37
4.6.1 Background on Genetic Algorithms 37
4.6.2 Non-dominated Sorting Genetic Algorithms (NSGA) 41
4.6.3 Fast Non-dominated Sorting Genetic Algorithms (NSGA II) 42
5 Simulation Result and Discussion 44
5.1 Study Area Description 44
5.2 Simulation Approaches, Parameters and Assumptions 46
5.2.1 Simulation Approaches 46
5.2.2 Simulation Parameters and Assumptions 49
5.3 Performance Results and Discussion 50
5.3.1 Capacity Oriented Topology 50
5.3.2 UE Outage Oriented Topology 56
6 Conclusion and Future Works 60

6.1 Conclusion..60

6.2 Future Works..61

Referances…………………………………………………………………………...60

List of Figures

Figure 1-1 Mobile data demand forecast in Addis Ababa [3]. 2

Figure 1-2 General methodology of the thesis 4

Figure 2-1 Global devices and connections growth [9] 8

Figure 2-2 Macro upgrades by doubling the number of sectors per site [15] 10

Figure 2-3 Existing paradigms to improve network capacity [11] 11

Figure 2-4 Heterogeneous network topology [13] 12

Figure 3-1 Addis Ababa sites LTE data traffic in daily basis time..................... 18

Figure 3-2 Current approaches to address data growth in ethio telecom 19

Figure 3-3 Small cell placement at hotspot [26] 20

Figure 3-4 ITU Regions [31] 23

Figure 3-5 Commercially launched LTE Networks [32] 24

Figure 3-6 ethio telecom spectrum usage [26] 25

Figure 3-7 Spectrum scenarios for outdoor small cells in Addis Ababa 27

Figure 4-1 Increased footprint of small cells with range expansion [39]............ 33

Figure 4-2 An example of Pareto front 36

Figure 4-3 A flow chart of typical genetic algorithm [43] 38

Figure 4-4 NSGA II procedure [49] 43

Figure 5-1 Existing sites in the selected study area 44

Figure 5-2 Traffic map showing non-uniform traffic distribution 45

Figure 5-3 User location(blue dot) in study area with base station (red). 46

Figure 5-4 Candidate locations along with macro cells in WinProp 47

Figure 5-5 System level simulator block diagram 48

Figure 5-6 Simulation flow 48

Figure 5-7 Aggregate capacity performance of optimized topologies.................. 50

Figure 5-8 Area spectral efficiency of optimized topologies 51

Figure 5-9 Aggregate capacity gain for different small cell density 52

Figure 5-10 User throughput for capacity-oriented 50 small cells deployment. 53

Figure 5-11 SINR performance for capacity-oriented topology........................... 54

Figure 5-12 Optimized topology for 50 small cells deployment 55

Figure 5-13 User throughput performance for 100 small cell deployments....... 55

Figure 5-14 UE outage rate against small cell number 56

Figure 5-15 User throughput for outage oriented 50 small cells deployment... 58

Figure 5-16 SINR performance for outage-oriented topology 59

Figure 5-17 User throughput for outage oriented 100 small cells deployment.. 59

List of Tables

Table 2-1 Details about Heterogeneous Network Nodes 13

Table 3-1 LTE Frequency bands and bandwidth 22

Table 3-2 Frequency band and bandwidth for macro and small cells. 26

Table 4-1 Site-related information 29

Table 4-2 Mechanisms in selection, crossover, and mutation of GAs 39

Table 5-1 Existing macro sites performance 46

Table 5-2 Simulation parameters 49

List of Acronyms

3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
CA	Carrier Aggregation
CAPEX	Capital Expenditure
CARG	Compound Annual Growth Rate
CoMP	Coordinated Multi Point
CSG	Closed Subscriber Group
DeNB	Donor eNodeB
DL	DownLink
eICIC	Enhanced Inter Cell Interference Coordination
eNB	Evolved NodeB
FDD	Frequency Division Duplex
GA	Genetic Algorithms
GHz	Giga Hertz
HeNB	Home eNodeB
HetNets	Heterogeneous Networks
IMT	International Mobile Telecommunications
ITU	International Telecommunications Union
KPI	Key Performance Indicator

LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
Mbps	Mega Bits Per Second
MHz	Mega Hertz
MIMO	Multi Input Multi Output
MOGA	Multi Objective Genetic Algorithm
NSGA	Non-dominated Sorting Genetic Algorithm
NSGA II	Non-dominated Sorting Genetic Algorithm II
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operating Expenses
PRB	Physical Resource Block
RN	Relay Node
RSRP	Reference Signal Received Power
SC-OFMDA	Single Carrier-Orthogonal Frequency Division Multiple Access
SINR	Signal to Noise Ratio
SON	Self-Organizing Network
STD	Spatial Traffic Distribution
TB	Tera Byte
TCO	Total Cost of Ownership
UE	User Equipment
UL	Uplink
UTM	Universal Transverse Mercator

1 Introduction

1.1 Motivation and Background

Globally, mobile network operators have been experiencing unprecedented growth in data traffic due to rise in demand for higher data rate and affordability of capable devices. It is estimated that the traffic growth will increase in sevenfold between 2016 and 2021 with a compound annual growth rate (CARG) of 47 percent from 2016 to 2021, reaching 49.0 Exabyte per month by 2021 [1]. This traffic growth has been and will be challenging network operators in meeting their customers' expectations.

Mobile network operators do have different options to expand their mobile network infrastructure to accommodate the growing mobile data traffic demand. Available traditional methods include using additional spectrum, higher order sectorization and deploying new macro sites. The aforementioned traditional methods incur high deployment costs as well as difficulty in achieving new spectrum, site location and required performance enhancement [2].

In order to meet the increasing capacity and coverage demand, a new network deployment approach called Heterogeneous networks (HetNets) has been introduced mainly since Long Term Evolution (LTE) Release 8. The idea of HetNets is to deploy small cells under the umbrella of macrocells to enhance network coverage and capacity. Small cells can be deployed randomly by end-user or in planned manner around hotspot areas by operators to increase network capacity and coverage while offloading data traffic from the macro network.

In Addis Ababa, High-Speed Packet Access Plus (HSPA+) and LTE networks are operational to provide mobile broadband data service. Similar to the global trend, mobile data traffic in Addis Ababa has been and will be increasing due to significant growth in mobile internet penetration and social media usage trend [3]. As shown in Figure 1-1, monthly traffic demand for Addis Ababa will be steadily increasing to reach more than 20TB per month in 2021. To accommodate this exponentially growing data traffic, homogeneous macro-only densification approach is not efficient in terms of deployment cost and addressing hotspot area demand of the city [2][survey on 3ggp].

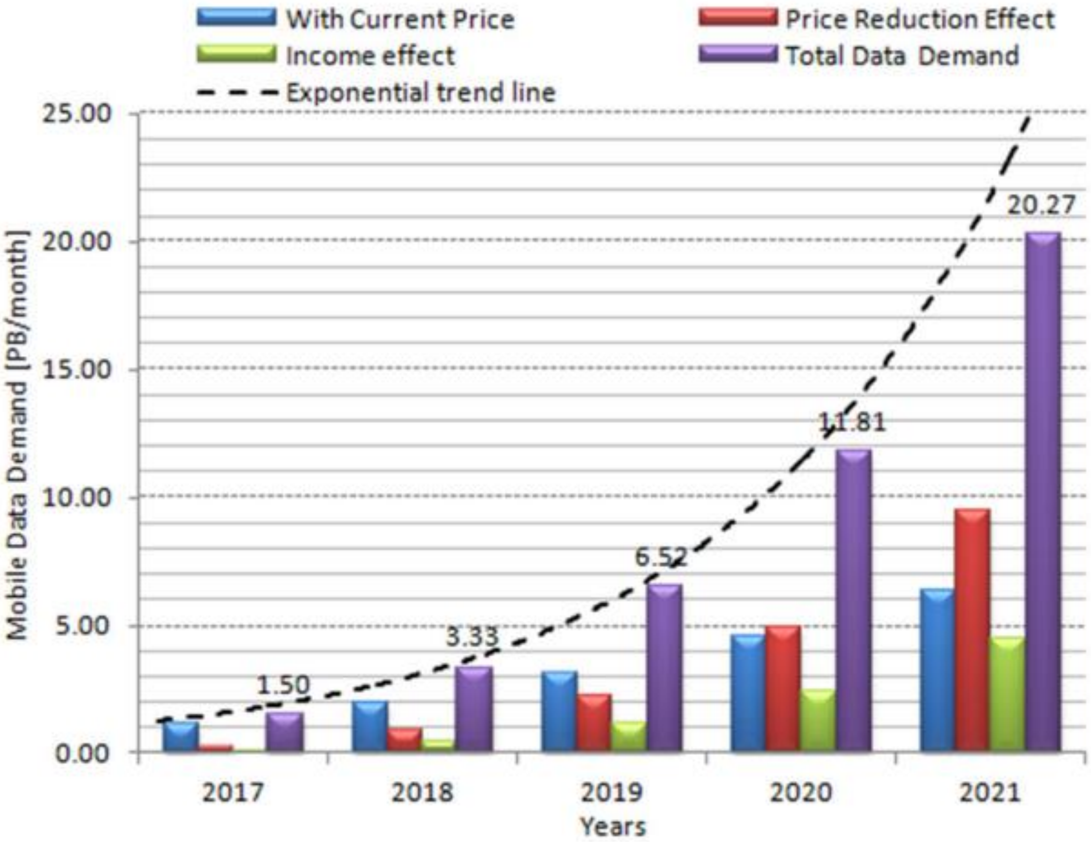


Figure 1-1 *Mobile data demand forecast in Addis Ababa* [3].

1.2 Statement of the Problem

In HetNets deployment, coverage and capacity performance is significantly affected by spectrum allocation among macro and small cell layers [4]. As a result, selecting the right spectrum allocation for macro and small cell layers is one key challenge of mobile network operators. To meet a given operator's capacity and coverage demand, applied spectrum allocation directly impacts the number of required small cells that in turn affect network cost. Therefore, spectrum allocation decision needs to analyze potential HetNets spectrum scenarios considering the capacity, coverage and cost targets of the operator from network planning perspective.

Till now in Addis Ababa, small cell has not been deployed in large scale but there is a practice of deploying small cell as pilot. For macro LTE deployment of Addis Ababa city, 20MHz bandwidth in 1800MHz band is utilized. When HetNet are adopted in large scale for Addis Ababa city, varieties of spectrum scenario options such as cochannel, dedicated or hybrid are available. In this regard, analysis on spectrum scenarios are not presented well considering ethio telecom Addis Ababa realistic network environment in outdoor small cell planning.

1.3 Objective

1.3.1 General Objective

The main objective of this thesis is to analyze and compare performance of spectrum scenarios from outdoor LTE small cell planning perspective for Addis Ababa.

1.3.2 Specific Objectives

To achieve the general objective, the following specific objectives are identified:

- Critically review works in the area of small cell planning and their spectrum usage;
- Identify high traffic area of Addis Ababa to select study planning area;
- Analyze traffic distribution for the study area and generate user distribution based on it;
- Prepare candidate locations for small cells based on traffic distribution of the study area;
- Implement multi-objective optimization algorithm for outdoor small cell planning;
- Define relevant spectrum scenarios for Addis Ababa;
- Analyze capacity, coverage and cost performance of the spectrum scenarios;

1.4 Methodology

Applied methodological stages for the thesis work is shown in Figure 1-2. This thesis work starts with intense literature review in the area of small cells planning, performance analysis and spectrum scenario in HetNet. The literature covered are journal article, conference paper, renowned company reports and books. Then followed by relevant data collection for Addis Ababa. The data includes existing macro site information, spectrum utilization, spatial traffic distributions, and digital map. Upon finishing data collection, target deployment area is selected.

For selected study area, candidate location for small cell deployment is obtained. Once deployment area identification and candidate location selection are done, macro and small cell are configured in WinProp. Following, propagation environment is captured by WinProp with deterministic propagation model. Then simulation environment is set up using MatLab based LTE system-level simulator. Here optimal location and number small cells are obtained using Multi-Objective Genetic Algorithm which is implemented in MatLab. In parallel with preparing the simulation environment, spectrum scenarios are identified considering ethio telecom Addis Ababa case. With simulation, small cell deployment with different spectrum scenarios are evaluated based on key performance indicators (KPIs). Finally, analysis and interpretation of performance result is done

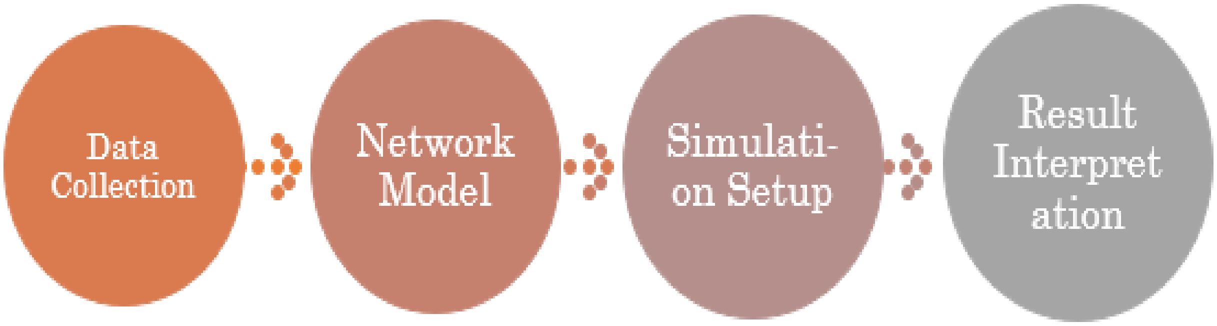


Figure 1-2 General methodology of the thesis

1.5 Related Work

In this section literatures that investigate small cell deployment from the spectrum scenario and planning perspective are selected for review.

According to [4], a comparison between co-channel and dedicated channel deployment is analyzed for varied deployment schemes with the aim of determining the best spectrum allocation that maximizes network performance. For this study, band available are 800MHz (bandwidth 10MHz) and 2600MHz (bandwidth 20MHz). The deployment scenario considered includes macro to outdoor Pico only, indoor Femto only and joint Pico-Femto with cochannel and dedicated spectrum scenario. The band 800MHz is allocated to macro only and 2600MHz allocated to macro and small cells. As a performance metric, outage rate and percentage of offloaded user equipment (UE) are used. To achieve 10% outage, the required number of small cells are fewer in dedicated channel deployment than co-channel deployment. In terms of offloaded traffic, the joint deployment of Pico-Femto provides the highest result. This study would have provided better results if it has considered an additional spectrum allocation scheme.

In [5], comparative study to determine the required number of Pico or macro to meet the growing traffic demand under a limited spectrum was done. The study area covers 5kmx5km containing four (each three sectors) existing 3G sites with 5MHz bandwidth at 2GHz band. Deterministic propagation model was applied with 3D building to capture propagation environment. The traffic growth of 3X and 5X, and traffic distribution obtained from existing 3G network traffic is utilized in this study. In this study, the authors carried out Monte Carlo simulation and found that 5 new Pico compared to 1 new macro is required to meet the growing 3X and 5X demand. Moreover, outdoor Pico is effective even when majority of users are indoors. The study considered only co channel deployment scenarios.

In [6], deployment option of picocell on 3 carrier LTE network for operators that own 5MHz from band 25 (2GHz), 20MHz from band 41 (2.6GHz) and 5MHz from band 26 (875MHz) is investigated to obtain the best way to use the available spectrum to maximize network performance and minimize cost (number of small cells). To do so, realistic deployment study is carried out by selecting area of interest covering 5kmx5km. The selected area is primarily composed of mixed residential and commercial locations with four macro cell sites, each with three sectors. To capture the propagation environment WinProp is used. Four picocell deployment scenarios are investigated including 2GHz/In-band, 2.6GHz/In-band, 2.6GHz/Dedicated and combination of half of the Pico cells on the dedicated 2.6 GHz carrier and half on the 2 GHz macro cell carrier. In each scenario, Picocells are added to reduce the percentage of users in outage until it is below the target of 5%. The authors separately studied the effect of carries addition on the system capacity. In carrier addition perspective, low-frequency carrier (875 MHz) enhances the system coverage and high-frequency carrier significantly improves capacity. In pico addition perspective, deploying in-band picocells in the high frequency/high bandwidth carrier provides a better user experience. Picocell deployment on a dedicated carrier requires fewer cells than a similar in-band carrier and provides better user experience. The study considered limited sets of spectrum allocation.

In [7], different combinations of macro to small deployment schemes are investigated to meet future capacity demands of cellular networks. This study tries to understand the tradeoff between basic cost vs network performance of different combinations of technologies according to case study operator network. The performance of four network upgrade approaches considered for this study includes carrier upgrade, macro densification, micro deployment in dedicated carrier and micro deployment reusing macro carrier. Each network upgrade path is simulated with a given network KPI. Then, performance gain and total cost of ownership are compared for each network upgrade path. Accordingly, hybrid of carrier upgrade in existing time division LTE (TD-LTE) macro with co channel micro site is more cost-efficient than dedicated micro site deployments. But out-band micro deployment provides the highest network throughput and is easier from cell planning and radio resource management point of view.

In [8], different network densification alternatives such as Micro, Pico and Femto are available in heterogeneous networks to enhance capacity of downlink LTE performance. Comparison of deploying various types of small cells (Micro, Pico and Femto) against tradition approach of macro base station densification is studied to find the required number of new sites for each deployment alternatives. Area selected for the study contains approximately 5000 residential apartments per square kilometer with uniform traffic distribution, seven existing macro sites, micro and indoor Pico. Micro base stations are deployed between building at height of 5m and indoor Pico are located at corridor with assumption of 80% indoor users. After selecting propagation model, simulation environment was set up with the required parameters. Based on simulation results, the number of Micro, Pico, Femto required compared to new macro site densification to achieve the same level of system performance are 7, 65, and 75, respectively. The price of a small cell is lower than macro cell. But considerable number of small cells are required which created some challenges on business as usual approaches. In this study, only co-channel deployment scenario is considered.

Spectrum scenarios considered in the above literature are either operator-specific or typical representative configuration. To the best of authors' knowledge so far, none of the literature has investigated the performance gain of spectrum scenario in outdoor LTE small cell considering Addis Ababa's ethio telecom realistic network environment as case study.

1.6 Significance of the Study

There is no efficient spectrum usage strategy for outdoor small cell planning for Addis Ababa as per authors' knowledge. So, performance analysis of deploying HetNet in different frequency band and bandwidth considering realistic network deployment scenario can provide planning performance insight for making an informed decision on efficient spectrum usage in the deployment of small cells for existing and upcoming mobile operators that serve Addis Ababa. Moreover, this study provides an insight and methodological input for telecom regulators like Ethiopian Communication Authority in their capacity building endeavor towards spectrum assignment. Furthermore, this thesis presented methodology for researchers to study various upcoming spectrum scenarios from small cell planning perspectives.

1.7 Scope and Limitation

This study focuses on identifying most suited spectrum scenarios specific to Addis Ababa outdoor small cell deployment and analyzing the performance based on defined metrics. Performance gains that are obtained by applying interference management technique, such as enhanced inter-cell interference coordination (eICIC) is not considered in this thesis. Moreover, study is limited to frequency division duplex mode of operation in LTE.

1.8 Outline of Thesis

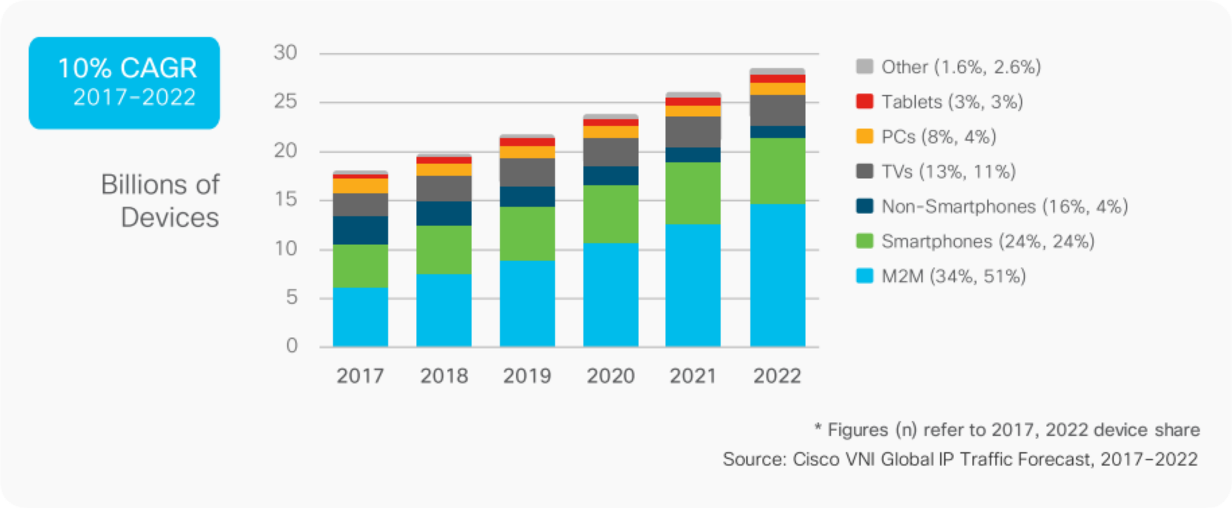
The rest of the document is organized as follows. Chapter 2 includes a description network upgrade trends, heterogeneous network, small cell types and deployment consideration for small cell deployments. Chapter 3 explains data traffic and mobile network of Addis Ababa city, network expansion approach of ethio telecom and HetNets spectrum scenario for Addis Ababa. Chapter 4 includes a description of the spatial traffic models, key performance indicators, small cell candidate selection, planning approaches and optimization methodology. In chapter 5 simulation approach, parameter and assumption are discussed. Moreover, performance results for each investigated spectrum scenarios are covered in this chapter as well. Summary of the main ideas and conclusions along with future works are presented in chapter 6.

2 Network Densification

In this chapter, contributing factors for network densification and various densification approach are covered. Thorough discussion is made on densification with small cells.

2.1 Growth in Device connections

Societal progress will lead to changes in the way mobile and wireless communication systems are used. Essential services such as e-banking, e-learning and e-health will continue to proliferate and become more mobile. On-demand information and entertainment are being delivered over mobile and wireless communication systems. Because of this, devices and connections are growing faster (10 percent CAGR) than both the population (1.0 percent CAGR) and Internet users (7 percent CAGR) [9]. This trend is accelerating the increase in the average number of devices and connections per household and per capita. Each year, various new devices in different form factors with increased capabilities and intelligence are introduced and adopted in the market. According to Cisco forecast, the average number of devices and connections per capita will grow from 2.4 in 2017 to 3.6 by 2022 [9].



* Figures (n) refer to 2017, 2022 device share

Source: Cisco VNI Global IP Traffic Forecast, 2017-2022

Figure 2-1 *Global devices and connections growth* [9]

This rapidly increasing average number of devices and connections requires the availability of enhanced data services. Unfortunately, existing wireless telecommunication infrastructure will not be sufficient to meet subscribers’ data requirements in the future [10][11]. Due to this, telecom operators encounter challenging problems that need to be addressed in the future.

2.2 Network Upgrade Trends

To keep up with the ever-increasing need for data service, there are various network upgrading solutions. These solutions can be given as follows: increased spectral efficiency, increased spectrum resources, and increased base station densification [2][11]. A brief introduction is provided below for each deployment solution.

Spectral Efficiency

Spectral efficiency is the ratio of the data rate that can be transmitted over bandwidth in a communication channel. Spectrally efficient technology deployment on different frequency bands is the basic measures to boost network capacity. In this regard, enhancements in third generation partnership project (3GPP) releases has been carried out. 3GPP Release 8 marks the first LTE standard [12]

The benefits of LTE become possible with the introduction of the orthogonal frequency-division multiple access (OFDMA) on the downlink(DL) and the single-carrier frequency-division multiple access (SC-FDMA) on the uplink(UL) [12][13]. Both access schemes use OFDM, which is a form of frequency-division multiplexing (FDM), in which many narrowbands, closely spaced subcarriers carry user data. The smallest frequency domain element that can be scheduled to a user is called a resource block and consists of 12 OFDM sub-carriers. The smallest element that a user can be scheduled, called a physical resource block (PRB) consist of a time slot in time domain and a resource block in frequency domain.

In 3GPP Release 8 downlink multiple-input and multiple-output (MIMO) technique was included to further boost spectral efficiency. Moreover, in later releases increased modulation order included to further improve spectrum efficiency [13].

Higher order sectorization is another solution to enhance the spectral efficiency by deploying higher number of sectors/antennas[12][14]. As shown in Figure 2-2 the most typical configuration is to double the number of sectors from 3 to 6 on the horizontal plane by installing narrow beam antennas. This approach allows mobile operators to fully exploit the existing sites and almost double network capacity despite practical limitations due to increased user handovers and interference between adjacent antennas [14][15].

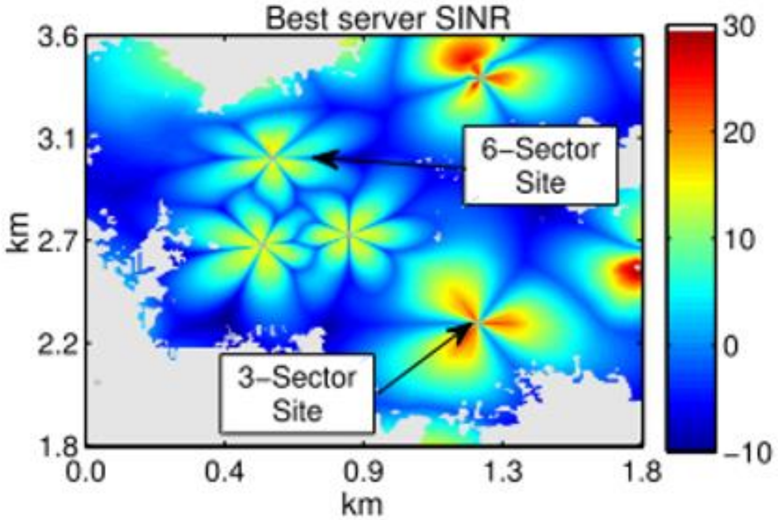


Figure 2-2 *Macro upgrades by doubling the number of sectors per site* [15]

Spectral Resource

Mobile network operators are dependent on the availability of radio spectrum to deliver the required services. Radio spectrum is a precious and limited resource that must be utilized in the most efficient way when various radio technologies are deployed. Deploying radio technologies with additional spectrum provides a simple and cost-efficient solution for upgrading the network when radio spectrum is available [15]. 3GPP introduced LTE advanced (LTE-A) in Release 12. One of the key features for LTE-A is “Carrier Aggregation (CA)”. With CA, it is possible to assign more than one LTE Release 8 downlink resource to UE to transmit and receive communication signal. Such a feature enables mobile operators to provide higher peak data rates and capacity by extending the overall transmission bandwidth beyond the 20 MHz upper limits set in the first releases of LTE [12].

Base Station Densification

All the above solutions can be applied to existing macro sites to boost the performance of macro deployments. As it is mentioned above, drastic increase in the number of connected devices and mobile traffic growth has been witnessed in recent years. To cope with the traffic growth, along with implementing advanced features that are discussed above, network densification with brand new macro site is done. Summary of network capacity enhancement approach is illustrated in Figure 2-3.

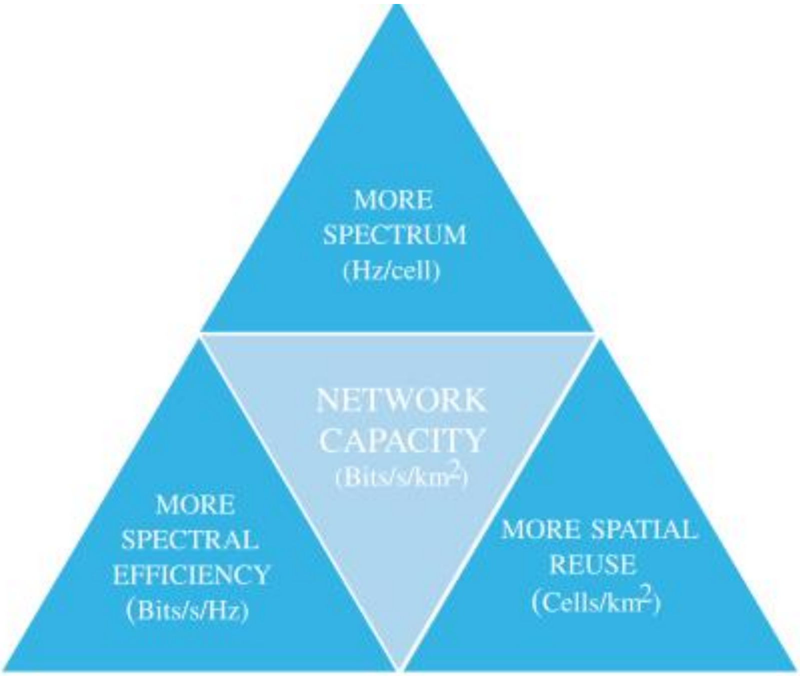


Figure 2-3 *Existing paradigms to improve network capacity* [11]

If the network operators follow any of the above approaches the challenge encountered is in three folds. The first major drawback with the above solutions is that they perform bad for localized (hotspot) traffic [15]. In this regard, the network operators need an alternative solution to address localized (hotspot) traffic. The second major drawback is deployment cost and extended installation duration while densifying the network with macro site. The third major drawback is that the above solutions may not be sufficient to meet capacity demand. Fortunately, network densification with small cells(HetNets) are a promising solution in terms of addressing the growing traffic demand with reasonable deployment cost and short installation duration [10][16].

As part of improving user experience, network densification with HetNets is also carried out to improve in-building coverage and cell edge performance. In urban area building loss, reduction in received signal strength by building, is becoming a growing challenge for outdoor to indoor communication. Due to this, UE received signal strength is poor for in-building users. Therefore, network densification with small cell base stations provides an opportunity for network operators to improve their network in terms capacity and user experience whenever the need arises.

2.3 Heterogeneous Networks

Mobile cellular networks are deployed as homogeneous networks comprising of macro base station only. The location of the macro base stations is carefully planned in order to maximize coverage and manage the interference. In these networks, all cells have similar transmit power levels (homogenous), antenna patterns and backhaul connectivity. Besides, all base station grants unrestricted access to the UEs in the network [17].

Heterogenous network is composed of small cells placed throughout a macro-cell layout in multi-layered approach. Small cells, a fully-featured mini base station, transmit with low power compared to a macro base station. Figure 2-4 presents a typical deployment for heterogeneous networks. In HetNet deployments, the overlay macro cell provides a wide area coverage umbrella while the small cells are deployed randomly or in a more targeted manner to eliminate coverage holes, increase network capacity, and improves user experience at traffic hot zones [13][17]

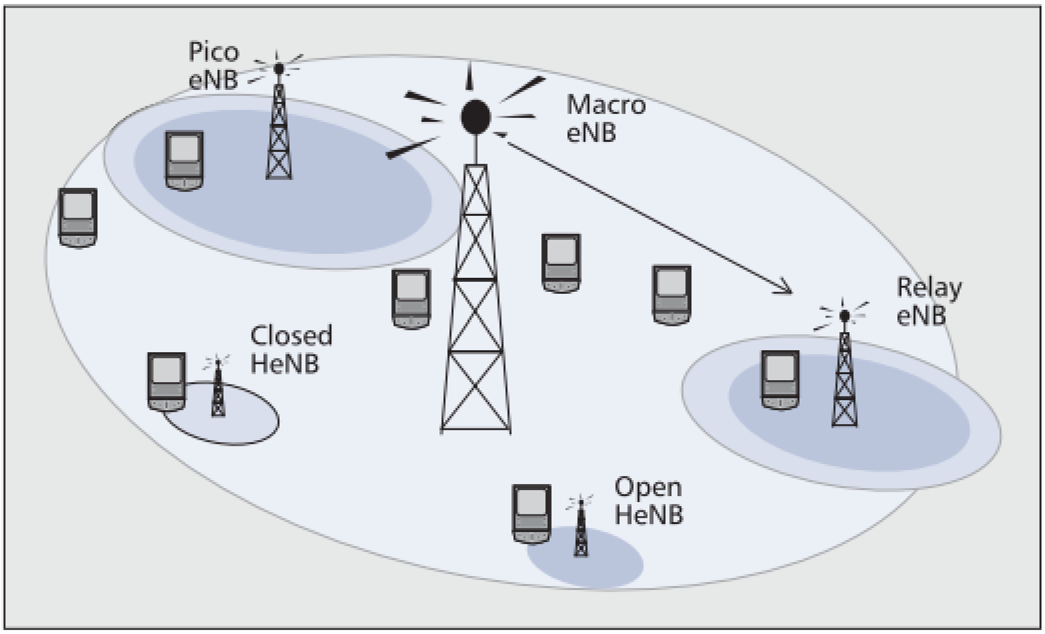


Figure 2-4 *Heterogeneous network topology* [13]

Various types of small cells are deployed in HetNets includes Pico evolved NodeB (eNB), home eNodeBs also called femtocells, and relays. Table 2-1 shows more details about heterogeneous network nodes [13]. Base station differs from each other in transmission power, backhaul connectivity, access methods, and coverage area.

Macro Cells

Macro cell is the conventional operator deployed base station with a dedicated backhaul, providing public access and wide area coverage up to a few kilometers with the largest coverage area within a mobile network [13]. The radio coverage distances varying depending on frequency band utilized and physical terrain. Macro cell base stations have a typical power output in tens of watts. Antennas for macro cells can be mounted on ground-based towers, rooftops or other existing structures. They are positioned at a height that is not obstructed by buildings or terrain. .

Table 2-1 *Details about Heterogeneous Network Nodes*

	TX Power	Backhaul	Access	Coverage	Notes
Macro Cells	46 dBm	S1 Interface	Open to all UE	Few km	
Pico Cells	23-30 dBm	X2 Interface	Open to all UE	<300 m	Placed indoors or outdoors.
Femto Cells (HeNB)	<23 dBm	No X2 as Baseline	Open, Closed, or Hybrid Subscriber Group	<50 m	Placed indoors. Consumer deployed
Micro Cells	30-37 dBm	X2 Interface	Open to all UE	<2km	Placed outdoors
Relay nodes	30 dBm	Through air-interface with a macro-cell	Open to all UEs	<300 m	Placed outdoors

Pico Cells

Pico cells are almost the same as the macro cells except that they have lower power and antenna length, thus coverage area is smaller compared with macro cells. The backhaul uses X2 interface for data communication and interference management. They are equipped with omni-directional antennas and are deployed indoors or outdoors often in a planned manner. Different outdoor small cell planning approaches are available. In [18], planning approaches based on multi objective optimization is proposed. To solve the optimization problem formulation, Genetic Algorithm (GA) is applied. Thorough discussion on Genetic Algorithms (GA) is made in chapter 4.

Femto Cells

Femto cells are usually users deployed for indoor purposes. Network operators do not need to provide power and backhaul connections where they are using the Internet connection like xDSL. They can be configured to be open, closed or hybrid. A closed access femtocell maintains a closed subscriber group (CSG) so that users need to be on the white list to get access. Hybrid access femtocells allow limited access to non-subscribed UEs and higher quality of service to CSG users. Open access femtocells provide the same quality of service for all users. Open femto is more like pico except for different backhaul connections [19].

Micro cells

Micro cells are similar to Pico cells, but their coverage area is bigger, usually around 2 kilometers, and they are deployed outdoors.

Relay Node

Relay Node (RN) is network node without a wired backhaul. The backhaul, which provides the attachment of the RN to the rest of the network, is wireless and uses the air interface resources of the wireless system. In case the backhaul communication takes place in the same frequency as the communication to/from UE on DL/UL, respectively, the relays are denoted as in-band. If the backhaul communication takes place at a frequency different from that used by UE in DL and UL, the relay node is classified as out-of-band. Note that unlike in-band relays, out-of-band relays do not pose many physical layer design challenges. Relay nodes are typically equipped with directional antennas in the backhaul link (pointing to the Donor eNB) and omnidirectional antennas in the access link. RNs are deployed indoors or outdoors. Relays are more beneficial in the areas where it is hard to deploy wired backhaul [19].

2.4 Deployment Considerations of Small Cells

There are a good number of features that make small cells a favorable choice for mobile network operators. To begin with, deploying small cells is relatively easy and straight forward [14]. They can be deployed by end-user when they are used for indoor purposes. During outdoor deployments, small cells can be easily deployed by low-skilled installers. Features that simplify the deployment and operation of small cell includes, but not limited, to self-organizing networks and backhaul to mention some.

Self-organizing networks (SON)

SON is a collection of procedures for automatic configuration, optimization, and healing of mobile networks. It is considered to be a major necessity in future mobile networks deployment and operations mainly due to possible savings in capital (CAPEX) and operational expenditure (OPEX) [20]. The SON functions are usually categorized into three main groups self-configuration, self-optimization, and self-healing.

The Self-configuration SON is a collection of algorithms that aims at reducing the amount of human intervention in the overall installation process by providing “plug and play” functionality in network elements such as the eNBs. This will result in faster network deployment and reduced costs for the operator in addition to a more integral inventory management system that is less prone to human errors. The self-configuration take care of all soft-configuration aspects of an eNB once it is commissioned and powered up for the first time.

SON self-optimization functions are aiming at maintaining network quality and performance with a minimum of manual intervention from the operator. Self-optimization functions monitor and analyze performance data and automatically triggers optimization action on affected network elements when necessary. This significantly reduces manual interventions and replaces them with automatic adjustments keeping the network optimized at all times.

Self-healing is a collection of SON procedures that detects problems and solves or mitigates these to avoid user impact and to significantly reduce maintenance costs. Self-healing is triggered by alarms generated by the faulty network elements. If it finds alarms that it might be able to correct or minimize the effects, it gathers more necessary correlated information, does deep analysis, and then trigger the appropriate actions.

Backhauling

When deploying small cell network operator has the flexibility in the selection of backhaul [19]. In a heterogeneous network, the backhaul portion of the network contains the intermediate links between the core network and small cell networks. Backhaul has the responsibility to carry traffic to and from the core network and it acts as a bandwidth provider which guarantees quality of service to the subnetwork users. A recent survey found 56% of operators citing backhaul as one of the greatest challenges, next to fundamental issues of site acquisition, power, etc [19]. The increase in traffic due to the advancement of radio access technologies and network densification requires better backhaul technologies so as to support the new transport capacity demand.

Generally, backhaul solutions can be categorized into wired (leased lines, copper or fiber) and wireless (point-to-point or point-to-multipoint over high-capacity radio links). Wired solution is usually expensive and often impossible to be deployed in some areas, making wireless solution a more suitable and viable option. There is no single backhaul technology, wireless or wired, that fits all small cell deployment needs and cost constraints [19][21].

In this study of outdoor LTE small cell planning, the backhaul section is not considered as a limitation that is to mean operator have enough backhaul resource.

3 HetNet Spectrum Scenarios in Addis Ababa

This chapter starts with a discussion on LTE network in Addis Ababa. Following, LTE HetNet spectrum scenario that are available for deployment of small cells are covered considering Addis Ababa case.

3.1 LTE Network in Addis Ababa

Ethio telecom, sole telecom operator in Ethiopia, deploys and operates GSM, UMTS, and LTE mobile networks. As of Dec 2018, unique mobile subscriber penetration rate reached 41.0% by subscription, comparable with Sub-Saharan African average of 44% [22][23]. GSM and UMTS networks are deployed throughout the country covering geographical area of 85% and 66% respectively [22].

In contrast to GSM and UMTS, LTE network coverage is available only in Addis Ababa city, capital of Ethiopia, with planned capacity of 399,735 subscribers. Currently, ethio telecom deployed 332 LTE and 729 UMTS base stations to support the mobile broadband mobile data traffic demand of Addis Ababa city. UMTS base stations are deployed throughout the city (downtown and outskirt area) while LTE deployment being limited to downtown only.

In cellular networks spatial distribution of base stations (BSs) heavily influences network performance [24]. Spatial distribution of base station density varies in Addis Ababa city. The city’s cellular network base station density can reach up to 10 base stations per square kilometer. For most of the area, the base station density is between 3 and 4 with minimum inter-site distance reaching as low as 200m. For LTE deployment in Addis Ababa city, 20MHz bandwidth is allocated in 1800MHz band.

In Addis Ababa city, as it is expected in mobile networks, spatial base station data traffic varies significantly in both temporal and spatial perspectives. Base stations serving business area and residential areas carry high traffic in day and night busy hours respectively. Figure 3-1 shows LTE base station traffic data volume download with red highlighted carrying high traffic and with green highlighted caring low traffic.

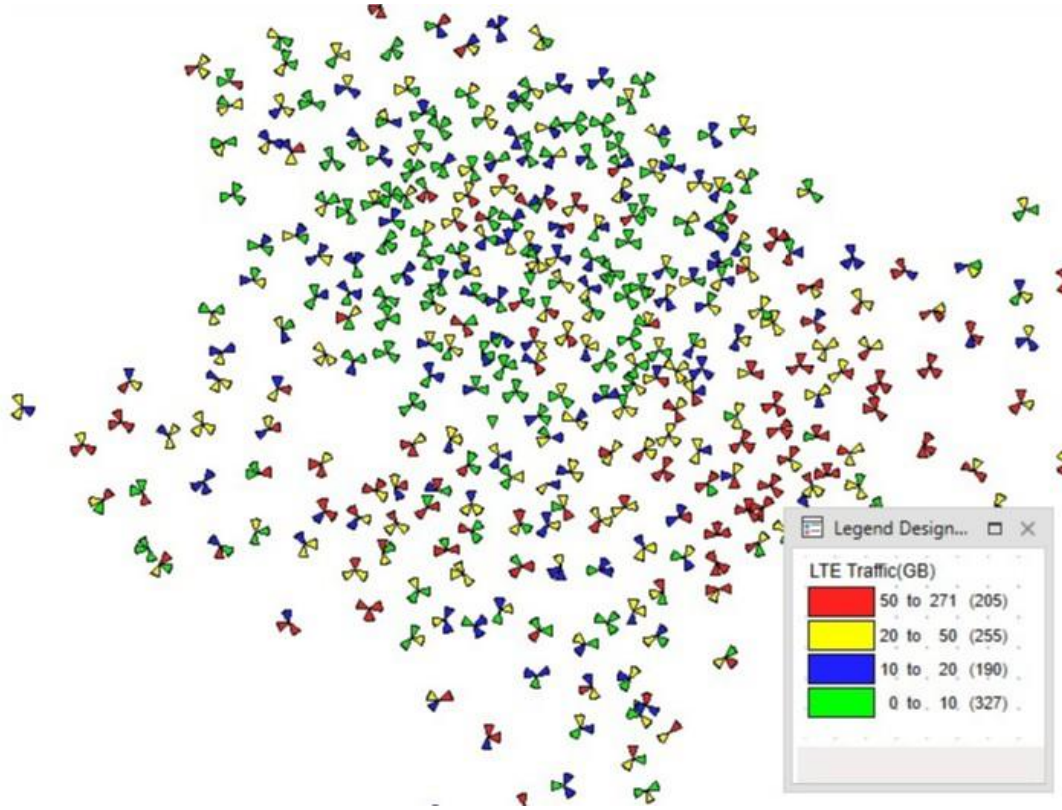


***Figure 3-1** Addis Ababa sites LTE data traffic in daily basis time.*

Terminals supporting mobile broadband data traffic (HSPA+ and LTE) are now easily available at cheaper price than before. In Addis Ababa city, more than 85% of the devices assessing the network are smartphones. Subscriber usage trends in social media and data-intensive applications is showing an increment trend. As a result of these two contributing factors, monthly data traffic trend for Addis Ababa city LTE network is growing at an exponential rate. As it is forecasted in [3], Addis Ababa city’s data traffic will reach more than 20 TB per month by 2021.

3.2 Densification Approaches

Mobile network operators can follow different network expansion roadmaps depending on the business and available resources to accommodate the exponentially growing traffic [10]. To understand the expansion approach that is being followed in ethio telecom, assessment was carried out. Accordingly, summary of the approaches followed by ethio telecom to absorb the growing data traffic is shown in Figure 3-2.

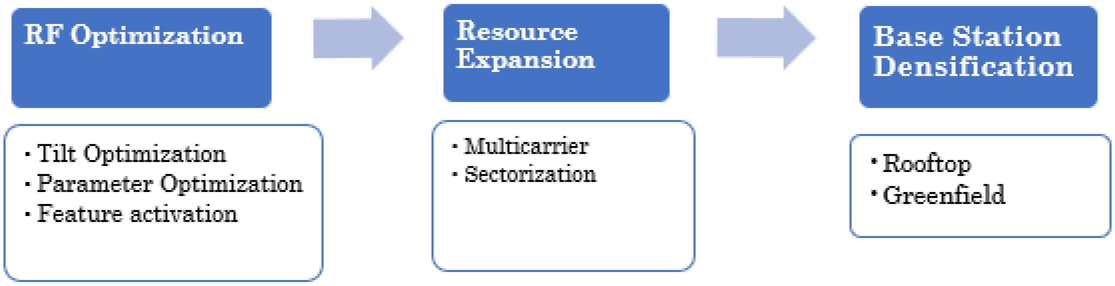


Figure 3-2 *Current approaches to address data growth in ethio telecom*

Radio Frequency (RF) optimizations are certainly the basic measures to increase network capacity. In the RF optimization phase, the base station radio performance data log is collected with probs. Based on analysis of the logged and performance KPI data, optimization activities such as antenna tilt adjustment, tuning of radio parameters and feature activation are applied to macro base stations to enhance the capacity and service performance of the network. If the capacity demand is not satisfied with RF optimization, network densification features such as multi-carrier and higher order sectorization are applied to the existing macro base station sites to further enhance network capacity in a more cost-efficient way. After exhaustively exploiting RF optimization and resource expansion, ethio telecom resorts to macro base station densification solution as an ultimate solution of capacity expansion. Densification solution implemented by ethio telecom partly aligns with Nokia solution networks recommendations on network expansion road map [10].

3.3 Outdoor LTE Small Cell for Addis Ababa

While closely examining the spatial data traffic distribution of base station of Figure 3-1, it reveals that base stations with high data download are neighbors to each other with inter-site distance reaching less than 200m. For the situation of this kind i.e., interference-limited, the gain from further densification with macro base station is limited.

In business areas or downtowns such as Meskel square, Bole and Megenagna finding location for deployment of macro base is very costly or sometimes impossible although inter-site distance permits macro deployments. Here, rooftop deployment can be raised as an alternative. Rooftop deployment can support the increasing traffic to certain magnitude by guaranteeing acceptable signal coverage over the serving area, but it incurs network complexity and can be expansive [25].

With the growing penetration of smartphones in Addis Ababa, high demand for capacity is often accumulated in certain highly populated areas called hotspot. Addressing the traffic demand in hotspot areas, for instance, Bolemedhanilun near bole international airport, with macro densification is challenging [25] [13].

Gathering of people in events such as sports, public holidays, etc creates temporary hotspot. To accommodate the traffic that arises from public gathering, Cell on Wheels (COW) base station (base station portable with a car) is deployed in Addis Ababa. The drawback associated with mobile base station are: limited capacity, cost, network complexity etc.

With ever-increasing traffic growth of Addis Ababa city, macro base station spatial distribution and the growing number of hotspots in Addis Ababa city, macro base station densification is expensive and inefficient in terms of coping up with urbanization of the city and accommodating the growing data traffic [25] [2] [10]. Therefore, shift towards heterogenous network with outdoor small cells is next step to densify ethio telecom network. Figure 3-3 shows typical hot spot location.

Figure 3-3 *Small cell placement at hotspot* [26]

Recently, several mobile operators have started outdoor LTE small cell deployment to enhance service performance in high-dense areas. Small cell solutions have become an alternative way of expanding coverage and increasing network capacity in recent times. They provide flexibility and increased service performance at a reasonable cost [27].

When ethio telecom densifies Addis Ababa mobile network with outdoor LTE small cell, one of the natural question that arises is spectrum scenario between macro and small cells.

3.4 Spectrum Scenarios in HetNet

In HetNets deployment several small cells are deployed under macro cell umbrella. Small cells are deployed as a complement for macro cell to improve coverage and enhance the capacity. To ensure targeted network performance with small cell deployment due consideration is given to the interference that arises among small cells and among small cells and macro cells. In this regard, the spectrum scenario followed by the operators determine the network performance.

Selecting spectrum for the small cell deployment is a key parameter [16]. It determines the overall network performance. Generally, it is recommended to use lower frequency (below 1GHz) for macro cell and higher frequency for small cells. Various small cell deployment solutions are utilized in the industry to enhance the performance of cellular networks. Spectrum scenario defined for small cell deployment includes co-channel, hybrid and dedicated.

In co-channel deployments, macro and small cells are assigned the same spectrum bandwidth. In such a case there will be interference between the macro and small cell layers so that macro cell-UEs will experience additional interference from small cells, and small cell-UEs will experience macro layer interference, thereby limiting the serving area of small cells.

In hybrid deployment, macro and small cell share part of the spectrum bandwidth. For this case, macro cell-UEs as well as small cell-UEs partly experience interference depending on the scenario.

On the contrary, in dedicated deployment macro and small cells are assigned separate spectrum bandwidth. This scenario macro cell-UE as well as small cell-UEs won't experience any interference from small and macro cell respectively. In other words, this deployment scenario eliminates cross-tier interference.

Various literature has investigated the performance gains in using the above spectrum scenarios. In [28], for instance, performance tradeoff between co-channel and dedicated channel are evaluated under hexagonal base layout approach for realistic user traffic model. Authors in [29] also investigated the performance of small cell deployment for the different deployment schemes with different user distribution and small cell density. The results obtained in the above literature vary depends on the traffic model, traffic distribution and input parameters such as network layout.

3.5 Spectrum Allocation Trend

3.5.1 Global LTE Spectrum Allocation

International Telecommunications Union (ITU) World Radio Conference (WRC) are held every three to four years to identify new radio spectrum for telecommunication system since 1992. In its first conference, 230 MHz radio spectrum was identified for Public Land Mobile Telecommunication System (PLMTS) later named to IMT-2000 (3G) [30]. To meet the growing new radio spectrum requirements, additional radio spectrums are identified with the name IMT-Advanced (4G). 3GPP technologies operate in a wide range of radio bands. As new spectrum becomes available, 3GPP updates its specifications for these bands. Several spectrum bands are available for LTE deployments. In Table 3-1 LTE frequency bands in 3GPP specifications are shown for paired bands [12]. Some of the bands are currently used by other legacy technologies.

Table 3-1 *LTE Frequency bands and bandwidth*

Operating Band	Uplink (MHz)	Downlink (MHz)	Width of Band (MHz)	Duplex Spacing (MHz)
Band 1	1920–1980	2110–2170	60	190
Band 2	1850–1910	1930–1990	60	80
Band 3	1710–1785	1805–1880	75	95
Band 4	1710–1755	2110–2155	45	400
Band 5	824–849	869–894	25	45
Band 6	830–840	875–885	10	35
Band 7	2500–2570	2620–2690	70	120
Band 8	880–915	925–960	35	45
Band 9	1750–1785	1845–1880	35	95
Band 10	1710–1770	2110–2170	60	400
Band 11	1427.9–1452.9	1475.9–1500.9	20	48
Band 12	698–716	728–746	18	30
Band 13	777–787	746–756	10	-31

Operators in various countries deployed LTE in different spectrum bands. For instance, deployments in US at 700 MHz, in Europe at 2.6 GHz and in Japan at 1500 MHz. Such use of unharmonized spectrum bands across operators or countries for LTE deployment influences international roaming operation. Harmonization of spectrum for LTE will lead manufacturers to produce equipment with similar types, which is desirable for achieving economies of scale and affordability of equipment. Therefore, as part of encouraging spectrum harmonization across the globe, the world is classified into three regions by ITU-R. ITU-R recommends that governments in each region and across the globe need to follow harmonized spectrum allocation scheme.

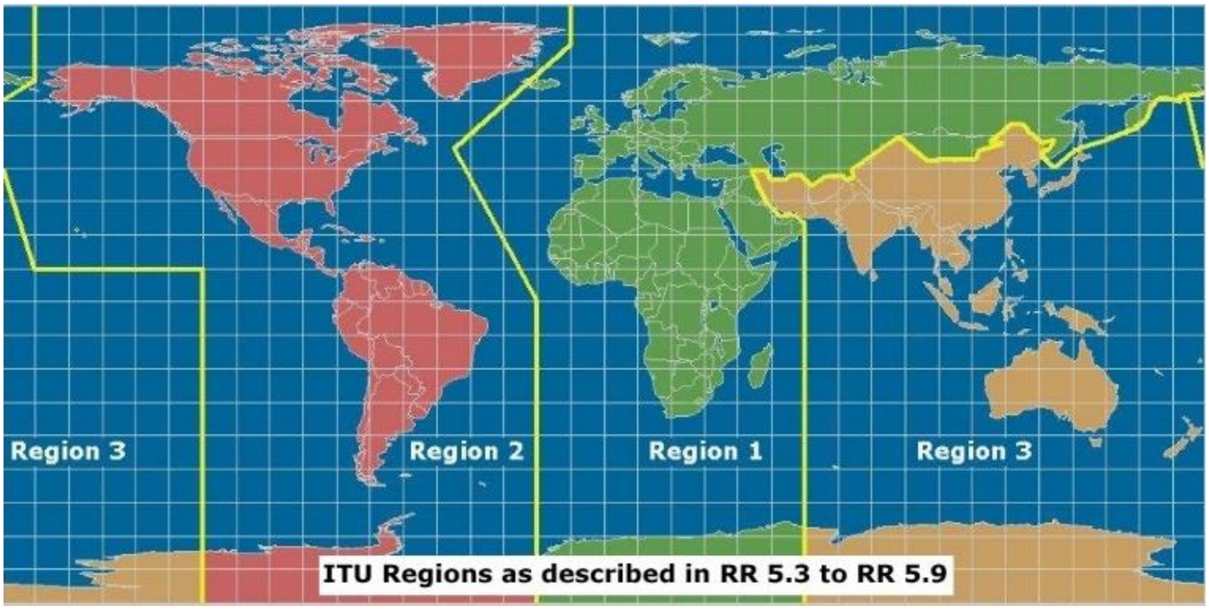


Figure 3-4 *ITU Regions* [31]

Globally, more than 480 commercial LTE networks are deployed in 170 countries [32]. Several spectrum bands are utilized for the LTE deployment. A growing number of operators are deploying LTE in similar bands. Figure 3-7 shows frequency band allocated for LTE deployment in commercial networks. Band 3 (1800MHz), band 7 (2600MHz) and 800 (MHz) are the most preferred band for LTE deployment.

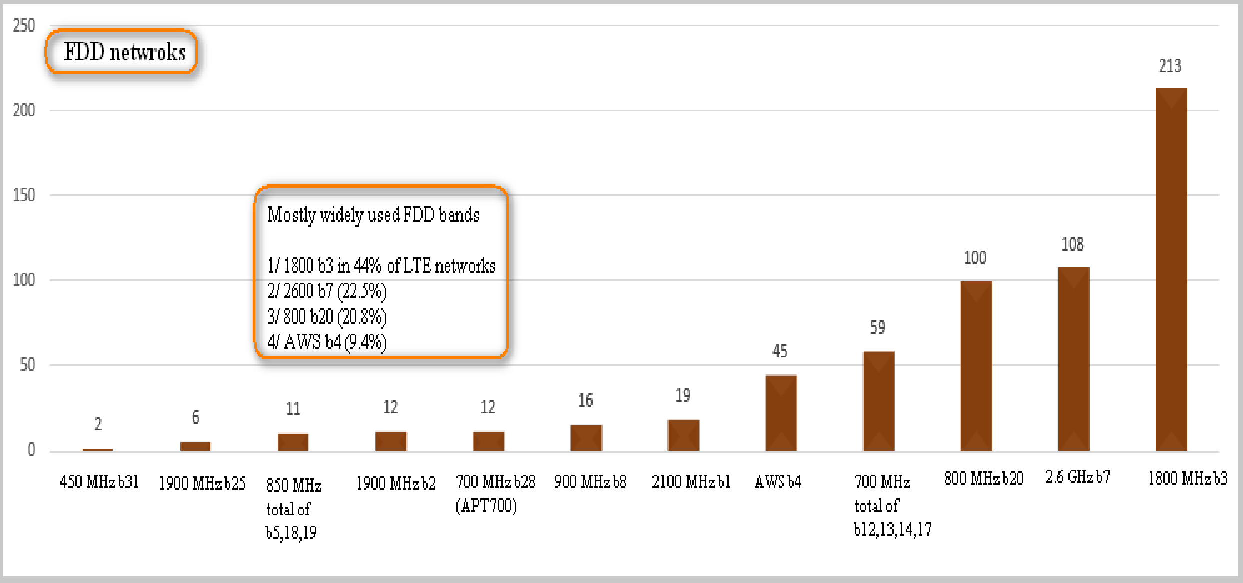


Figure 3-5 *Commercially launched LTE Networks* [32]

3.5.2 Sub Saharan African LTE Spectrum Allocation

Sub Saharan African countries are included in ITU Region 1 as shown in Figure 3-4. Regulators in Sub Saharan Africa countries are releasing additional spectrum for deployment of LTE to support the growing data traffic [23]. It is important that any additional spectrum released in Sub Saharan Africa is at globally or regionally harmonized frequencies since network equipment and end-user devices are manufactured on a global or regional scale.

The released spectrum bands by Sub Saharan Africa regulators for the deployment of LTE are 800MHz and 2600MHz [33]. Sub Saharan Africa that completed the migration of digital dividend bands are utilizing lower band (800MHz) for rural and indoor urban coverage. Most Sub Saharan African counties including Ethiopia have not completed digital switch over [34] and hence lower band (800MHz)is not utilized. Similar to the global trend Sub Saharan African countries are planning to deploy or already deployed LTE in band b3(1800MHz), band b7(2600MHz) and Band b20(800MHz) [33] [35].

3.6 Spectrum Scenarios for Addis Ababa

In Addis Ababa, small cells are deployed as pilot project in few commercial buildings to enhance indoor coverage and capacity. When ethio telecom adopts small cells to expand the capacity of

Addis Ababa city on a large scale, a lot of spectrum scenario alternatives are available. As mentioned frequently Ethiopia's telecom market is not liberalized. Currently ethio telecom spectrum holdings in GSM, UMTS and LTE mobile networks summarized in Figure 3-6.

The spectrum utilization in Ethiopia being at its infancy gives the opportunity to select convenient spectrum for small cell deployment. In frequency band wises ethio telecom can deploy small cell, for instance, in 1800MHz,1900MHz, 2100MHz and 2600MHz. As mentioned above ITU-R recommend that when spectrum is assigned for cellular network deployment it is better to maintain spectrum harmonization.

In this regard, frequency bands such as 1900MHz and 2100MHz are utilized in a few countries with market share of less than 10% in the global commercial LTE network [32]. Accordingly, frequency bands such as 1900MHz and 2100MHz are not preferred bands for the deployment of outdoor LTE small cells in Ethiopian context. Frequency bands such as 1800MHz and 2600MHz, on the other hand, share more than 60% of global commercial LTE network.

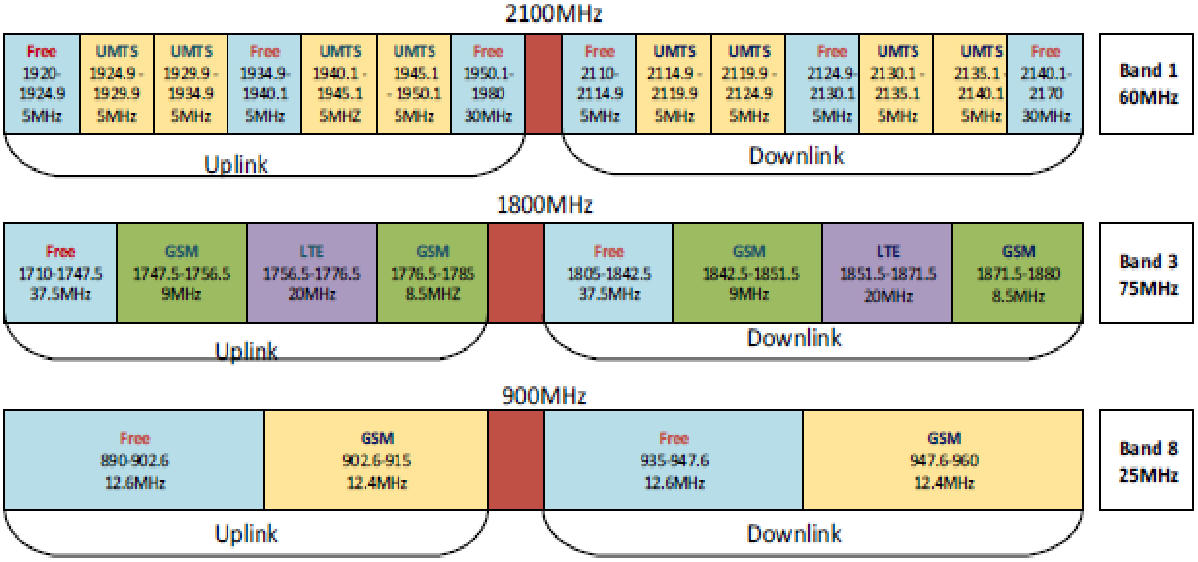


***Figure 3-6** ethio telecom spectrum usage* [26]

Currently in Ethiopia, frequency band 2600MHz is not released and ethio telecom does not hold spectrum bandwidth in 2600MHz. It is expected that Ethiopian regulator releases 2600MHz spectrum band for LTE deployment by following the trend of Sub-Saharan Africa countries regulators. As an incumbent operator, it is expected that ethio telecom will invest in acquiring additional spectrum for outdoor LTE small cell deployments.

Currently, ethio telecom assigned 20MHz bandwidth in 1800MHz band for macro cell LTE deployment in Addis Ababa. Table 3-2 shows the frequency band and bandwidth utilized for this study. While formulating spectrum scenario for this case study, the following key considerations are taken into account.

- ITU-R recommendations
- 3GPP small cell scenario description
- ethio telecom current spectrum allocation
- Sub Saharan Africa operators’ trend [35].
- related literature works

Table 3-2 *Frequency band and bandwidth for macro and small cells.*

Base station	Frequency band	Spectrum bandwidth	Remark
macro cell	1800MHz	20MHz	ethio telecom realistic data
small cell	1800MHz or 2600MHz	10MHz or 20MHz	related literature [4][6]

Accordingly, the spectrum scenario for the deployment of outdoor LTE small cells in Addis Ababa is presented in Figure 3-7.

In cochannel scenario, both macro and small cells are assigned 20MHz in 1800MHz in the same spectrum bandwidth. In hybrid scenario, from the total available 20MHz spectrum bandwidth only 10MHz is assigned for small cells and macro cells are assigned 20MHz. For both cochannel and hybrid scenarios, a total of 20MHz spectrum bandwidth is available for HetNets deployment.

For the situation when ethio telecom wants to start deploying outdoor LTE small cells with dedicated spectrum bandwidth smaller than macro cells, Dedicated Scenario #1 is the configuration scenario. In Dedicated Scenario #1, macro cells are assigned 20MHz and small cells are assigned 10MHz separate spectrum bandwidth in 1800MHz. In Dedicated Scenario #1 total of 30MHz is utilized for HetNets deployment. With Dedicated Scenario #1 deployment, performance gain utilizing smaller dedicated bandwidth is analyzed.

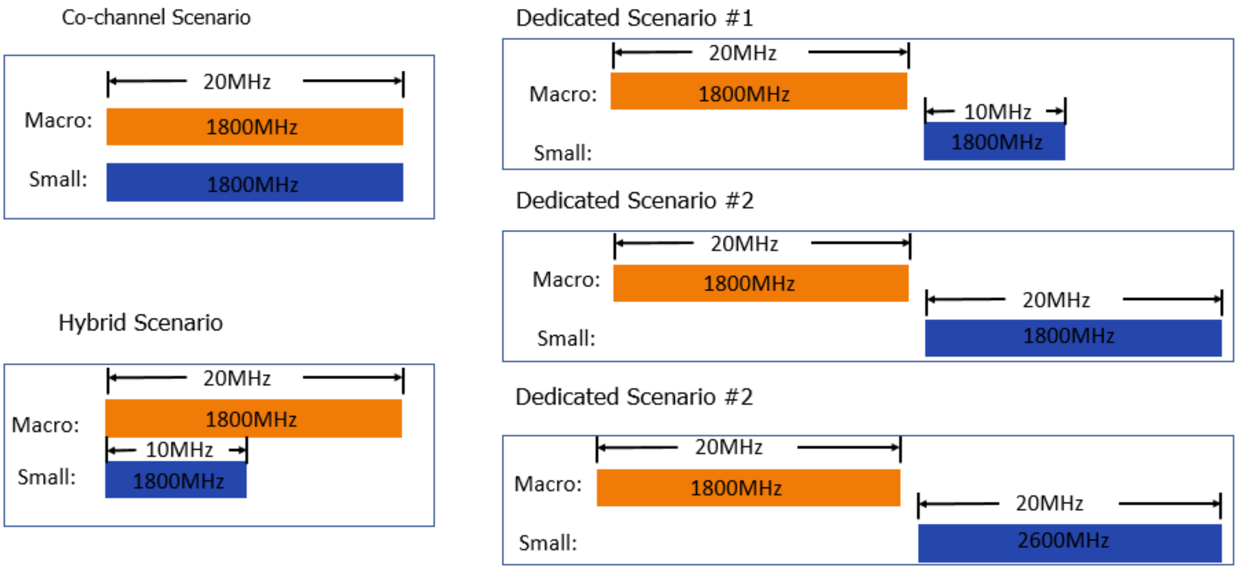


Figure 3-7 *Spectrum scenarios for outdoor small cells in Addis Ababa*

In Dedicated Scenario #2 and Dedicated Scenario #3 separate 20MHz spectrum bandwidth is assigned in 1800MHz and 2600MHz respectively utilizing a total of 40MHz spectrum bandwidth.

4 Network Modeling and Planning Approaches

In the previous chapter, five spectrum scenarios are identified for performance investigation in small cell deployment. In this chapter, a description of network modeling and planning approaches utilized in the performance evaluation of different spectrum scenarios is covered.

4.1 Network Layout and Traffic Distribution

This study consists of macro cell and outdoor LTE small cells. To properly setup of the network layout, input data required are macro cell network layout and small cell network layout

4.1.1 Macro Cells Network Layout

Several studies that use the 3GGP regular hexagonal network layout for macro cell are available. These studies have a limitation in fully capturing the actual network layout. In this study, however, realistic network data is utilized that is to mean the existing LTE macro base station data is considered as an input for the selected study area to get improved accuracy in performance evaluation of small cell spectrum scenarios. The required data related to the base stations are listed below:

- Site coordinates: Geographical position of the sites is given in Universal Transverse Mercator (UTM) or World Geodetic System-84 (WGS-84) coordinate systems specifying the easting and northing coordinate pairs in the investigated area.
- Antenna: Real antenna products with azimuth and vertical radiation patterns. Besides the pattern, vertical tilting angles and antenna height of the existing deployed LTE network of the selected area. Table 4-1 presents site related information.

4.1.2 Small Cells Candidate Locations

Macro cell parameters such as base station location, antenna height and tilt are obtained from ethio telecom realistic deployment. Since outdoor LTE small cells are not deployed in Addis Ababa, antenna height and base station locations are not available. Different methodologies can be followed to obtain small cell location. A more accurate in the selection of possible deployment locations, so called candidate location, result in batter analysis in the performance comparison of small cell deployment.

Table 4-1 *Site-related information*

Parameter	Sector 1	Sector 2	Sector 3
Antenna height	24	24	24
UTM Coor Northing	993949.6	993949.6	993949.6
UTM coor Westing	476173.9	476173.9	476173.9
Azimuth	30	130	280
Vertical tile	2	4	4

The goal here in this section is to find the optimum subset of base station locations. The selection of candidate sites for the deployment of small cells for this study is based on a load simulation of the network as opposed to others approach in which the selection, for instance, depends only on demand. Considering load in candidate selection has been extensively analyzed in [36] where terminologies are adopted.

Let us denote $\rho_k \in K$ to be a load factor of macro cell k in the set K of all cells under study, with the total number of cells denoted by N_k. The network-wide load vector of all cells is $\rho = (\rho_1, \ldots, \rho_{N_k})$. Let us also assume that every pixel m is part of the coverage area of that macro cells which can provide the strongest signal at the corresponding location.

Users in pixel m require a joint aggregated data traffic demand D_m in bit per second. Correspondingly, for each user in pixel m the achieved throughput is obtained using the approach discussed in section 4-3. In each pixel m, the achieved throughput (B_{mk}) of cell k is obtained by summing user throughput.

Cell k needs to allocate the fraction of its resources to satisfy the aggregated user demand D_m in pixel m. The total load for each cell can be obtained by summing over its allocated pixels:

$$\rho_k = \sum_{m \in M_k} \frac{D_m}{B_{km}} \qquad (4\text{-}1)$$

Once the load due to each pixel is computed, then the next is to select pixel locations that require many resources from a cell in order to satisfy their user demands. In these pixels, either the demand is very high or the achievable SINR of the allocated base station is very low, for example at the cell edges. Deploying small cells in the corresponding pixel locations can assist in fulfilling the user demand in that area. To identify pixels that satisfy these criteria ‘site suitability function` is constructed in [36]

$$\gamma_m = \sum_{m^*, ||m^*-m||< R} \rho_k \ \frac{D_m}{B_{km}} \qquad with\ \ m^* \epsilon M_k \tag{4-2}$$

With ‘site suitability function` the resource consumption in a neighborhood of radius R around pixel m is considered.

Now Nc candidate sites are extracted for small cell deployments from the locations of pixels m ∈ M_k with the Nc highest entries in the site suitability function. Here the number of candidate locations for each cell is based on network-wide load vector. The obtained candidate locations are assumed to be available for small cell deployment without any limitation for site availability. In a fully realistic deployment, however, the small cell positions may be shifted in proximity of the selected ones due to practical installation limitations. Here, in propagation computation phase, the obtained candidate locations are re-mapped to more realistic locations consistent with the geography of study area.

4.1.3 Spatial Traffic Distribution

Network layout consisting of macro and small cells is obtained with the above approaches. The location of users (Spatial Traffic Distribution) accessing the network in other words user distribution is another task in network modeling. Spatial Traffic Distribution (STD) is a way to represents subscriber traffic distribution. Spatial Traffic distribution has crucial importance in evaluating the performance of small cell deployment [15].

STD can be classified into different types. Those types are uniform and non-uniform STDs. In uniform STD, subscriber service demand is simply uniformly distributed all over the service area. It means that service demand per area is constant. In non-uniform STD, subscriber service demand is variable in different part of the service area because of several factors. Non-uniform spatial traffic distribution can be extracted from network monitoring tool for pixel resolution that depends on the data source. Spatial traffic information is not easily available in the form of a preprocessed traffic volume map that can directly be used to position users in the study area.

The supposed area of interest is rectangular with length L and width W. To generate user traffic distribution, the area is divided into $N_a \times N_b$ number of pixels. Each pixel may be chosen to place user. For k^{th} pixel, c_k is used to represent the data traffic in the pixel. Normalized traffic density is defined in [37] for pixel j as

$$\frac{c_j}{\sum_{k=1}^{Na \times Nb} c_k} \tag{4-3}$$

The normalized traffic density is a simple approximation for representing the intensity of user traffic demand in a unit area. In addition, it indicates also the spatial difference of traffic demand across different pixels. In this study, users are dropped according to normalized traffic density based on collected data traffic. The following approach which is adapted from [37] is used to approximate user location

I) Each user has probability of $\frac{c_j}{\sum_{k=1}^{\mathrm{Na} \times \mathrm{Nb}} c_k}$ to be assigned to pixel j

II) For each user that is assigned to pixel j, uniformly generate a position within pixel j.

The location of each user will be used in computing the pathloss for the subsequent computations in WinProp.

4.2 Propagation Model and Cell Association

In the downlink performance analysis, it is important to have an accurate estimation of the link budgets between a base station and UE. To accurately estimate link budgets, a 3D ray-tracing tool is widely applied. Such a tool models the radio propagation at street level by considering realistic positions and heights of the buildings that are imported from the 3D building map. To further improve the accuracy of the propagation computation, the tools also consider topological terrain data.

In this study, the pathloss is evaluated using deterministic path model implemented in the WinProp propagation modeling tool [38]. The building penetration loss is assumed to be 20dB and in-building losses are approximated by an exponential decay model. The path loss predictions are available at a height of 1.5 m for user with pixel resolution of $5x5m^2$ that provides the right tradeoff between modeling accuracy and feasible computational time. Here the average received power is assumed to be constant within the whole pixel area.

From the above section, we have the knowledge of base station location, user distribution and propagation loss between base station and users. Now the received power can easily be obtained for each user from all cells (macro and small cells). The question of cell association with the user raises here. In traditional homogeneous macro networks, cell association is typically decided by the criterion of maximum downlink reference signal received power (RSRP). The user is usually connected to the base station with the maximum downlink received power.

In heterogeneous networks, however, due to large transmit power disparity between macro and small cells, the received signal power from small cells will be much less than that from macro cells, hence, the dominant portion of users will choose macro cells as their serving cells. Therefore, small cells will be under-utilized, and cell splitting gain will be reduced [39].

A more effective cell association strategy, termed cell range expansion, was proposed for heterogeneous networks [40]. In this strategy, the user will select its serving cell according to the following rule:

$$j = \text{argmax}\ \{RSRP(i) + BIAS(i)\} \tag{4-4}$$

where, j is the selected serving node, RSRP(i) is the downlink received signal from cell i and BIAS(i) is the predefined bias value for cell i, which is zero for macro cells, and is positive for small cells node. Clearly, the bias value can be used to control the number of users connected to small cells.

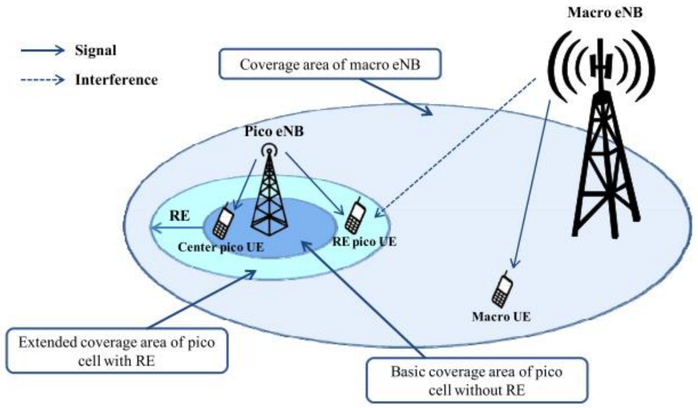


Figure 4-1 *Increased footprint of small cells with range expansion* [39]

4.3 Throughput Computation

Users are attached to the base station with cell association strategy mention earlier. Now the goal here is to discuss the throughput achieved by users.

The study area has a maximum of S predefined candidate small cell locations that are obtained using the earlier approach. Each candidate location represents a possible placement location for a small cell with transmit power P_{max}. Also, the study area has M macro sites leading a maximum of L=S+M base station. Let us assume that the pathloss is computed configuring small cell along with macro cell. Then RF propagation path loss matrix is represented by the matrix $\mathscr{L} \in R^{A\times L}$, whereby, $\mathscr{L}(a, l)$ represents the path loss between the a^th pixel and the l^th small or macro cell. The link loss is then utilized to calculate the user received signal power from each of the transmitting nodes. In the selection of serving cell, user received power from the macro cells and active small cells with some bias is considered. Active cells of the network are indicated using a vector x of size $N_M + N_S$. When k^th cell is active, x(k)=1. Otherwise x(k)=0. That is, x defines the network topology.

Received power of a user from k^th cell is computed as

$$P_k^{Rx} = P_k^{Tx} L_k^{SF} \, |h_k|^2 G_k / L_k(d_k) L^o \tag{4-5}$$

Where P_k^{Rx}, L_k^{SF} , h_k, G_k, $L_k(d_k)L^o$, and L^o refer to the transmit power, shadow fading, channel gain, antenna gain, average pathloss and other losses(e.g. cable loss) from k^th cell. Shadow fading is modeled with log-normal distribution.

By means of that, the average downlink SINR for the l^{th} user with respect to cell k is calculated as follows:

$$SINR_{lk} = P_k^{Rx} / \left(\sum_{s \in S_n} P_s^{Rx} + \sigma^2 \right) \tag{4-6}$$

where P_k is the full transmission power for cell k; S_n is a set of cells transmitting at full power Ps and interfering with cell k.

For each user, the achieved throughput (TP) is obtained by mapping the SINRs results using a modified Shannon formula [41].

$$TP = N_{PRB} BW_{PRB} min\left(S_{max}, BW_{eff} log_2 \left(1 + \frac{SINR}{SINR_{eff}} \right) \right) \tag{4-7}$$

where N_{PRB} is the number of PRBs, and BW_{PRB} is the bandwidth per PRB. Note also that S_{max} is the maximum spectral efficiency, $SINR_{min}$ is the minimum required SINR, BW_{eff} adjusts bandwidth to fit with LTE system bandwidth efficiency and $SINR_{eff}$ adjusts for the SINR implementation efficiency. When obtained SINR is less than required minimum SINR, throughput becomes zero.

4.4 Performance Metrics

As mentioned earlier, several spectrum scenarios are available for mobile operators to choose for when adopting small cells. To evaluate the network performance of different spectrum scenarios, it is important to define the KPI that must be considered and specify the performance targets to be achieved. For this study, the main metrics utilized, and their explanations are given below:

- Number of Base stations (f_1): Defines the number of outdoor LTE small cells in mobile networks. More base stations can provide more capacity and coverage; however, more base stations increase the costs of the network operators.

- Aggregate Capacity (f_2): Defines the total aggregate throughput in mobile networks.

- User in Outage(f_3): Defines the fraction of users that cannot be served with a predefined minimum data-rate. In [15], user in outage is defined as

$$f_3 = \frac{1}{N}\sum_{l=1}^{N} 1\{R_l < r_{min}\} \quad (4\text{-}8)$$

where R_l stands for the downlink average data rate experienced by the lth active user, and r_{min} is a predefined minimum required data rate.

For the sake of simplicity, only the downlink transmission will be addressed in this study. It is also assumed that for a given network traffic load, users download data according to a full buffer traffic model, implying that all users have infinite data to download.

4.5 Small cell Planning Approach

During cellular network dimensioning, the goal of network operators is to maximize capacity and coverage in a service area while minimizing the cost associated with it. In order to reduce costs, smaller number of base stations are deployed in service areas. In this study outdoor LTE small cell are used as base station for network densification. To achieve the dimensioning targets, candidate location has to be found using the earlier approach for small cell placement.

Given that we are deploying outdoor LTE small cells for selected area, the main objective here is to find the deployment locations such that the overall downlink network outage is decreased, or aggregate capacity is increased. So optimal small cells location or topology has to be selected from the available candidate places. Thus, optimization algorithm can be used to find the optimal location of base station.

In order to apply this approach, different network optimization formulations are considered. If the target of the small cell deployment is in favor of enhancing aggregate capacity, aggregate capacity is used in selection of optimal topology. On the other hand, user in outage (f3) may have priority in topology selection. Therefore, user in outage metric (f3) can be used in topology selection.

In this study, for each deployment solution the number of small cells is compared against achieved aggregate capacity or network outage. Therefore, network capacity metric (f2) or user in outage metric (f3) can be optimized with the number of base stations (f1). Obviously, there is a trade-off between those metrics.

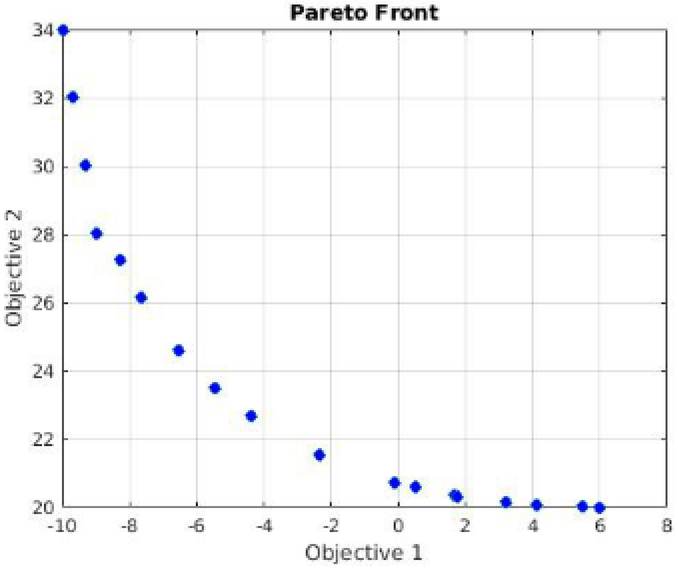


Figure 4-2 *An example of Pareto front*

This trade-off creates multidimensional optimization which is named as multi-objective optimization. Actually, the trade-off can be characterized by the Pareto front that refers the possible solutions for multi-objective optimization. In Figure 4-2, an example of the Pareto front is given with Objective 1 and objective 2. An increment in one of them causes a decrement in the other one.

In [18], multi-objective optimization problem formulation is proposed considering the trade-off between the number of base stations and aggregate capacity as follows:

$$minimize\ f = [f_1, -f_2] \tag{4-9}$$

Similarity, the number of base stations and user in outage can be found by the proposed formulation as follows:

$$minimize\ f = [f_1,\ f_3] \tag{4-10}$$

Both Eqn 4-9 and 4-10, the problem is categorized under NP-complete class (combinatorial optimization problems, proof of solution optimality is computationally infeasible). In this study search space of optimization is a set of $2^C - 1$, where C is the number of candidate locations in the service area. Even for the small number of the set, the search space can be huge. Moreover, search space is highly non-linear and full of discontinuities because of mathematical nature of (f2) and (f3).

4.6 Optimization Methodology

Several approaches are available in literature to solve the above optimization problem. For this study Non-dominated Sorting Genetic Algorithm II (NSGA-II) is used for multi-objective optimization.

4.6.1 Background on Genetic Algorithms

Evolutionary Algorithms (EAs) are the computational systems that mimic the efficient behavior of species and seek fast and robust solutions for complex optimization problems. They are stochastic algorithms and can be used to find out the approximate optimal solutions for NP-hard optimization problems.

GAs are the earliest EAs introduced by Holland in 1975 [42]. A genetic algorithm applies the biological principles of natural evolution in the artificial systems. In nature, weak and unfit species within their environment are faced with extinction by natural selection. The strong ones have greater opportunity to pass their genes to future generations via reproduction. In the long run, species carrying the correct combination in their genes become dominant in their population. Sometimes, during the slow process of evolution, random changes may occur in genes. If these changes provide additional advantages in the challenge for survival, new species evolve from the old ones. Unsuccessful changes are eliminated by natural selection.

NP-hard optimization problems can be solved using traditional optimization algorithms and GAs approaches. Traditional optimization algorithms such as gradient method require the function to be continuous and differentiable. In this approach the function is evaluated for every point in the search space leading to time complexity to find minima or maxima.

To minimize the time complexity associated with traditional optimization algorithms, GAs did not evaluate the function at each point. Instead, GAs applies population of selected points to provide near optimal solution thereby minimizing time complexity. The feature of population selection makes GAs to have parallel nature [43].

When searching for minima or maxima from the available search space, the algorithms transit from one point to another. Here the transition is based on deterministic rules in traditional algorithms. While using these rules, the search may finish by finding local extrema instead of global extrema that results in wrong solutions. In GAs, however, the transition is based on probabilistic rules that leads to near optimal solution.

Generally, GAs are widely used to solve engineering optimization problems that have complex nonlinearity and discrete nature [44]. Figure 4-3 presents flow of typical genetic algorithms. The procedure of GAs starts with a population of individuals generated randomly, known as initial population set. Each individual of the population represents a possible solution of the problem that is being analyzed. Individuals are encoded in an abstract representation known as a chromosome.

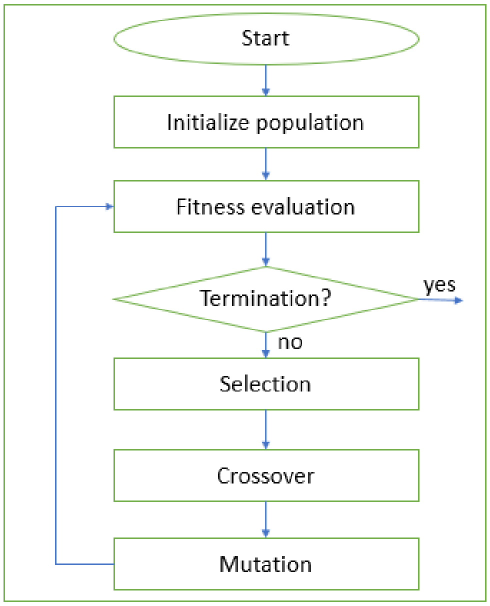


Figure 4-3 *A flow chart of typical genetic algorithm* [43]

There are many ways to encode a chromosome. Table 4-2 lists the most popular encoding ways proposed in recent literatures [44]. Among the various encoding schemes, binary encoding is the earliest encoding method and has been widely used in GAs, but it generates many chromosomes even for a problem with small search space and may not suitable for some optimization problems.

The evaluation sub-process defines a fitness function to evaluate the fitness of a solution. Fitness functions are corresponding to the objectives. They are the objective functions of optimization problems.

Table 4-2 *Mechanisms in selection, crossover, and mutation of GAs*

Process	**Mechanism**	**Description**
Initialization	Binary encoding	A solution is a bit string with each element as 0 or 1
	Value encoding	A solution is a string with elements integer, real numbers, characters, or objects
	Permutation encoding	A solution is a sequence of numbers
	Tree encoding	A chromosome is a tree form of objects
Selection	Relative tournament	Two members are randomly chosen, and parent is the one with higher fitness
	Roulette wheel	The probability an individual to be chosen as parent is depends on their fitness
	Relative pooling tournament	Population are thrown into a competition, and the winners are the parents
	Elitism	Population with the higher fitness from all the population generated so far form parents
Crossover	One-point	Randomly generate a cross over point
	Two-point	Randomly generate two crossover point
	Uniform	Use a fixed mixing ratio between two point
	Cut and spice	Allow each point to have its own choice in deciding crossover points
	Ordered chromosome	Switch the positions of genes
Mutation	Bit-string	Randomly flip the value of genes
	Flip bit	Flip the value of selective genes
	Boundary	Replace the value of a gene with the upper or lower bound of the value
	Gaussian	Add a unit gaussian distribution random value to the selected chromosome
	Uniform	Replace the value of a selected gene with a uniform random value with the user specified bounds

A fitness function provides a mechanism to evaluate the solutions of a problem. Since the fitness function is utilized by each population to evaluate its fitness at each iteration, carefully designing the fitness function can reduce the convergence time of a GA and hence improve the performance of a GA [42]. If the fitness function passes the termination criteria, the next step is parent selection.

Selection is used to form a parent set to feed into crossover and mutation functions. A selection function is carried out in a particular way to select the members with higher fitness value to form a parent set for later crossover and mutation. Different selection approaches may require different methods to generate and assign probability to make sure the diversity and the improvement of the new populations.

As listed in Table 4-2, the typical selection mechanisms used in current GAs include: 1) relative tournament evaluation; 2) roulette wheel selection; 3) relative pooling tournament evaluation; and 4) elitism.

Crossover subprocess generates a child by mixing the genes of two parents. crossover operation exploits the best traits of the current chromosomes, and strong chromosomes are more likely to be selected as parents. As listed in Table 1, the typical crossover methods consist of: 1) one-point crossover; 2) two-point crossover; 3) uniform crossover; 4) cut and splice; and 5) ordered chromosome crossover.

As mentioned before individual with strong chromosome (higher fitness value) are more likely to be selected as parent and, hence there is a big chance that the new chromosomes may become similar after several generations. As a result of this the diversity of the population may decline and lead to population stagnation. To inject diversity into the population and avoid the population stagnation, mutation operation explores chromosomes to discover new traits. The mutation subprocess generates a child by randomly changing some of the genes in chromosomes. The typical mutation methods used in GAs consists of 1) bit-string mutation; 2) flip bit; 3) boundary; 4) uniform; and 5) Gaussian, as shown in Table 4-2.

While applying GAs to solve optimization problem due consideration has to be given for parameter such as population size, generation, crossover and mutation etc. Population size, for example, has to be set considering the trade-off between computational complexity and premature convergence of GAs. Moreover, crossover and mutation operation parameters have to be selected in a way to keep randomness of the population.

GAs has been applied in various research works in telecommunication engineering for optimization coverage, Qos, and energy to name a few. In [45], the performance of deploying small cell in realistic urban area is investigated with metric of energy efficient and converged target. The authors applied genetic algorithm to find the best set of locations and transmission power parameters. In doing so, the 12.0% improvement in energy efficient and 15.2% in coverage ratio was achieved. Authors in [46] investigated the potential of deploying indoor small cell in mmW (28GHz) with metric such as aggregate capacity, cell edge and energy. For optimal placement of indoor small cell, multi-objective genetic algorithm is formulated. Based on aggregate capacity 54% gain is obtained by deploying indoor small cells in 28GHz as compared to 2.6GHz. The authors concluded that mmW are a very attractive alternative for indoor deployments. In [47], the authors investigated the approaches of using multi-objective optimization for small cell planning in unlicensed band(5GHz) as instead of the traditional iterative approaches of planning. Accordingly, result shows that significant performance gain is achieved with multi-objective approach as compared to random deployment.

Several GA based multi-objective algorithms are available in the literatures. Some of these includes such as Multi-objective Genetic Algorithm (MOGA), Non-dominated Sorting Genetic Algorithm (NSGA) and NSGA-II, and Pareto-Archived Evolution Strategy (PAES). The central concept in multi objective algorithms is finding pareto optimal solution for the given optimization problem. In the next sections, NSGA and NSGA-II are introduced.

4.6.2 Non-dominated Sorting Genetic Algorithms (NSGA)

NSGA is a type of multi-objective optimization algorithm that is based on GAs. The main feature that differentiate NSGA from other is parent selection process. First fitness value is evaluated for each initial solution. The first step of an NSGA is to sort the population P according to non-domination. After the non-dominated sorting, the population members are classified into non-dominated sets (front). Any two members from the same front cannot be said to be better than one another with respect to all objectives. Then, using the fitness values, sorting is carried out to find different pareto fronts of non-dominated sets. For each front dummy fitness value, usually equal to population size, is assigned. Here individual solution in each front are assigned the same dummy fitness value. In GAs, diversity is the main criteria to minimize premature convergence of the solution. So, to maintain diversity in the population, the concept of fitness sharing is applied. Based on fitness value that is assigned for each solution after fitness sharing, parent selection is done. Thereafter, operation of crossover and mutation undergone to create next generation. This process repeat until the iteration is finished or optimal solution obtained [48].

Although NSGA is effective in the assignment of fitness according to non- dominated sets, there are some disadvantage associated with NSGA. The first disadvantage of NSGA is high computational complexity of nondominated sorting. The currently used nondominated sorting algorithm has a computational complexity of $O(MN^3)$ (where is M the number of objectives and N is the population size). This makes NSGA computationally expensive for large population sizes. This large complexity arises because of the complexity involved in the nondominated sorting procedure in every generation. The second disadvantage is lack of elitism. With elitism, it is possible to prevent the loss of good solutions once they are found. The third is the need of specifying the fitness sharing parameter to maintain diversity in the population. Traditional mechanisms of ensuring diversity in a population so as to get a wide variety of equivalent solutions have relied mostly on the concept of sharing. The main problem with this approach is that it requires the specification of a sharing parameter. In other words, diversity is dependent on the specified sharing parameter.

4.6.3 Fast Non-dominated Sorting Genetic Algorithms (NSGA II)

To improve the performance of NSGA, author in [49] proposed fast Non-dominated sorting genetic algorithms(NSGA II). NSGA II address the criticism of NSGA. Figure 4-4 illustrates the procedure of NSGA II. In the beginning, a random parent population Pt is created. The population is sorted based on the nondomination. Each solution is assigned a fitness value equal to its nondomination level. At first, the usual binary tournament selection, crossover, and mutation operators are used to create offspring population Q_t of size N. Then, the two populations are combined together to form R_t, of size 2N. Instead of making nondominated sorting on offspring population Q_t, as it was the case in NSGA, nondominated sorting is done in R_t and the solutions are assigned to different fronts. Since all previous and current population members are included in

R_t, elitism is ensured. Obviously, P_{t+1} accommodate N solution. Solution in each front are added to P_{t+1} in descending order of fitness value as long as P_{t+1} is less than N.

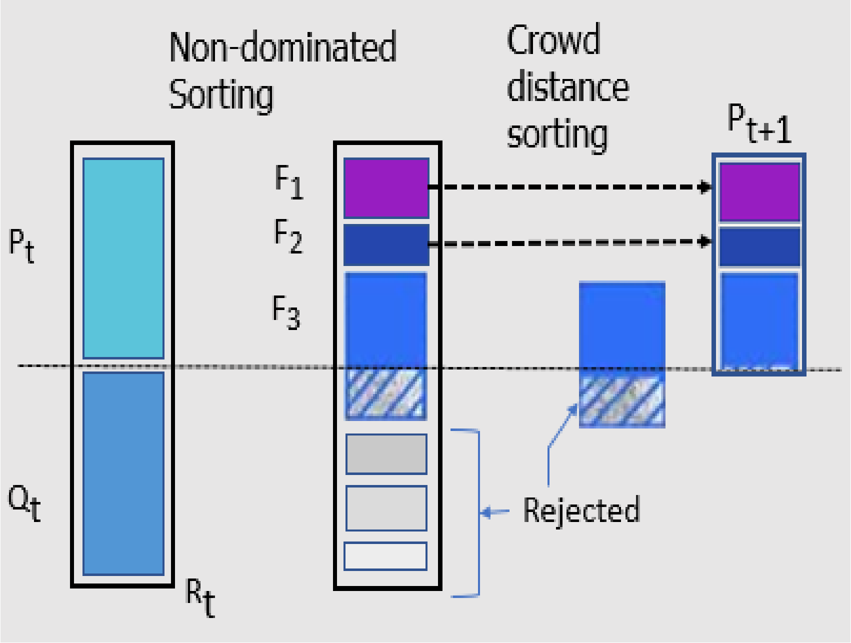


Figure 4-4 *NSGA II procedure* [49]

If P_{t+1} could not accommodate all the solution of front i, for example, then crowding distance sorting on the solutions of front i is performed. With crowd distance sorting, some solutions in front i are rejected. To obtain Q_{t+1}, crowded tournament selection, crossover and mutation operations are performed on P_{t+1}. This procedure repeat until optimal solution are achieved or the iteration is finished.

5 Simulation Result and Discussion

5.1 Study Area Description

This study is based on data from realistic environment in Addis ababa. Investigation area that typically represent Addis Ababa city scenario is selected with reasonable approach in order to obtain reliable conclusions. In the selection of target investigation area for this study, base station data traffic as well as morphology are taken into consideration.

With one-week Addis Ababa city ethio telecom network performance data, base stations that carry high traffic are identified. To observe the nature of base station traffic spatially, MapInfo tool is utilized. Base stations that carry high data traffic are geographically located in close proximity. With base station spatial traffic distribution, we can able to zoom the study area to a specific location. Now considering the morphology, a study area covering 2km by 2km is selected in dense urban area. The rationale behind limiting the study area to 4km^2 is to reduce the complexity that may arise during computation.

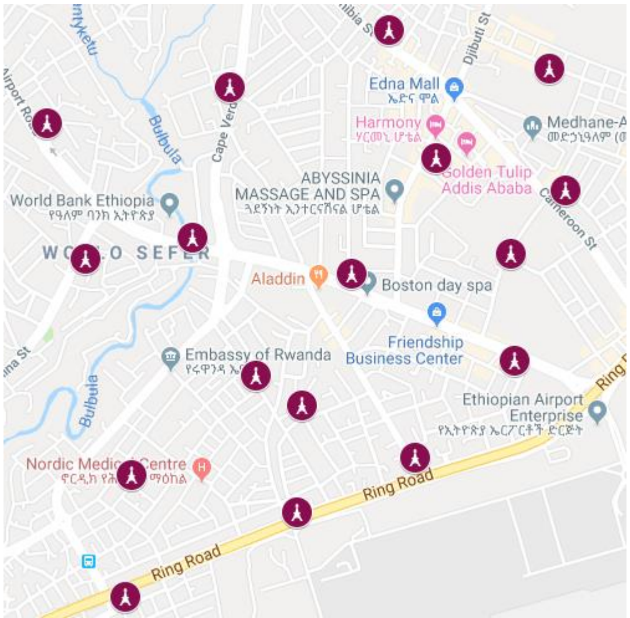


Figure 5-1 *Existing sites in the selected study area*

The selected area is located in Bole sub-city near Bole International Airport and it is largely covered by shopping malls, restaurants, and entertainment malls and residential area. The study area has 17 macro sites – each equipped with 3 sectors meaning a total number of 51 sectors. Figure 5-1 presents the location of the existing site in the study area.

For each base station in the study area, busy hour has been identified. Based on busy hour information the spatial traffic distribution is obtained from Network Monitoring Tool. Traffic data obtained from Network Monitoring Tool has a pixel size of 50mx50m.This pixel traffic is distributed spatially using MapInfo to see the nature of the traffic. Figure 5-2 shows the intensity map of the spatial traffic density over the study area.

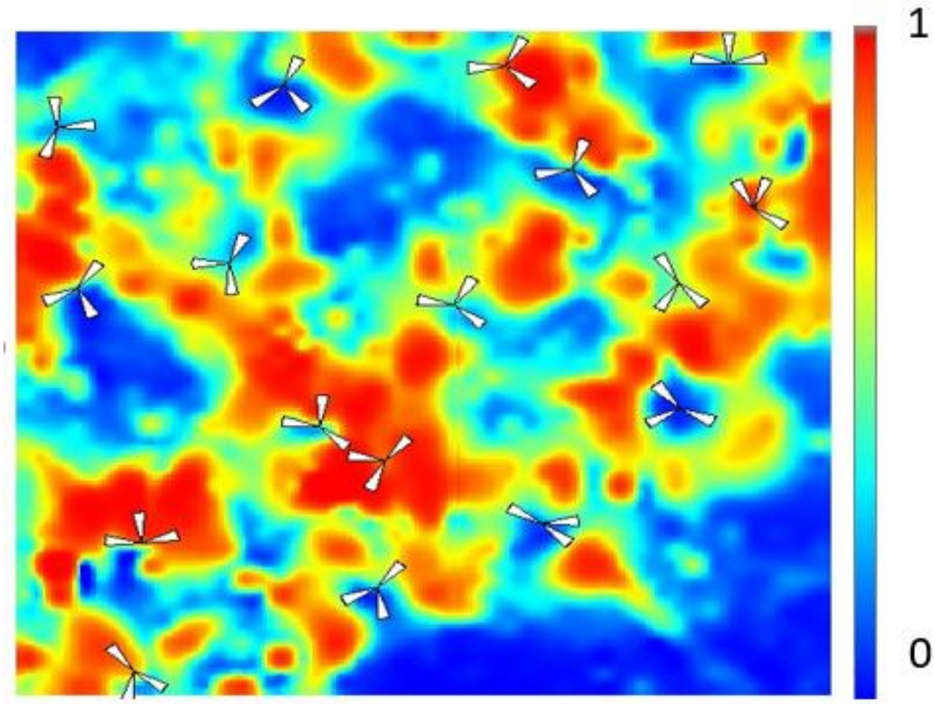


Figure 5-2 *Traffic map showing non-uniform traffic distribution*

Traffic distribution in the study area is showing non-uniform meaning traffic per unit area is different for each pixel resolution of 50m. Instead of assuming uniform user distribution while generating user location during simulation, utilizing the traffic intensity map obtained from Network Monitoring Tool provides more accurate results. Figure 5-3 shows generated user location for a single snapshot.

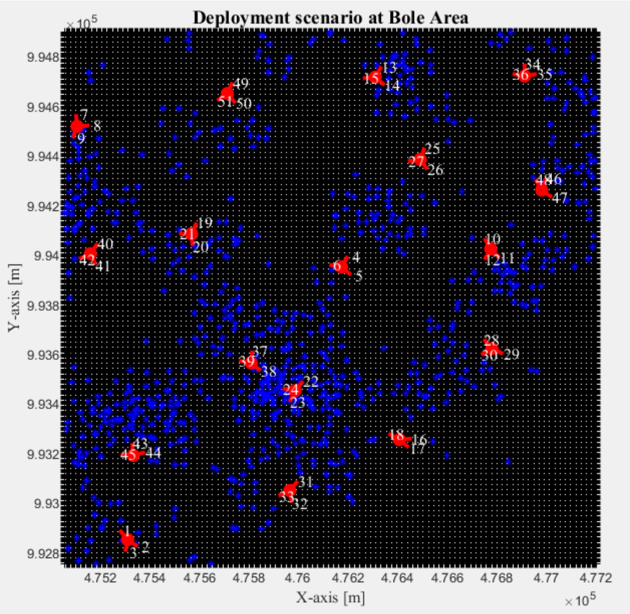


Figure 5-3 *User location(blue dot) in study area with base station (red).*

Table 5-1 *Existing macro sites performance*

Number of cells	Aggregate capacity	10th percentile	50th percentile	90th percentile
51	0.98Gbps	110Kbps	615Kbps	2.78Mbps

5.2 Simulation Approaches, Parameters and Assumptions

5.2.1 Simulation Approaches

Now investigation area and base station serving the area are identified, and user distribution are generated according to the traffic intensity map, we are in a position to import relevant parameters of the study area to simulation environment. For this study, MatLab based LTE static system level simulator is utilized. The main input data to LTE static level simulator are propagation environment, also called pathloss data and spatial traffic distribution data. Propagation environment (pathloss data) is computed with WinProp. To do so, relevant data such as digital building map and terrain has to be imported. Following, properly configure parameters for macro and small cells. Figure 5-4 illustrates the configured macro and small cells along with building and terrain data. After setting the parameters in WinProp, we run propagation computation to get pathloss data in text format. The obtained pathloss data from WinProp is not suitable to be supplied to LTE Simulator.So, the pathloss data is converted into the format that LTE simulator can accept.

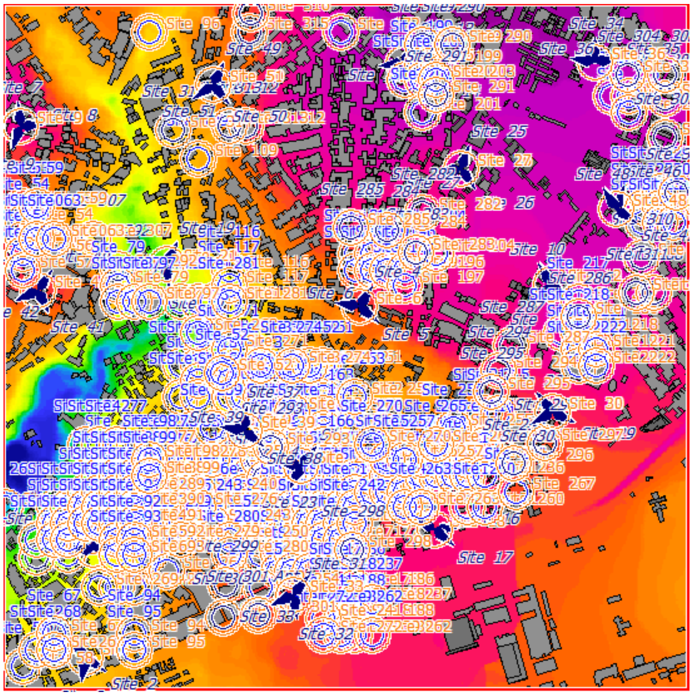


Figure 5-4 Candidate locations along with macro cells in WinProp

From pathloss data, LTE system level simulator extracts cell location information, transmit power, antenna location and pathloss for each pixel from each site. Block diagram representation of static system level simulator is presented in Figure 5-5. Once the inputs are provided to LTE system level simulator, throughput and SINR achieved by users is obtained by with the approached discussed in Section 4.3.

For optimization of small cells MatLab based NSGA II is employed. It searches the optimal location of small cells from the available small cell candidate location by favoring particular performance metric. In this study NSGA II starts with initial population of 100. This population represents the different topologies of small cells. While searching for optimal topology NSGA II requires fitness value for each topology. Accordingly, system level simulator evaluates the fitness value for each topology. Searching for optimal topology ends when termination criteria of the genetic algorithm is met. Figure 6-5 presents simulation flow.

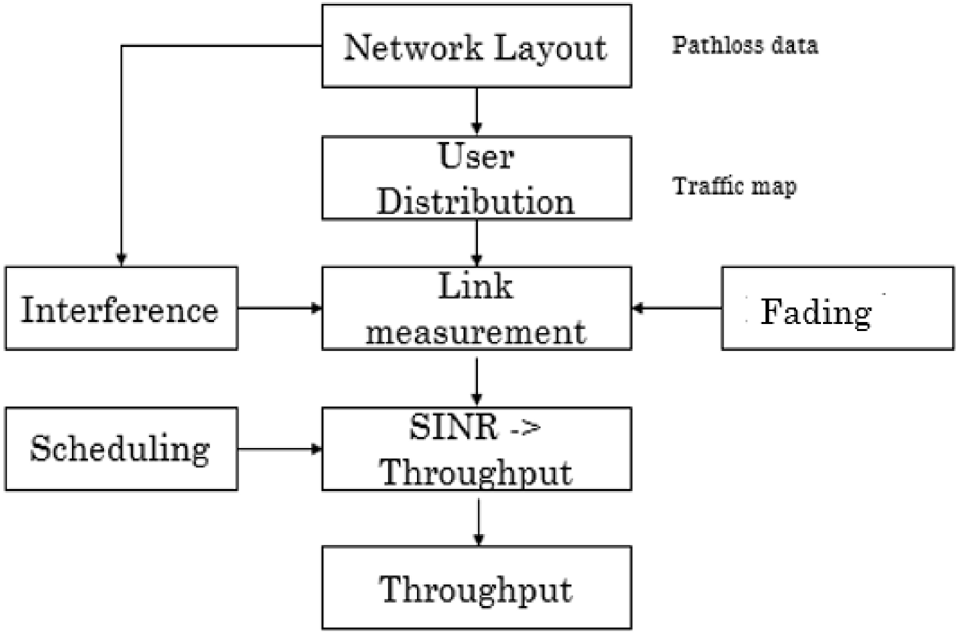


Figure 5-5 *System level simulator block diagram*

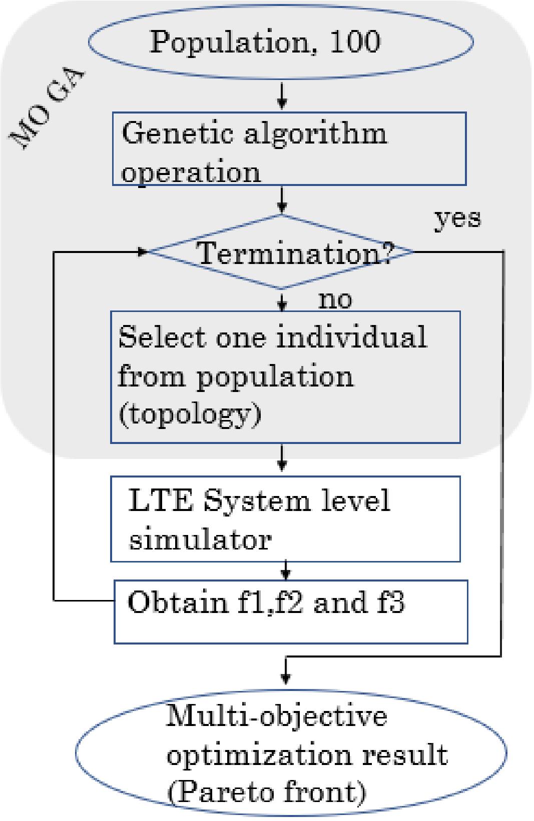


Figure 5-6 *Simulation flow*

5.2.2 Simulation Parameters and Assumptions

The main simulation parameters related to macro and small cell configuration and network scenario is summarized in Table 5-1

Table 5-2 *Simulation parameters*

Parameter	**Values/Assumptions**	
Deployment Scenario	Outdoor small cells deployment with overlaid macro network	
Carrier Freq./ Bandwidths	According to formulated spectrum scenario	
Simulations	Radio propagation modeling (WinProp)[38], MO and static system level simulator (MatLab), 5 m resolution	
SINR-throughput mapping	SINRmin (dB)	-10
	BWef	0.6
	SINRef	1.8
Macro Cells Parameters		
Transmit Power	46dBm	
Antenna Location/Height	Realistic ethio telecom scenario	
Antenna Patterns	Kathrein 742215	
Small Cells Parameters		
SC candidate location/Height	241 SCs, located using 'site suitability function' and deployed at height of 10m	
SC downlink	Omni antenna, 33 dBm transmit power	
UE Parameters		
UE number	850	
UE Location	UEs dropped in according to traffic intensity map.	
UE Noise Figure	9dB	
Buildings, Fading and Scheduling Characteristics		
Shadow Fading	Log-normal with standard deviation of 8 dB and decorrelation distance 50 m	
Buildings	Penetration loss: 20 dB	
Cell association	Cell association: based on RSRP with 6dB cell selection bias for small cells	
Scheduling	Round robin scheduling	

5.3 Performance Results and Discussion

This section presents performance evaluation of the different spectrum scenario in small cell deployment under realistic LTE environment in Addis Ababa. To obtain optimal topology, the metrics defined Section 4-4 are applied. For this case study aggregate capacity oriented and user outage-oriented topologies are obtained. In the subsequent sections a discussion is made on the results of each topology.

5.3.1 Capacity Oriented Topology

In this subsection small cells deployment performance is evaluated by highlighting two essential metrics: the achieved aggregate capacity and the number of deployed small cells or the sensitivity to small cell density. The pareto front for aggregate capacity against number of small cells illustrated in Figure 5-7.

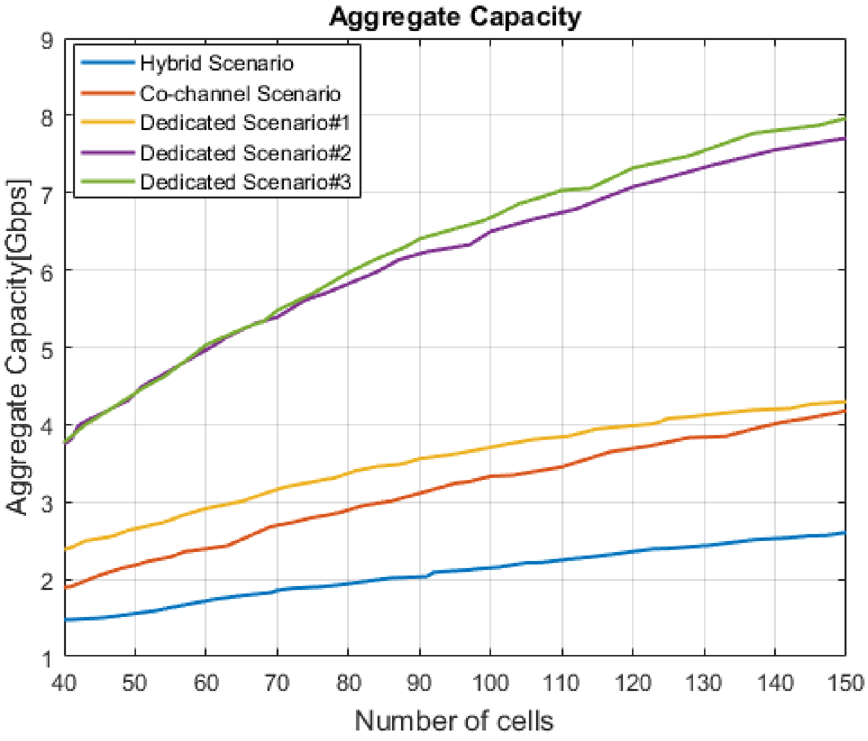


Figure 5-7 *Aggregate capacity performance of optimized topologies*

For all investigated scenario the aggregate capacity increases as the number deployed small cells increases with varying increment rate. For Dedicated Scenario #1, for instance, the increment in aggregate capacity for low small cell density is greater than high small cell density. On the other hand, for cochannel deployment scenario, the aggregate capacity increases linearly without flattening out for higher small cell densities. The difference in capacity increment rate is due to varying cell splitting gain of each scenarios. From all investigated spectrum scenario, Dedicated Scenario #3 outperforms all other spectrum scenarios in achieved aggregate capacity if more than 70 small cells are deployed. It can be observed that spectrum scenario with larger total bandwidth achieved larger aggregate capacity. For three small cell per sector deployment, the aggregate capacity achieved are 0.66, 1.03, 1.08, 1.96 and 1.99 Gbps per square km in hybrid, cochannel deployment, Dedicated Scenario #1, Dedicated Scenario #2 and Dedicated Scenario #3 respectively.

The efficiency of spectrum bandwidth utilization can be measured by considering the achieved aggregate capacity of the scenario per Hertz per unit square kilo meter (Area Spectral Efficiency). Accordingly, efficient utilization of available spectrum scenarios varies according to deployed small cell density. For relatively higher number of small cell density, cochannel deployment outperforms all other scenarios. Figure 5-8 illustrate area spectral efficiency for each scenario.

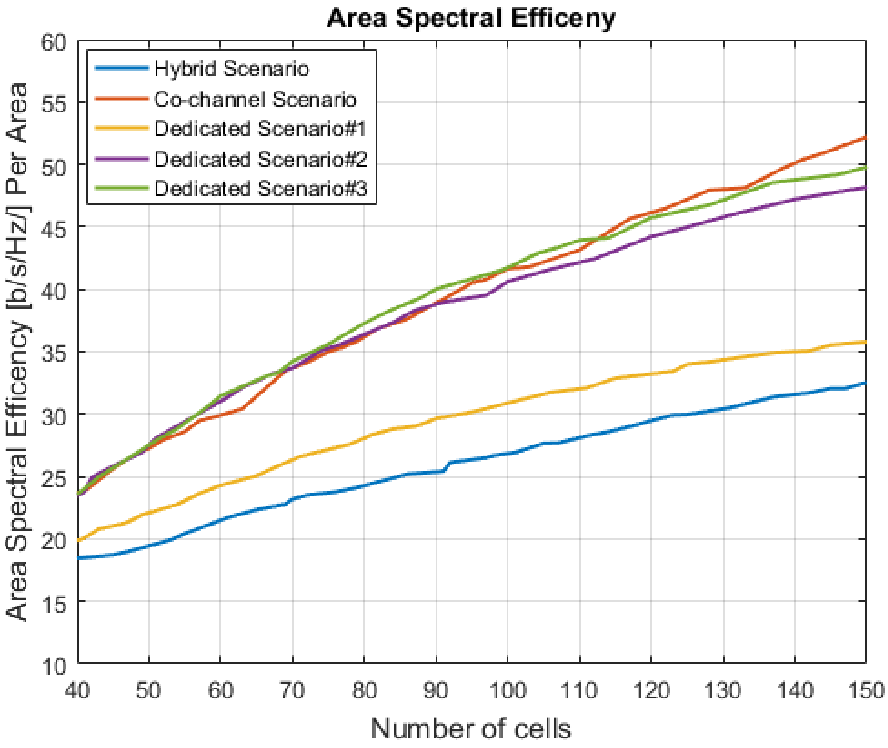


Figure 5-8 *Area spectral efficiency of optimized topologies*

When mobile network operator upgrades the existing network capacity with small cell deployment, the required number of small cells vary according to the implemented spectrum scenario. If the operator wants to upgrade network capacity, for instance, 4 times (aggregate capacity of 3.95Gbps) from the reference macro only scenario, the required number of small cells are 138, 117, 42 and 42 cochannel deployment, Dedicated Scenario #1, Dedicated Scenario #2 and Dedicated Scenario #3 respectively. Here, a total of 96 and 75 small cells are saved by deploying small cell in Dedicated Scenario #2 and #3 instead of cochannel deployment and Dedicated Scenario #1 deployment respectively. As the cost of network upgrade with small cell deployment is proportional to the deployed small cell number, it means that 78.57% (Dedicated scenario #1) and 128.57% (cochannel) cost saving will be achieved from cochannel deployment and Dedicated Scenario #1 respectively as compared to Dedicated Scenario #2 and #3. The performance gain achieved by Dedicated Scenario #2 and #3 are obtained at the cost of additional bandwidth.

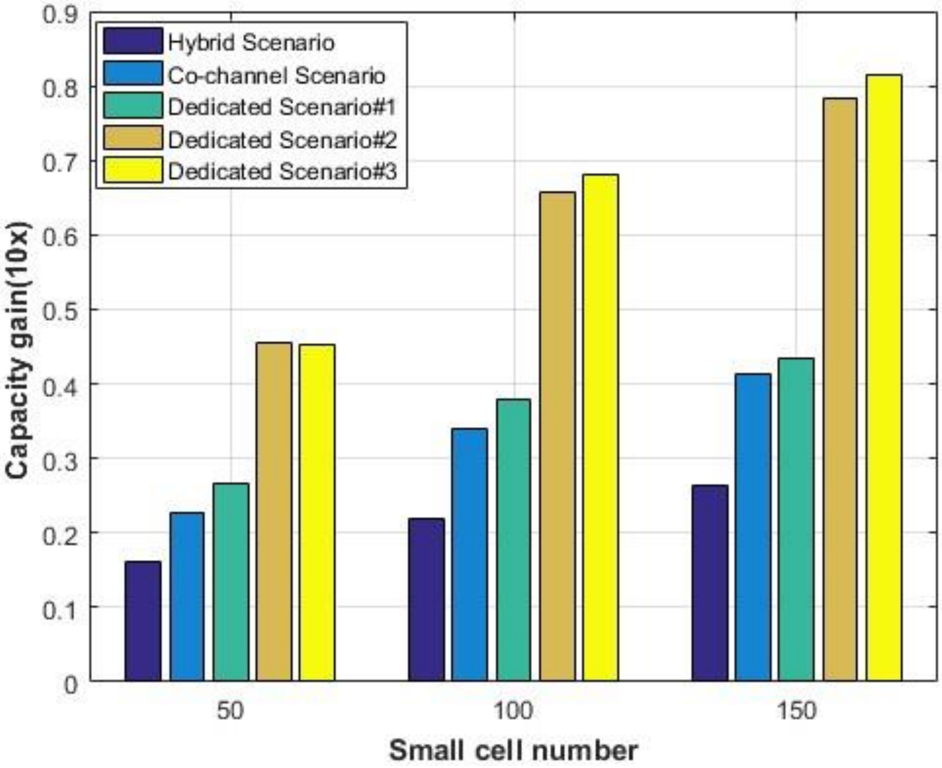


Figure 5-9 *Aggregate capacity gain for different small cell density*

When the operator decides to deploy fixed number of small cells, the achieved performance gain in terms of aggregate capacity vary according to the deployed small cell number (small density). To make performance gain analysis, deployment scenario with small cell number 50,100 and 150 are chosen to refer different small cell densities. In Figure 5-9, detail performance gain of each scenario is presented.

For 100 small cell deployment (two small cells per sector), capacity gain of 2.18, 3.38, 3.79, 6.58 and 6.80 times macro only scenario is achieved for hybrid, cochannel deployment, Dedicated Scenario #1, Dedicated Scenario #2 and Dedicated Scenario #3 respectively. With varying small cell density aggregate capacity gain difference between spectrum scenario will either increase or decrease. The capacity gain difference between Dedicated Scenario #2 and Dedicated Scenario #3, for instance increased with small cell density. Therefore, the achieved aggregate capacity difference between spectrum scenario is sensitive to small cell density.

Based on aggregate capacity, the performance of different spectrum scenarios is analyzed above for different small cell densities and an insight is being found on network performance. Obviously, relying on aggregate capacity only does not give us full picture of the network performance.

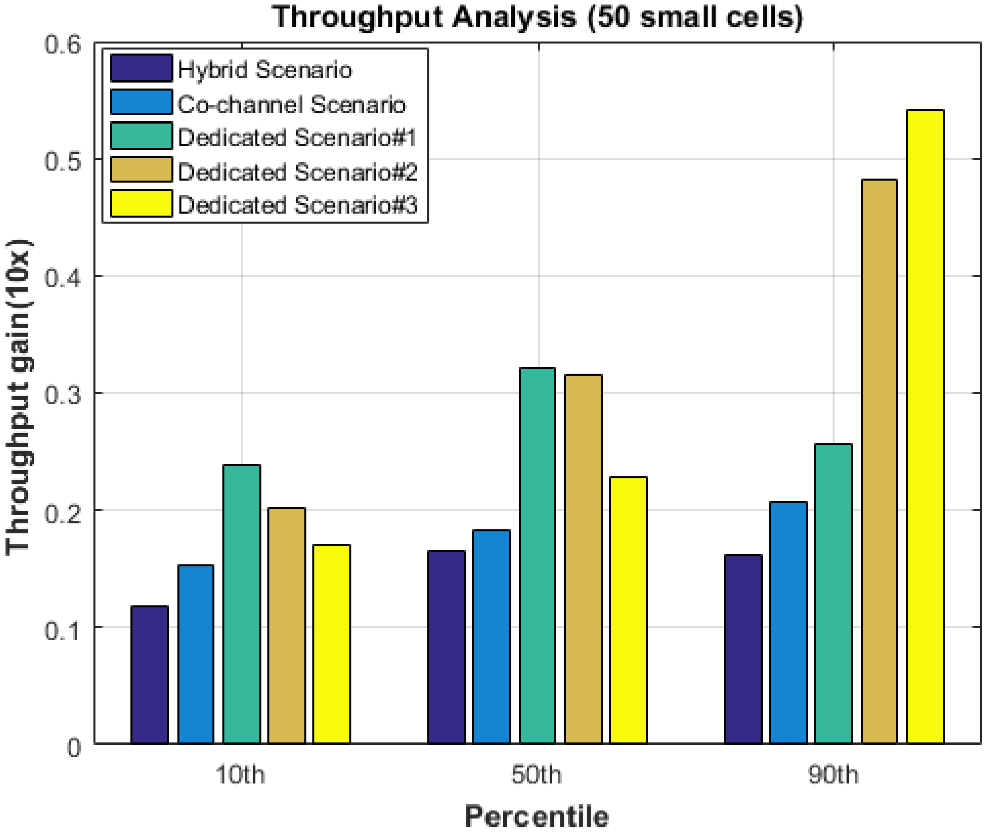


Figure 5-10 *User throughput for capacity-oriented 50 small cells deployment*

In order to have a better knowledge on the performance of the network, achieved user throughput are evaluated with respect to different small cell deployment density. User throughput analysis indicate the achieved throughput for cell edge, median and peak user. User throughput performance for each spectrum scenario is presented in Figures 5-10 and 5-13.

Again, compared with macro only scenario, median (50%-ile) user throughput increases 1.66, 1.82, 3.31, 3.16 and 2.28 times for deployment scenarios hybrid, cochannel deployment, Dedicated Scenario #1, Dedicated Scenario #2 and Dedicated Scenario #3 respectively when the network is upgraded with small density of 1 small cell per sector (50 small cells). With 1 small cell per sector deployment Dedicated Scenario #1 outperforms other deployment scenarios in terms cell edge and median user throughput although limited resource(10MHz) is assigned to small cells. Such performance achievement can be explained with the better SINR conditions experienced by users. Dedicated Scenario #1 outperforms all other scenario in terms of achieved user SINRs. Figure 5-11 presented the achieved SINR for 50 small cell deployment.

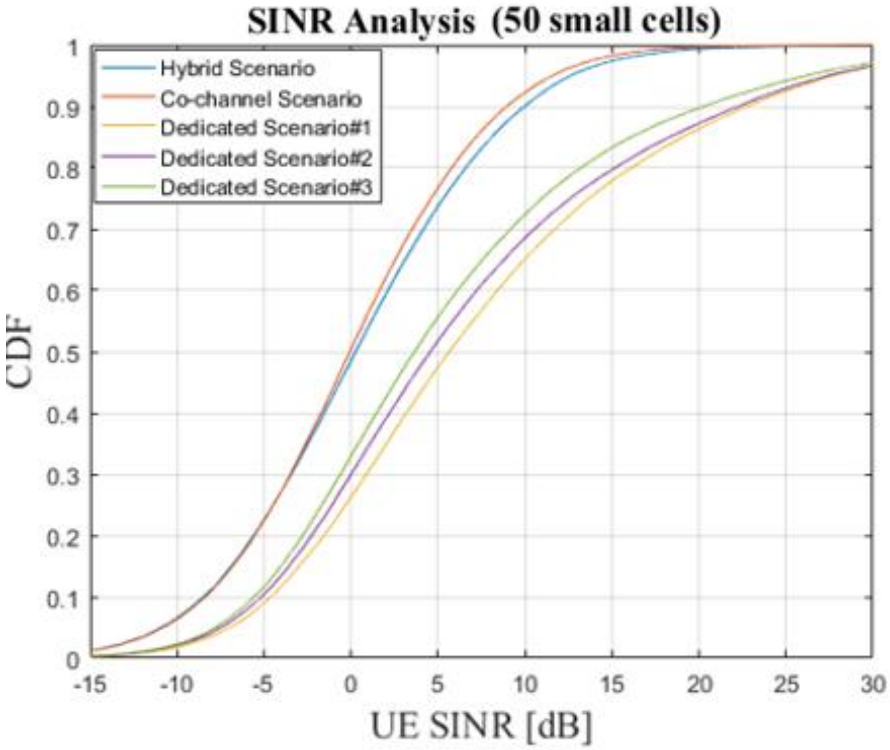


Figure 5-11 *SINR performance for capacity-oriented topology*

In terms of peak user throughput, however, Dedicated Scenario #3 outperforms other deployment scenario as more resource (20Mhz) are assigned to small cells. To know the whereabout of small cell, 50 optimal location are selected from 241 candidate location.

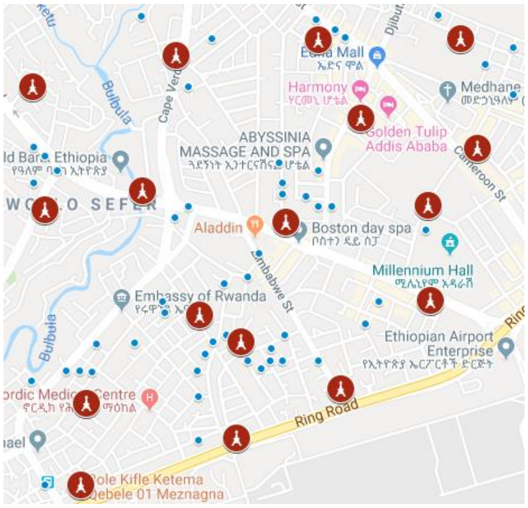


Figure 5-12 *Optimized topology for 50 small cells deployment*

When compared to the spatial traffic density in Figure 5-2, optimal topology for 50 small cells is consistent with the areas of highest traffic density. Here in this case, the obtained optimal small cell locations are not limited to main street only.

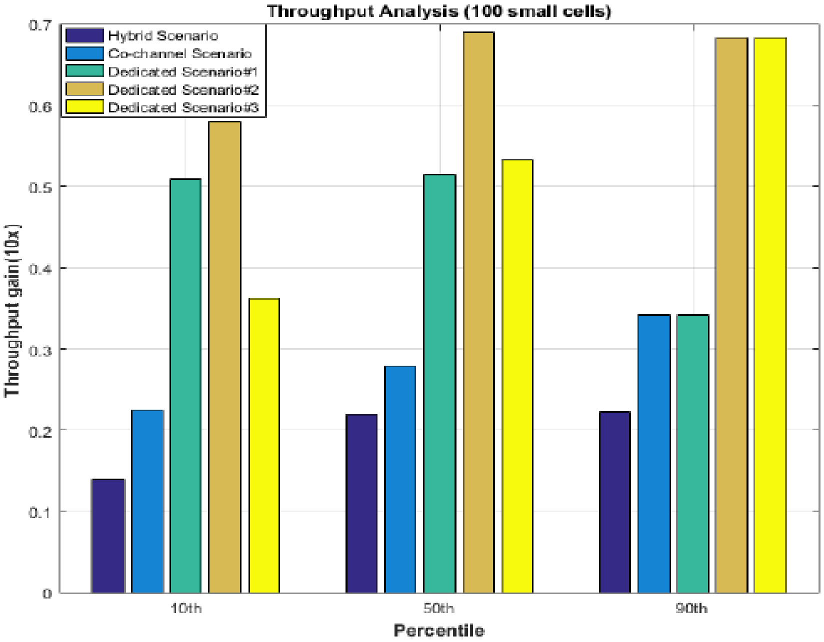


Figure 5-13 *User throughput performance for 100 small cell deployments*

When the network is upgraded with small cell density of two small cells per sector (100 small cells), median (50%-ile) user throughput increases 2.19, 2.79, 5.14, 6.90 and 5.32 times for deployment scenarios hybrid, cochannel deployment, Dedicated Scenario #1, Dedicated Scenario #2 and Dedicated Scenario #3 respectively compared with macro only scenario.

With 2 small cells per sector deployment Dedicated Scenario #2 outperforms other deployment scenarios in terms of cell edge and median user throughput. Dedicated Scenario #3 achieves better median user throughput next to Dedicated Scenario #2. It be observed that varying small cell density impacts user throughput for each spectrum scenario. In summary, user throughput performance in each spectrum scenario is sensitive to deployed small cell density.

5.3.2 UE Outage Oriented Topology

In this section, performance evaluation for spectrum scenario is discussed based on UE outage rate and number of deployed small cells. The obtained pareto front for outage rate against number of small cells illustrated in Figure 5-14.

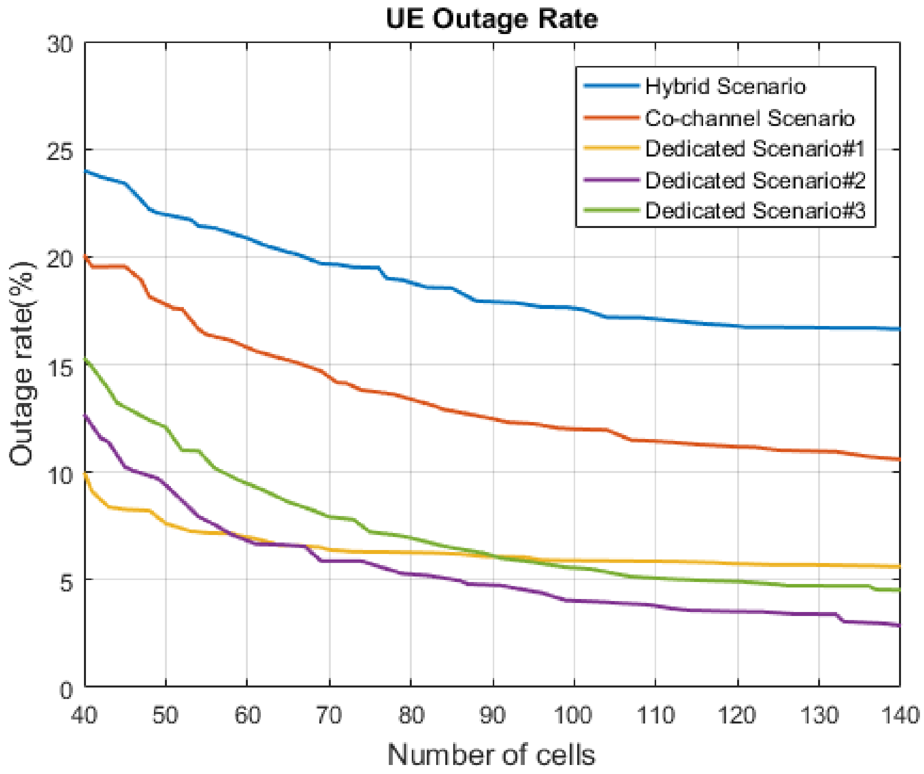


Figure 5-14 *UE outage rate against small cell number*

For all investigated spectrum scenarios, UE outage rate decreases as the number of deployed small cell increase. The rate of decrement varies along with small cell density for each scenario. UE outage rate in Dedicated Scenario #1, for instance, decreases as small cell density increase for around one small cell per sector deployment and it saturate around 6% after 2 small cell per sector deployments (100 small cells). In Dedicated Scenario #3, on the other hand, UE outage rate decreases with increase in small cell density that is to mean it is more sensitive to small cell density.

At around 1 small cell per sector deployment (50 small cells) density Dedicated Scenario #1 outperforms other spectrum scenarios. Dedicated Scenario#2 outperforms others spectrum scenario at around 2 small cell per sector deployment density. Dedicated Scenario #3 performs better than Dedicated Scenario #1 for two small cell per sector deployment.

Analysis considering outage rate only provides insight limited to cell edge user only. So, with in-depth analysis the achieved user throughput we can get full picture of the performance of each spectrum scenario. In this regard, user performance for 50 and 100 small cells deployment are selected.

User throughput performance for one small cell per sector deployment is shown in Figure 5-15. In terms of median (50%-ile) user throughput dedicated scenario#2 outperforms all other scenario. Here, dedicated scenario#1 outperforms dedicated scenario#3 although dedicated scenario#1 has less spectrum bandwidth than dedicated scenario#3. Such performance gain can be explained using achieved SINR similar to above case. Figure 5-16 illustrated the SINR analysis for one small cell per sector deployment. Dedicated scenario#1 achieved better performance than all other scenarios in terms of user SINR. Best median (50%-ile) user throughput with dedicated scenario #2 is obtained at the cost of bandwidth (more spectrum resource). Significant SINR performance difference is observed between dedicated scenario#1 and dedicated scenario#3. Such disparity directly impacts the achieved user median throughput.

For two small cell per sector deployment (100 small cells), dedicated scenario#2 outperforms other scenarios both in cell edge and median user throughput. Figure 5-17 illustrated the User throughput performance for two small cells per sector deployment. A compared to capacity oriented small planning approach, outage driven deployment results in better user throughput performance both in cell edge and median user throughput.

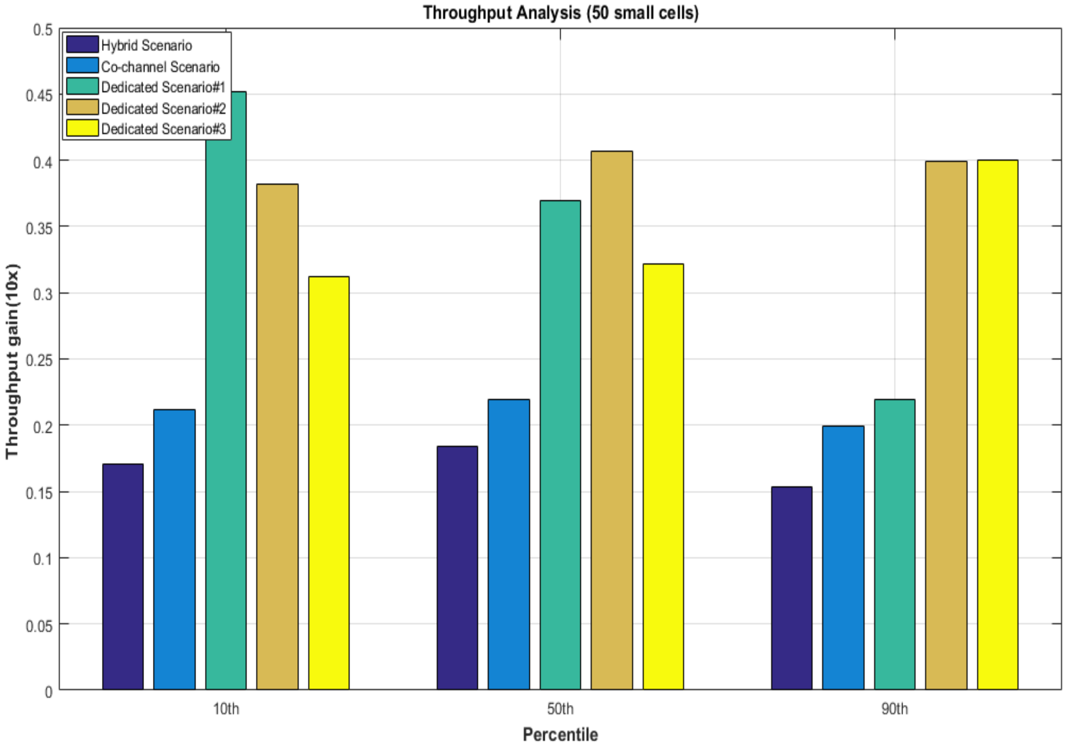


Figure 5-15 *User throughput for outage oriented 50 small cells deployment*

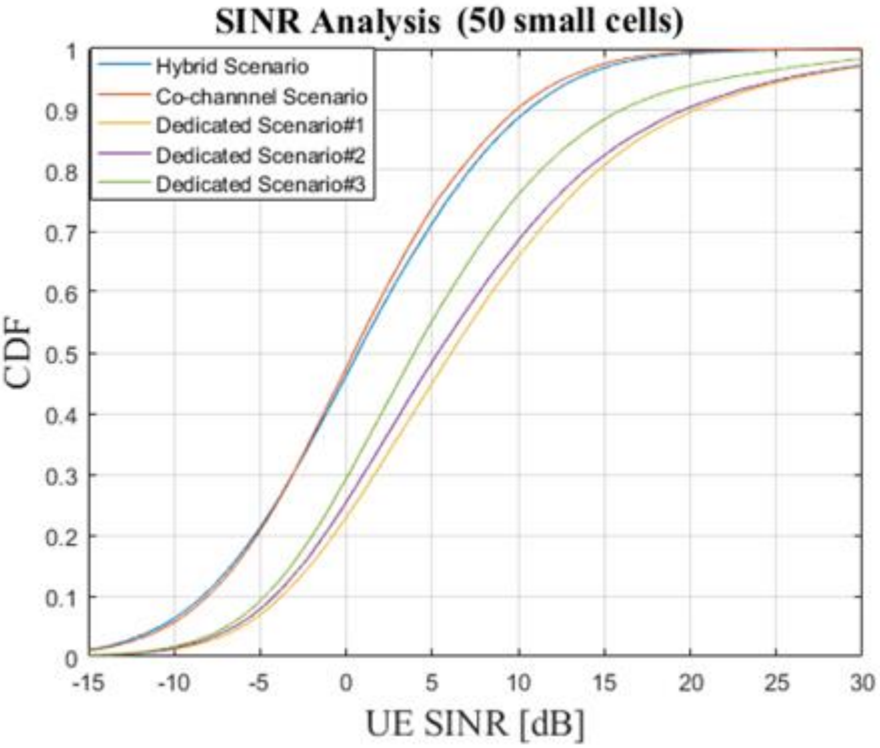


***Figure 5-16** SINR performance for outage-oriented topology*

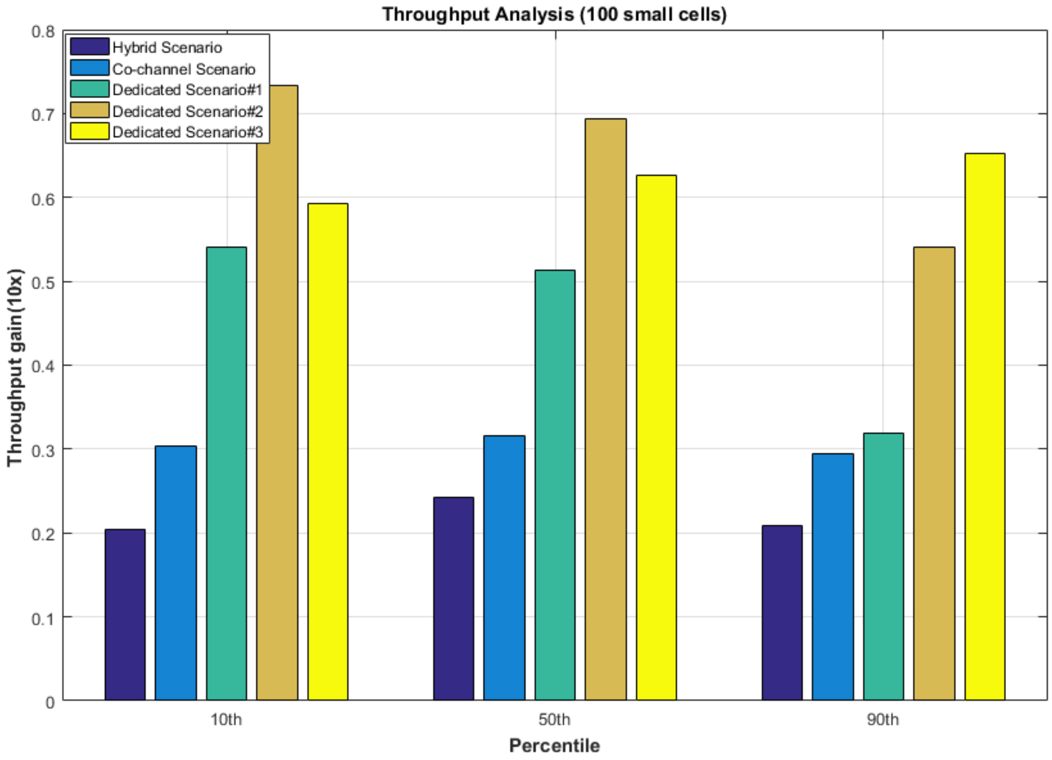


***Figure 5-17** User throughput for outage oriented 100 small cells deployment*

To achieve 5% UE outage rate target, 85 and 110 small cells are required for Dedicated Scenario #2 and #3 respectively. For the dedicated scenario#1, cochannel and hybrid scenarios even 140 small cell deployment is no sufficient to bring the outage to 5% target.

6 Conclusion and Future Works

6.1 Conclusion

Mobile network operators are experiencing exponential data growth explosion due to high penetration of smart devices and data intensive applications. Besides data traffic growth, mobile network operators are being challenged by the requirement of high data rate with reliable quality of service and uniform user experience when delivering data service. To accommodate the traffic growth and address the new challenges, a new approach called HetNet is being followed.

Exponential data growth is witnessed in Addis Ababa city. When small cells are deployed to accommodate exponentially growing traffic, variety of spectrum scenario are available to choose for. In line with this, the spectrum scenarios are formulated for Addis Ababa city including cochannel, dedicated or hybrid. Performance investigation of the various spectrum scenarios is undertaken from planning perspective considering realistic Addis Ababa network scenario. To do the planning, multi-objective based on GA is applied while the realistic network environment is being captured with WinProp. From achieved results, the following trends were observed:

- Dedicated 20MHz bandwidth in 2600MHz achieves an aggregate capacity gain of 1.83% more as compared to similar deployment in 1800MHz for three small cells per sector optimal deployment.
- Dedicated 20MHz bandwidth in 1800MHz provides higher median user throughput than similar deployment in 2600MHz.
- For relatively low small cell density (one small cell per sector), dedicated 10MHz bandwidth in 1800MHz provide better cell edge user throughput than similar 20MHz bandwidth in 1800MHz.
- Dedicated 20MHz bandwidth in 1800MHz achieves outage rate of 2.82% with three small cell per sector optimal deployment.
- Cochannel deployment of 20MHz bandwidth performs better than similar Hybrid 10MHz bandwidth deployment in 1800MHz.
- With Cochannel deployment of 20MHz bandwidth user outage rate less than 10% cannot be achieved even with three small cell per sector optimal deployment.

- Cellular network operators can follow capacity driven or outage driven small cell planning approach while deploying small cells based on operators' interest.

In summary, we conclude that selection of best spectrum scenario for outdoor small cell planning is determined by deployed small cell density and considered performance metrics such as aggregate capacity, achieved user throughput and user outage. With respect to selection of location for outdoor small planning, instead of limiting the deployment in the main street only consideration should be given for secondary roads as well.

6.2 Future Works

Potential future work includes:

1. Analyzing spectrum scenarios applying different interference mitigation technique including eICIC and feICIC.
2. Investigating the scenarios from planning perspective considering other multi-objective optimization algorithms.
3. Evaluating other potential scenarios with other useful licensed, unlicensed and millimeter-wave bands considering Addis Ababa network environment.

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