Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Techno-Economic Investigation of Street Furniture Usage for Outdoor Small Cell Planning: The Case of Addis Ababa, Ethiopia

By

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Telecommunication Engineering Graduate Program

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Approval by Board of Examiners

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Declaration

I declare that the work contained is my own, has not been summited for a degree in any other university or professional qualification, and all sources of materials used for the thesis have been fully acknowledged.

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Place: Addis Ababa

Date of Submission: _____/____/_______

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

Dr. Beneyam Berehanu ___________________

Advisor’s Name Signature

Abstract

For more than a decade, mobile network data traffic and users' demand are considerably increased due to the advent of evolving mobile technologies, capable end-user devices and data-intensive content. Different forecasts show that the growth will continue for similar reasons. To accommodate the increasing network traffic and users' demand, operators should continuously expand the capacity of their mobile networks using different capacity enhancing technologies. Network densification using small cells is one of the important capacity enhancement methods that are being implemented.

To successfully exploit capacity benefits of network densification, efficient network planning is needed to address its deployment challenges including availability and cost of site, energy source and backhaul while minimizing interference and maximizing network capacity and users' throughputs. Using street furniture including lamp posts and utility poles during the planning of dense/ultra-dense networks is being considered as one method to address the availability of sites and cost challenges. But techno-economic benefits of using the furniture and usage methods are not studied in the context of Addis Ababa.

In this thesis work, the techno-economic benefits of using the furniture from an outdoor network planning perspective for a selected area of Addis Ababa will be investigated. The outdoor planning optimization is performed using technical and economic objectives while considering lamp posts and utility poles of the selected areas as part of candidate locations for small cells. The multiobjective optimization is solved using Genetic algorithm and its implementation and result analysis are performed using MATLAB. Propagation computation for network simulation is undertaken using a deterministic dominant path model that is implemented within WinProp.

Empirical economic analysis results show that using streetlamp posts and utility poles decreases deployment cost by 17% compared to using a new standalone pole (dedicated pole used for only small cell deployment). Furthermore, obtained Pareto optimal networks from outdoor planning simulation that considers 143 lamp posts and 81 utility poles as candidate cells provide 53 lamp posts and 43 utility poles. Thus, only 24% is consumed by street posts for 96 sites while for 13 sites using new standalone pole 57% of the total deployment cost is consumed.

Keywords: *LTE, Small Cell, Densification, Street Furniture, Lamp Posts, Utility Poles, Multiobjective optimization, Users' Demand, Cost-Benefit, Techno-Economic, Addis Ababa*

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List of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AACRA	Addis Ababa City Road Authority
AAiT	Addis Ababa Institute of Technology
AC	Alternating Current
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
DC	Direct Current
DG	Diesel Generator
EEU	Ethiopian Electric Utility
FAP	Fixed Access Point
FCC	Federal Communications Commission
GAs	Genetic Algorithms
GPS	Global Positioning System
GSM	Global Systems for Mobile Communications
ITU	International Telecommunication Union
LTE	Long Term Evolution
MBSs	Macro Base Stations
MOO	Multiobjective Optimization
MOPs	Multiobjective Problems

NGN	Next-Generation Network
NSGA	Non-dominated Sorting Genetic Algorithm
O&M	Operation and Maintenance
ONT	Optical Network Terminal
OPEX	Operational Expenditure
PON	Passive Optical Network
PRS	Performance Report System
PS	Packet Switch
RF	Radio Frequency
RT	Remote Terminal
SCF	Small Cell Forum
SCs	Small Cells
UMTS	Universal Mobile Telecommunications Systems

Chapter 1 - Introduction

1.1 Background and Motivation

Rapid mobile data traffic growth has been/is being experienced by operators around the globe[1, 2]. According to [2] mobile data traffic has grown exponentially 4,000 fold for the last 10 years up to 2016. Over the last few years, there are more than 4 billion people connected through mobile communication all over the world [3]. To serve those customers, around three million cellular network base stations are deployed which contribute about 3% of global energy consumption and 2% of carbon emissions [4]. By 2020 the global mobile data traffic expected to grow 30.6 Exabyte per month [2]. As per International Telecommunication Union (ITU) prediction, by 2030 with and without Machine to Machine communication (M2M) the overall mobile data traffic will grow exponentially and will reach 5 Zettabytes (ZB) per month as shown in Figure 1-1.

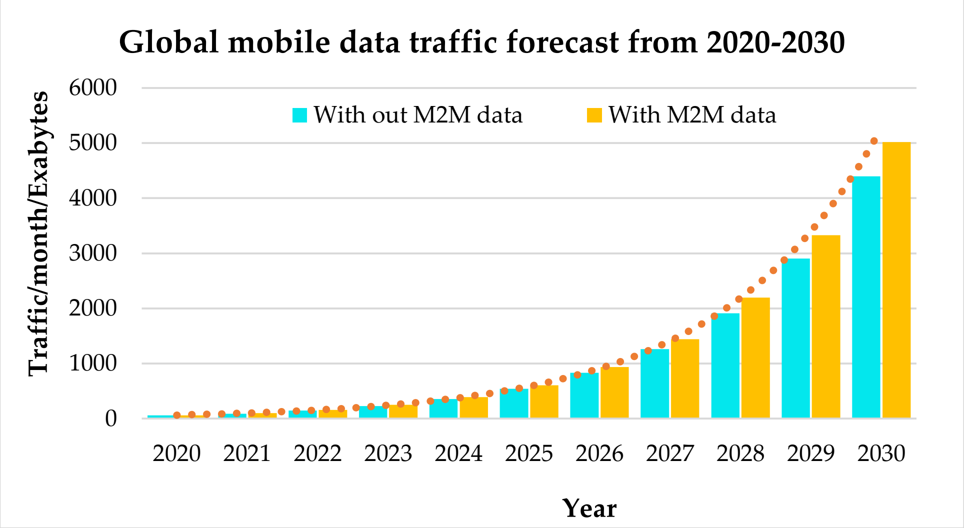


Figure 1-1 Global mobile data traffic forecast by ITU [1].

In the Ethiopian context, telecommunication services were expanded by using different government-owned telecom administration structures in different periods of time. From those services, Second Generation (2G) was first begun in 1998 in Addis Ababa with 6,740 subscribers and a capacity of 36,000 users. To expand the different telecom infrastructure and services, Next Generation Network (NGN) project agreement was signed on December 31, 2006. This project has enabled 64% mobile network coverage throughout the country with a capacity of 25 million subscribers in both Global Systems for Mobile communication (GSM) and Third Generation (3G) [5]. Ethio telecom has adopted a 3G network in 2009 in Addis Ababa 8 years late since its invention [5].

After completion of the NGN project, in January 2015, in Addis Ababa 3G network was also launched in major cities. The project contract between HUAWEI, ZTE, ERICSSON and ethio telecom increased the mobile service capacity to 59 million. Through this contract, the country's telecom network total coverage increased to 85 % [5]. ethio telecom has launched the Fourth Generation (4G) Long Term Evolution (LTE) service in Addis Ababa on March 21, 2015, with a network capacity of 400,000 subscribers using Macro Base Stations (MBSs) [6].

Nowadays as per ethio telecom’s current report, the number of mobile phone subscribers is around 65.7 million (based on a subscription-only) and from these, about 43.67 million are active customers [7]. Figure 1-2 depicts ethio telecom’s mobile customer growth from January 2009 - October 2019 on average around 4 million per year.

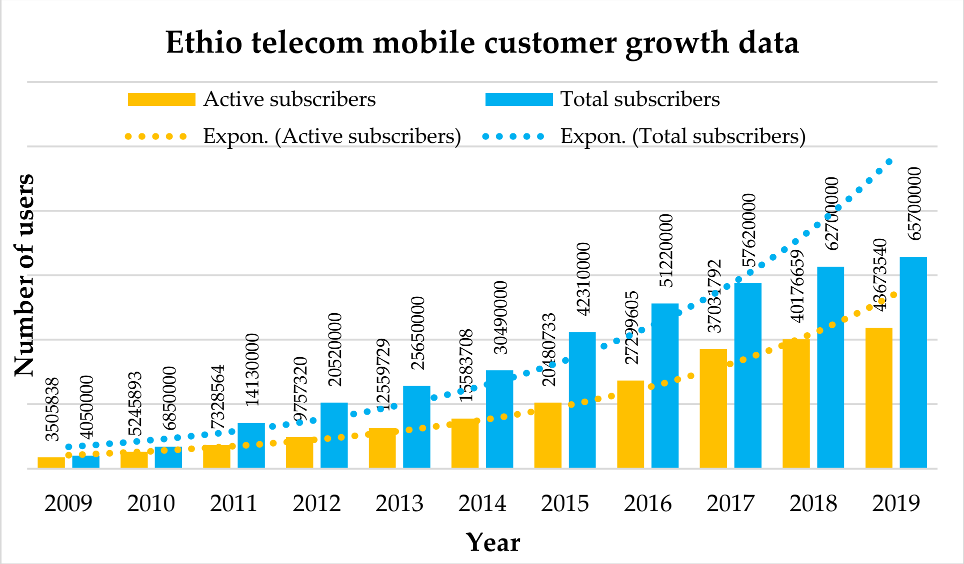


Figure 1-2 Ethio telecom customer growth from Jan. 2009 - Oct. 2019

Beyond the rapid growth of cellular network users, mobile tariff adjustment made on August 23/2018 maximized customer data usage experience which caused congestion in 3G customers. In Figure 1-3 it is shown that 2G Packet Switch (PS) traffic is almost constant throughout the year while there exists a rapid traffic growth in both 3G and 4G. From November 2018 onwards, 4G customers lead 3G in data traffic usage.

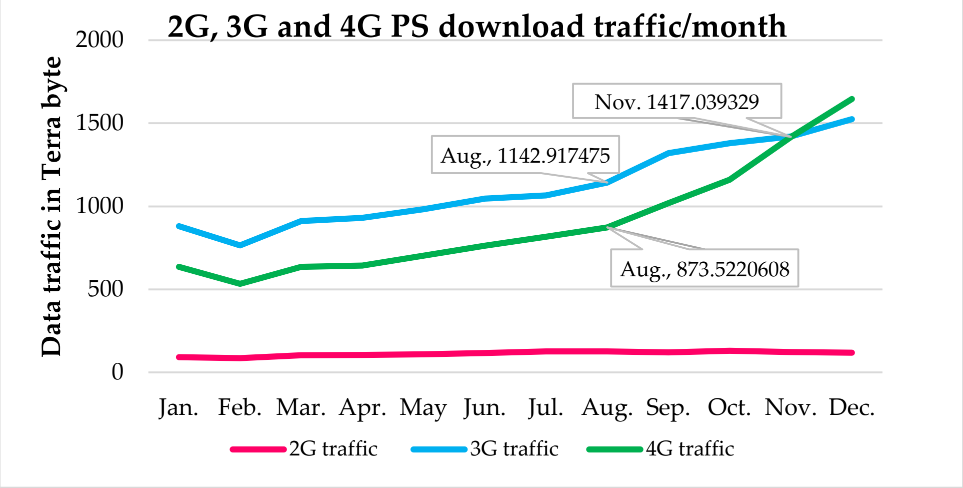


Figure 1-3 All Addis Ababa 2018 mobile network packet switch traffic/month

All the above mobile services are deployed using MBSs which has higher energy consumption. In particular, 60-80% of the operator's power is consumed by base stations, which makes the design and deployment of a key element [3].

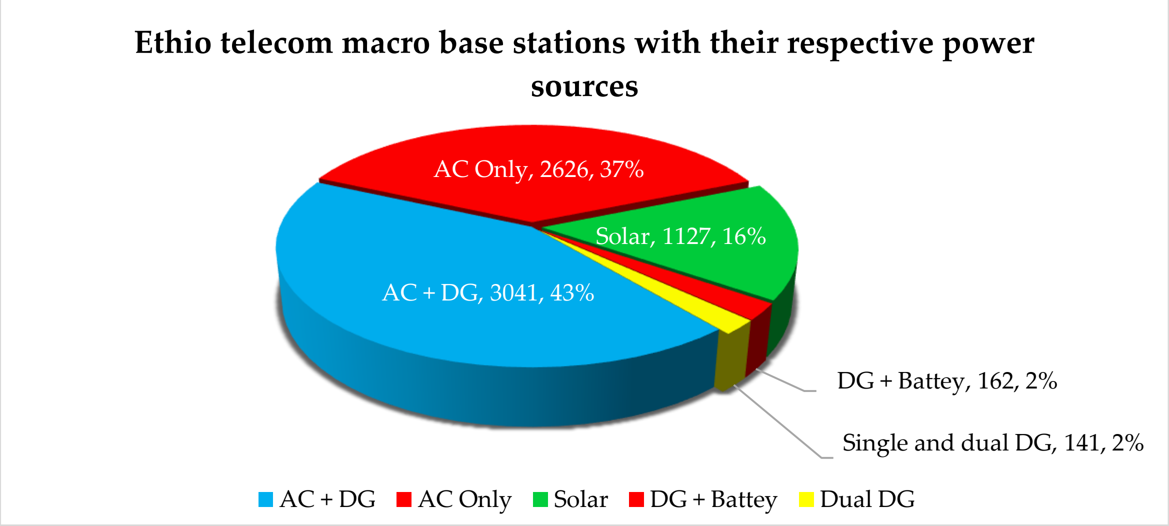


Figure 1-4 Ethio telecom base stations with their respective source type

Figure 1-4 depicts the total number of MBSs installed in Ethiopia with their corresponding power source Alternating current (AC), Diesel Generator (DG), solar, battery and their respective percentage power consumption. From the total number of deployed base stations, 37% of them are powered from commercial power which results in service interruption on 2,626 sites during a power outage.

During a commercial power outage, supplying base stations from the generator maximizes Operational Expenditure (OPEX). For example, in the case of ethio telecom, the annual fuel consumption (2017/2018) for 3171 MBSs is around 169 million as shown in Table 1-1.

Table 1-1 2017/2018 Zonal & regional sample diesel consumption

Site Location	No. of Sites	Diesel in Liter	Diesel consumption in Birr
Regional	2,380	8,241,317	135,157,608
Zonal	791	2,054,601	33,592,730
Total	3,171	10,295,918	168,750,338

Due to the expectation of customers to be always connected, operators are facing the pressure of providing high data capacity while maintaining an efficient and low-cost network with a minimum outage. To overcome this problem, base station densification is one of the promising solutions that need efficient site selection where small cell deployments using street furniture to provide maximum spectral efficiency and improved utilization with low energy consumption compared to macro base stations.

During small cell base station densification using street furniture, evaluating investment feasibility based on technical and economic assessment is an essential step that is mainly performed in this study. The result from techno-economic analysis evaluates the benefits of street furniture usage to overcome site acquisition problems during base station densification. Globally, if deployment barriers were removed today, the deployment of Small Cells (SCs) in dense or hyper-dense environments can be performed easily and reach almost 14million from the current 3million by 2025 [8].

1.2 Statement of the Problem

Network densification needs several requirements including availability and cost of site, energy source and backhaul while minimizing interference and maximizing network capacity. In urban areas, site acquisition is one major challenge for mobile service providers during base station densification which has a significant amount of rental fees. For example, in ethio telecom, there are 108 rooftop sites in Addis Ababa and only 13 of them are placed on a governmental building without a rental fee. According to sourcing and facility department, ethio telecom pays around 11,400,000 Birr per year for 95 rooftop site rentals located in Central, East, West, South, North and South West Addis Ababa Zone (CAAZ, EAAZ, WAAZ, SAAZ, NAAZ and SWAAZ) as shown in Figure 1-5. From those rooftop sites, only 50 of them are powered from both commercial and diesel generators while the rest affected by a commercial power outage.

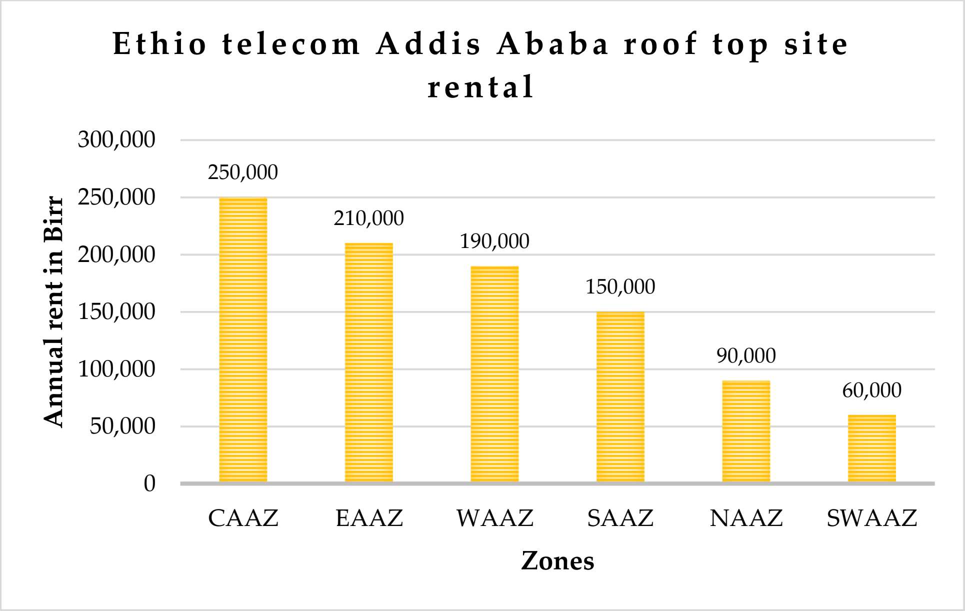


Figure 1-5 Ethio telecom monthly rooftop site rental in Birr per zone [9].

To minimize site rental and site acquisition, power source problem and to enhance the capacity demand, operators should do their best to deploy energy-efficient outdoor small cells using street furniture. However, where and how to deploy outdoor small cells efficiently using the furniture is a very relevant research question that does not have a straightforward answer. This is because their efficient and cost-effective usage is not well studied using a real network, particularly in the context of Addis Ababa.

1.2Objective

1.2.1 General Objective

The main objective of this thesis is to present the techno-economic performance investigation of using street furniture for outdoor small cell planning for Addis Ababa.

1.2.2 Specific Objectives

The general objective is achieved by undertaking the following specific objectives:

- To study small cell planning and deployment considerations in terms of cost and site selection.
- To study approaches that can be applied to effectively use street furniture for small cell deployment.
- To formulate a techno-economically efficient method for selecting street furniture as candidate sites for outdoor small cell planning.
- To formulate and implement Genetic algorithm-based network planning over formulated candidate cells.
- To evaluate the techno-economic performance of resulted network topologies of network planning implementation.

1.3 Methodology

In this thesis, the following methodology is applied during the study of techno-economic performance investigation of outdoor small cell planning.

Literature review on how to minimize the challenges in site acquisition, site rental, and energy source during base station densification in order to address the capacity demand. Data related to MBSs deployed in Addis Ababa with their respective locations are collected from ethio telecom. The streetlamp post, utility concrete pole and, building locations are collected physically by using Maps with me (MAPS.ME) global positioning system application tool.

Deployment area selection is done by using 50mx50m pixel traffic data and the total capacity demand is calculated by the summation of rejected plus served traffic as shown in (4-5). In addition to the capacity demand deployment area is selected by identifying areas where street posts exist. Finally, to find optimal small cell topologies, the Genetic algorithm based Multiobjective Optimization (MOO) technique is applied. Figure 1-6 depicts the overall methodology and system model used in this thesis work.

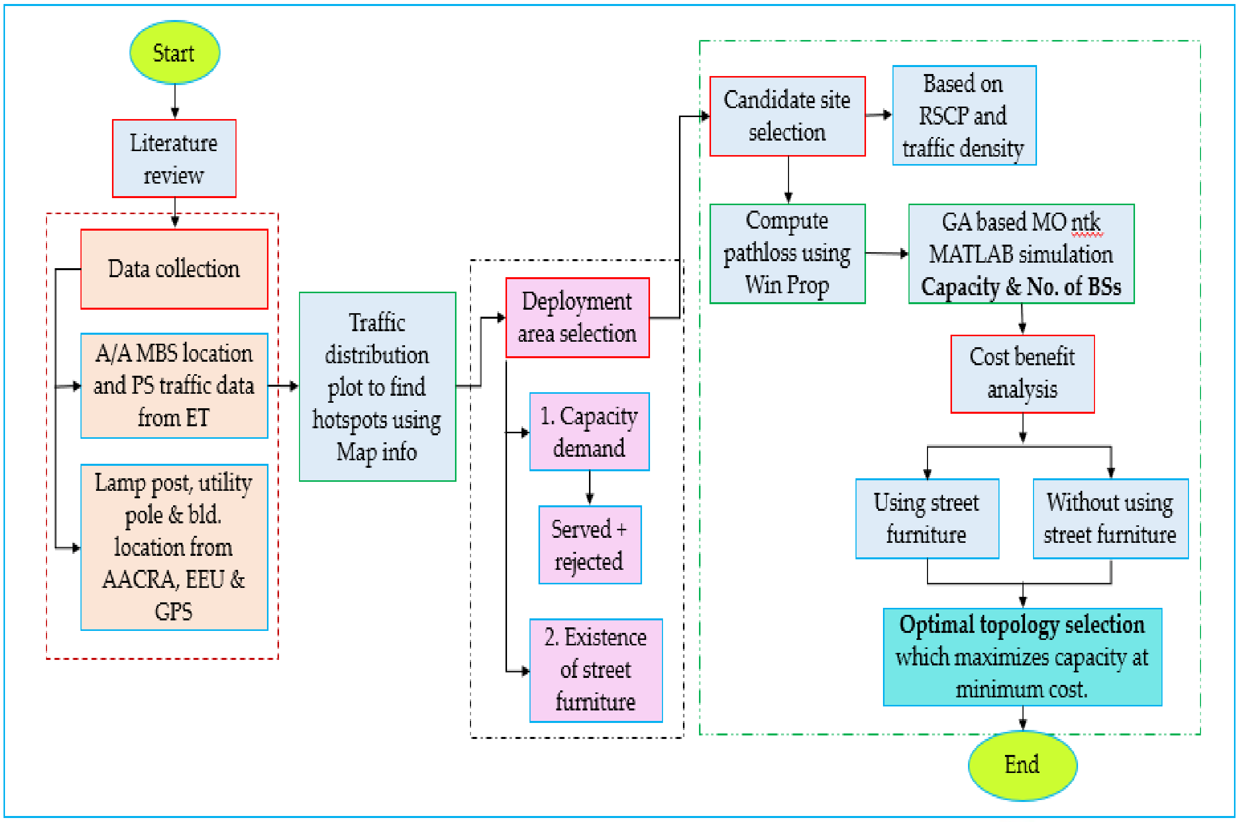


Figure 1-6 System model/methodology

1.4 Related Works

The rapidly expanding traffic volume enforced mobile network operators to upgrade their network to be capable of the capacity demand [4,10,11]. In cellular network technology, network densification has been recognized as a promising solution to boost capacity and enhance coverage with low cost and power-efficient infrastructure [12]. Denser small cell deployments have several challenges, such as site acquisition, site rental, backhaul, interference, energy source including the increased complexity in network planning and optimization.

To minimize the challenges in site acquisition, site rental, and energy source, [11, 13]mobile network base stations in dense urban and urban areas can be deployed on utility poles, street lamp posts, traffic lampposts and building block rooftops. Existing furniture usage along roadside pave the way for high-speed connectivity to vehicles, rail passengers, buildings, cafeterias, street markets, universities and other nearby cellular network users. Using existing furniture provides fast small cell deployment with a reduced cost. In order to achieve small cells' potential lower cost per bit, operators need to be very precise about the location where to deploy small cells.

Third parties that deploy small cell networks creates new business opportunities for mobile service providers to fill their financial gaps [14]. The author studied service providers' benefit for various small cell deployments using techno-economic aspects of existing infrastructure. The mobile service provider leases the small cell infrastructure from small cell operators to offload their traffic. Due to this reason, the service providers get relief from initial investment costs during network expansion or new small cell deployment.

Using small cells in streetlamp posts have a significant impact on the future business ecosystem [15]. It enables city planners to envision long term goals for smart cities with smart pole capabilities and small cells. This will bring new value, improved efficiency and a source of revenue for cities. Compared to the macro base stations, mass deployed small cells on street furniture can carry traffic at a lower cost. Furthermore, towards the operators they can bring much more flexibility to add new functionalities and offset the growth of mobile data in a way that is cost-effective by selecting the best outdoor locations close to the society which will offer the best connectivity to their customers. In order to achieve this, it needs proper small cell planning to come up with efficient topologies.

In [16,10] performance impacts of several fundamental characteristics of ultra-dense network investigated that mobile operators and vendors should consider during deployment. Moreover, performance degradation due to the covered carrier signal power can be addressed by reducing small cell base station antenna height using street posts which improves battery lifetime for mobile users.

The above works of literature state on denser network deployment for capacity improvement, performance impacts of ultra-dense network and cost reduction with a reduced number of base stations. However, where and how to deploy (fix) those small cells and cost-benefit of street furniture usage is not clearly discussed. This thesis addresses the performance investigation of existing street furniture usage for outdoor small cell to improve current capacity demand in a cost-efficient way.

1.5 Scope and Limitation

The scope of this thesis is performance investigation of street furniture usage for outdoor small cell planning in Addis Ababa scenario. Only Addis Ababa network mobile traffic data is used during deployment area selection.

During street furniture data collection, there was a limitation of getting the real locations from both AACRA and EEU due to this reason physical candidate post data collection was done. To come up with optimal site selection from candidate posts more than two hundred, it needs a computer with higher processing capacity which is addressed for this work by using AAiT's high-performance computer.

1.6 Contribution

The main contribution of this thesis consists of:

Capacity enhancement with optimum site selection: Performance investigation of existing posts usage is analyzed having the same number of posts selecting the optimum topology which maximizes capacity. This encourages mobile network operators to implement MOO during small cell planning and deployment.

Cellular network deployment cost reduction: most literature presented cost can be reduced by selecting an optimum number of base stations without affecting the capacity demand. Furthermore, this work presents deployment cost reduction can be achieved by using street furniture for small cell base station densification in urban areas which minimizes the investment cost by 33% compared to using a new standalone pole.

Additional income sources for street furniture owners: existing post usage for small cell deployment generates additional income for utility companies and city administrators without extra investment. This study can be used as an input for both telecom service operators and utility companies to use existing infrastructures for small cell deployment.

1.7 Thesis Outline

The remaining part of the thesis work is organized as follows:

Chapter 2 - Covers the role of mobile network evolution towards fulfilling the traffic demand. It also presents the role of base station densification to address the traffic demand. Finally, deals with the main challenges during small cell planning and deployment.

Chapter 3 - Global experiences on existing post usage for small cell deployment and techno-economic benefit analysis will be discussed here to assure the advantage of using street furniture. Once the benefit analysis is described, the next stage deals with how to use those posts to get economic benefits based on global best experiences.

Chapter 4 - Here the main tools used for this study to come up with the final simulation result will be discussed followed by the system model which supports the MOO problem. Furthermore, the deployment scenario, simulation approach and assumptions and key parameters used to come up with the result will be addressed here.

Chapter 5 - In this chapter, the result is analyzed based on three different street furniture usage. The first result is done using only small cells on streetlamp posts combined with the existing macrocells. The second simulation is performed in addition to the first stage it includes nearby buildings and new posts. Finally, the hybrid simulation result is done using the second candidate posts with utility concrete poles.

Chapter 6 - This is the final chapter that concludes and discusses the overall findings of this thesis work with possible areas of future work.

Chapter 2 - Evolution of Mobile Technology and LTE Network Planning

The evolution of wireless networks begins with First Generation (1G) in the 1980's with a data rate of up to 2.4kbps. 1G has limitations like capacity, thoughtless handoff, security and others. To overcome the gap in 1G, 2G was introduced in the late 1990s. GSM was used for voice communication, Short Message Service (SMS) and email having a data rate up to 64kbps. Packet switching along with circuit switching is applied in 2.5G system having data rate up to 144kbps. The main 2.5G technologies were General Packet Radio Service (GPRS), Enhanced Data rate for GSM Evolution (EDGE), and Code Division Multiple Access (CDMA) 2000 [18]. Figure 2-1 depicts the evolution of mobile network from 1G to 4G.

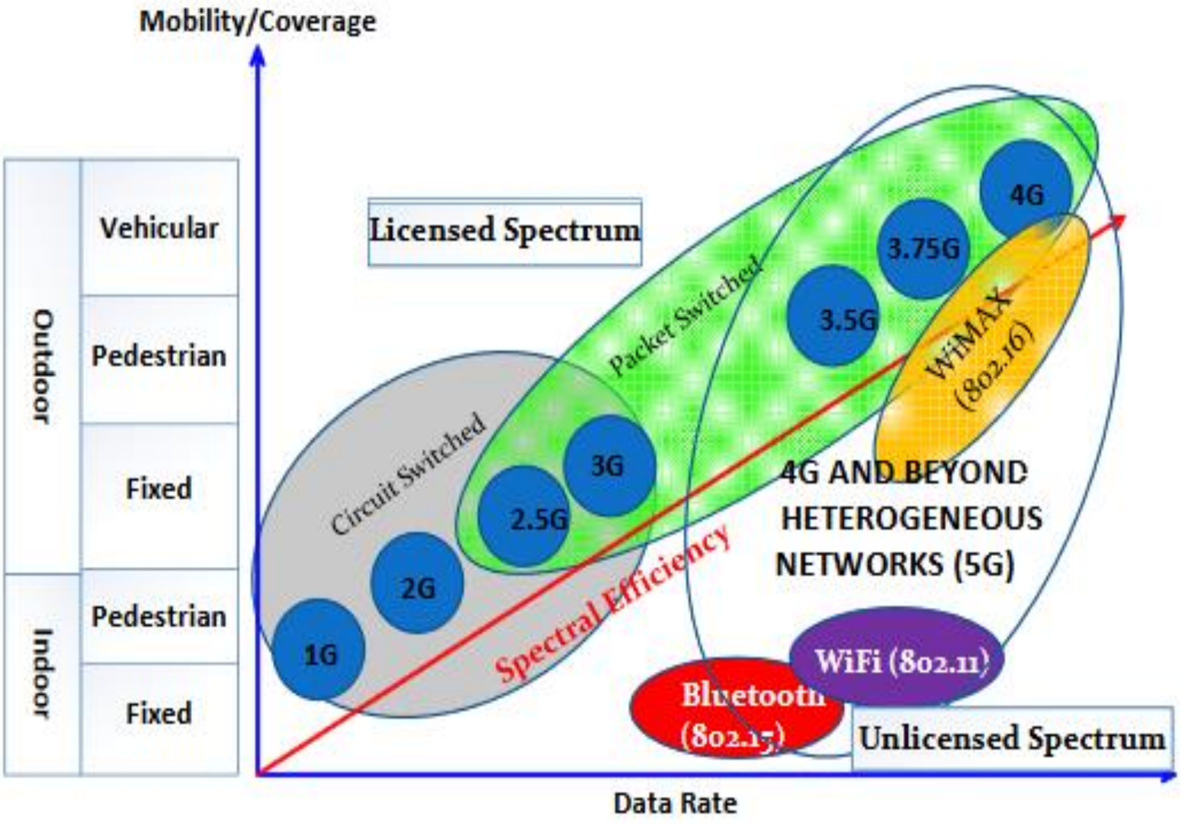


Figure 2-1 Evolution of mobile technology [18].

In late 2000 3G was established with a data rate up to 2Mbps based on internet protocol. 3G involves the introduction and utilization of Wideband Code Division Multiple Access (WCDMA), Universal Mobile Telecommunications Systems (UMTS) and CDMA 2000 technologies. The evolving technologies like High-Speed Uplink/Downlink Packet Access (HSUPA/HSDPA) and Evolution-Data Optimized (EVDO) have made an intermediate wireless generation between 3G and 4G named as 3.5G with an improved data rate of 5 Mbps to 30 Mbps [17, 18]. LTE and fixed Worldwide Interoperability for Microwave Access (WiMAX) have the potential to supplement capacity and provide a substantial number of users to access a broad range of high-speed services [18].

2.1 LTE Network Planning

In the evolution of UMTS, after GSM and CDMA LTE is the successor technology in a cellular network. It was defined by the Third Generation Partnership Project (3GPP) Release 8 specification and transmits at data rates of over 100 Mb in the downlink and over 50 Mb/s in the uplink. It also supports from 1.4MHz to 20 MHz scalable bandwidths that can be used for both frequency and time division duplexing [20]which demands proper network planning and deployment.

LTE network planning process considers infrastructure cost and services, the system configuration of each parameter and service performances. To start planning, input data such as deployment area characteristics, data traffic behavior, eNodeB parameters and user distribution should be known [21]. The cell performance of the LTE network can be affected by building height, terrain features and the number of potential users in the deployment area. The operating frequency band gives certain configuration guidelines for the eNodeB and imposes the use of certain types of user devices.

LTE uses Orthogonal/Single-Carrier Frequency Division Multiple Access (OFDMA/SC-FDMA) for downlink and uplink respectively. The main phases that should be considered during LTE network planning are cell dimensioning, from radio link budget and capacity dimensioning, based on the traffic demand [21]. The final output of these two phases will give us the number of eNodeBs that provide traffic demand in the selected area. Since LTE supports higher data rates than its predecessors, the need for experiencing broadband networks increased the data traffic demand [20]. In order to address the data traffic demand from cellular network users' operators need to study the behavior of their demand growth to fulfill their customer requests.

2.1.1 Demand Growth

Due to the introduction of new technology, improved device capabilities increased data-intensive content and other reasons, there exists a continuous challenge for telecom operators to upgrade their network to address the capacity demand. Globally mobile data traffic demand from 2017 to 2022 is expected to grow to 77 Exabyte per month which is a sevenfold increase over 2017. In 2017, 3G coverage reached almost 90% of the world's population [22], while more than 70% of the global population were covered by a 4G network.

Around 5.1 billion people in the world subscribed mobile services by the end of 2018 which accounts for 67% of the global population [23]. Having an average annual growth rate of 5% a total of 1 billion new subscribers have been added in the four years since 2013. According to [16] the average monthly data consumption of global mobile traffic growth estimated a tenfold increase from the current 2-5 to 20–50 GB/month by 2020. Moreover, in the next decade subscriber growths of 5%–15% are expected from emerging markets.

According to International Mobile Telecommunications (IMT) the main drivers behind the anticipated traffic growth are, M2M communication, cloud computing, audiovisual and media streaming, shifting demography, evolution in usage, subscriber behavior, fixed broadband replacement by mobile broadband and others as discussed on [24].

The evolution in usage and traffic characteristics of the current and emerging services changing the utilization rates and the net average up and downlink traffic per device globally as well as in Ethiopia context.

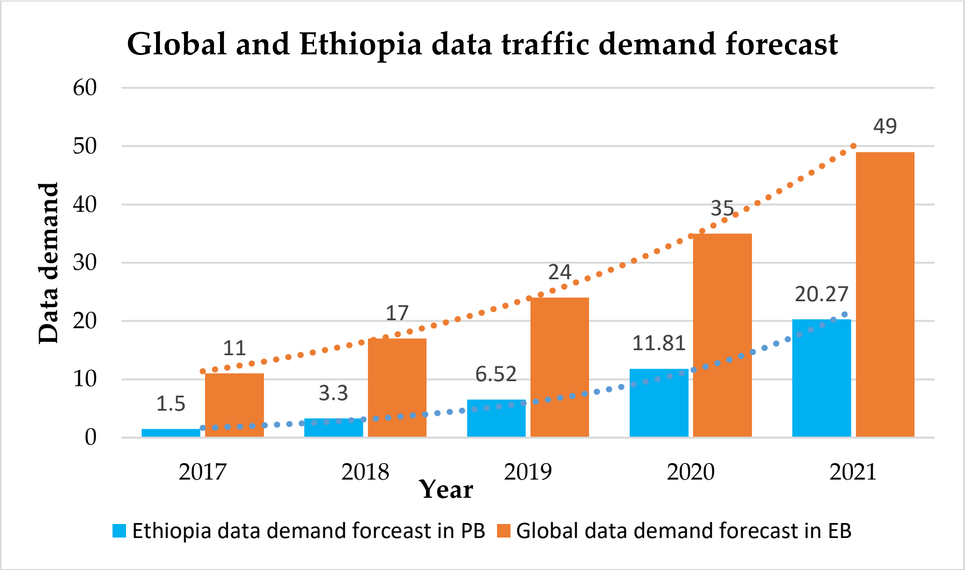


Figure 2-2 Global and Ethiopia data demand forecast from 2017 to 2021 [25].

Figure 2-2 depicts the global and Ethiopia data traffic forecast from 2017 up to 2021. It indicates the existence of exponential data growth globally and in Ethiopia context in Exabyte and Terra byte respectively. From Ethiopia, this exponential data growth mostly appears in urban areas especially in Addis Ababa around Bole, Mexico, Jemo, Megenagna, Yeka Abbado condominium, Meskel Square, Stadium and others.

In this work, the selected area (Megenagna) consists of hot spots due to marketplaces, schools, cafeterias, business areas and buildings. Within 2x2km^2 at the Megenagna area, there are 12 macrocells that serve users in the specified area. As an example, Figure 2-3 shows weekly HSDPA traffic distribution in GB from January 9-15 /2019 on daytime, night and weekend bases for selected area macro base stations.

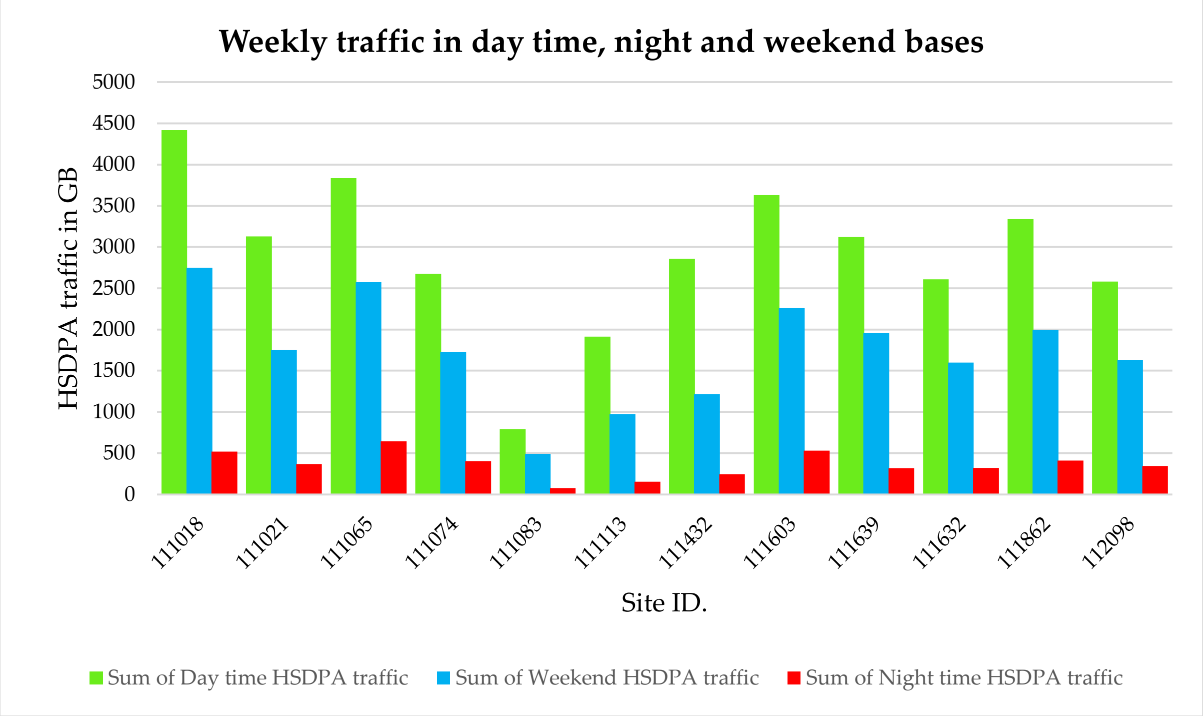


Figure 2-3 Weekly generated HSDPA traffic in GB

From Figure 2-3 it is shown that there exists high traffic in daytime and weekend while very small traffic at night. Since the selected area is a business area, there are very small users at night. In order to accommodate the traffic demand and to maximize revenue in hotspot areas shown in Figure 4-7 operators should deploy more base stations in a cost-efficient way.

2.1.2 Base Station Densification

The idea of network capacity enhancement using network densification gains serious attention after the introduction of 2G networks [26]. Deployment of additional network nodes with a minimum distance between base stations accommodates more user equipment especially in hotspot areas that can be achieved by using macro and small cells.

Macro base station densification improves the transmission rate in urban and hotspot areas. Additional deployment for capacity and coverage improvement causes interference in adjacent macrocell base stations. To avoid interference in the adjacent base station, different mitigation techniques can be used. From those techniques, frequency reuse and sectored base station technologies have been developed for macrocell densification, where the density is about 4-5 sites/km [27]. Moreover, it is envisioned that macrocell networks will continue to provide the outdoor coverage layer with small cells satisfying outdoor and indoor capacity demands.

Small cell base station densification is the latest cellular network deployment which can provide high throughput for hotspot areas with high capacity demand. According to [28], small cell is a general term for operator-controlled low-powered radio access nodes that can be deployed indoors or outdoors. Their type includes femtocells, picocells and microcells which enhance spectrum reuse and coverage while providing high data rate services that can operate in licensed and unlicensed spectrum. Small cell technologies can be classified with respect to the coverage area as follows:

Metro cell is a compact mobile base station used for densification in urban areas that can be mounted on lampposts, sides of buildings or found indoors in stadiums, transport hubs and other public areas. The range of metro cells is from 1- 2 kilometers [29].

A microcell allows low power cellular base station covering a limited area such as a mall, hotels, stations and transportation hub with a range of 0.1 up to 1 kilometer [29]. It provides financial opportunities for municipality, utility companies, private building owners for congested urban centers where there is a need for more bandwidth.

A picocell is a small cellular base station mainly used in-building, offices, shopping malls, train stations, aircraft, etc. It extends coverage of the outdoor environment to indoor areas not covered by macro sites. Most cellular technology such as GSM, CDMA, UMTS and LTE uses picocell for capacity and throughput improvement [29].

Femtocells are lower cost base stations which currently account for 96% of small cell base stations [13]. They are consumer deployed base stations with low power consumption. Figure 2-4 shows the different types of cellular network base stations.

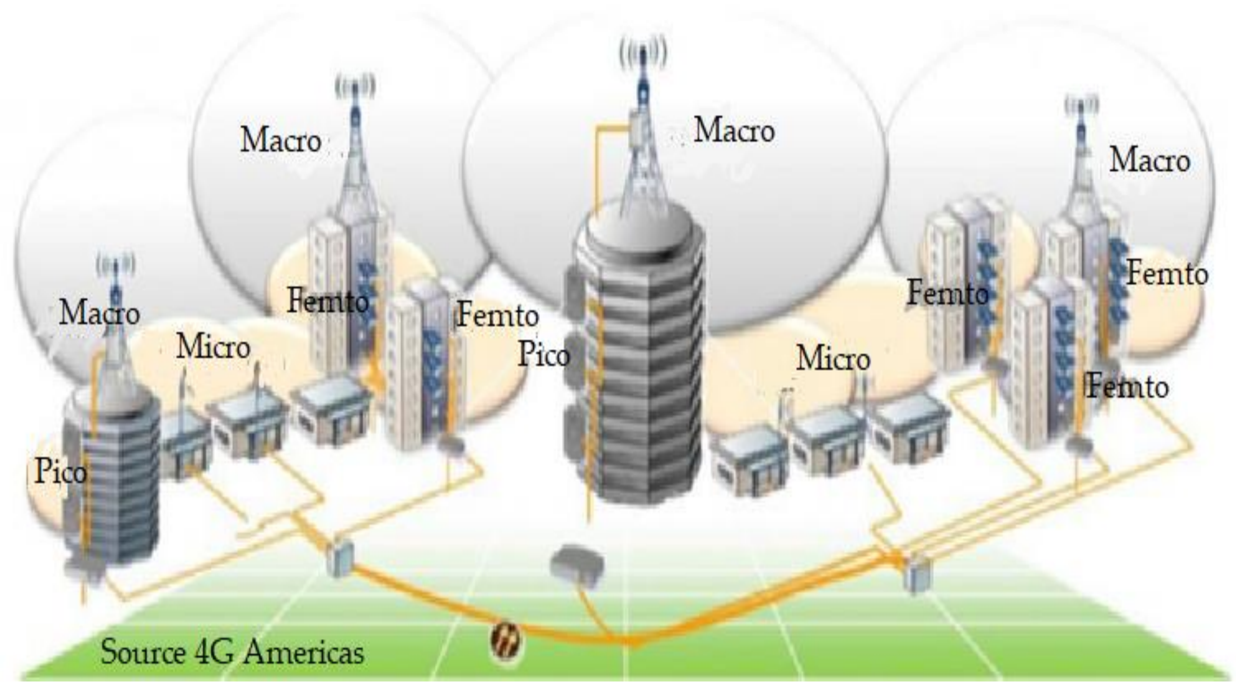


Figure 2-4 Types of base stations in the cellular network

Table 2-1 summarizes base station types with their respective number of active users served at a time, coverage in km, Radio Frequency (RF) in watt and deployment locations.

Table 2-1 Base station types with respective users, coverage, RF and location [30]

Type of base station	Number of active users	Coverage in km	RF in W	Location
Femtocell	1- 30	0.01- 0.1	0.001-0.25	Indoor
Picocell	30 - 100	0.1- 0.2	0.25-1	Indoor/outdoor
Micro/metro	100 - 2000	1 - 2	1-10	Indoor/outdoor
Macro cell	>2000	5-32	10 to >50	Outdoor

2.2 Small Cell Planning and Deployment for LTE Network

Small cell planning: The network planning process is considered as one of the most important and crucial issues in the wireless design. It should be done with a reduced cost, a small number of base stations and better quality of service while keeping the required coverage and capacity constraints [31]. Figure 2-5 shows small cell planning and deployment phases.

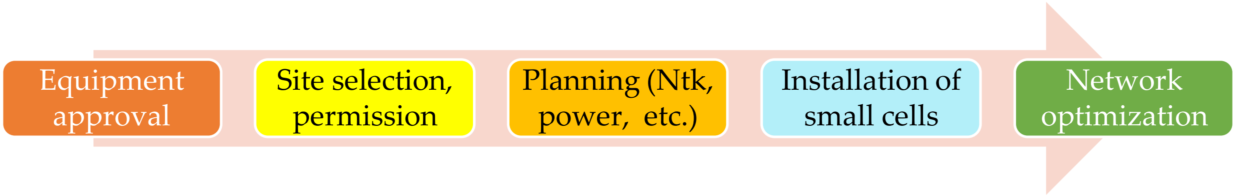


Figure 2-5 Small cell planning and deployment phases [32].

At the initial stage, the type of small cell equipment used should be approved by the telecom regulator within the country based on international standards. Next, identification of the optimum location of the small cell and planning permission will be granted. This enables us to perform design and planning of network, backhaul, power and other requirements. The installation will be performed based on the selected location during the planning stage. Detail cellular network design and planning process is discussed in [19]. Finally, optimization is performed to determine the efficient number and locations of the base stations in order to meet coverage and capacity requirements which can be achieved during the planning and deployment stage.

Small cell deployment: Proper planning minimizes the challenges during deployment and enables the team to install small cells on the specified location as per the plan. During network densification, the placement of new small cell sites determined based on the existence of traffic demand and suitable site location [33]. The location of small cells should be selected properly to maximize the capacity gain at a minimum cost. Due to this reason, operators should think during deployment for an optimum location to minimize investment and operational costs.

2.2.1 Small Cell Planning and Deployment Challenges

There are several challenges during the planning and deployment of both macro and small cells. From them, site acquisition and approval process, power source, backhaul and human exposure to Electromagnetic Fields (EMF) need the operator’s attention.

Site acquisition and approval processes: Identifying best location is the major task that needs external support from different stakeholders which minimize constraints such as delayed permitting processes, lengthy procurement, exaggerated fees, old rules and regulations that prevent existing infrastructure usage. To maximize the deployment of small cells in urban areas, it needs proper rules and regulations of local authorities which encourage mobile service providers.

Many operators have challenges during site selection and approval of deployment permission. To come up with a simplified, and acceptable set of processes, during site acquisition both telecom operators and street furniture administrators should work together. This enables operators to use street furniture for small cell deployment [32].

In Ethiopia context, since there are so many streetlamp posts, utility poles and other options that can be used for small cell densification, it is better to come up with a joint agreement between ethio telecom, Addis Ababa city road authority and Ethiopian electric authority. In doing this, beyond solving the site acquisition problem, it is possible to power the base stations from streetlamp and utility posts which minimizes small cell power source problems.

Power source: Even if the energy consumption of small cells is very low compared to macro base stations, it needs proper power design and implementation to minimize outage and to enhance the quality of service in a cellular network. Small cells can be supplied from commercial power, solar, wind, generator and other sources. [35]. Based on global experience, some of the existing options are described below.

- Power from the grid: Regardless of the investment cost, obtaining an AC power source on time from the utility grid is one of the difficult tasks in powering wireless networks. However, using streetlamp posts and utility pole eliminates this problem since they are already connected to commercial power.

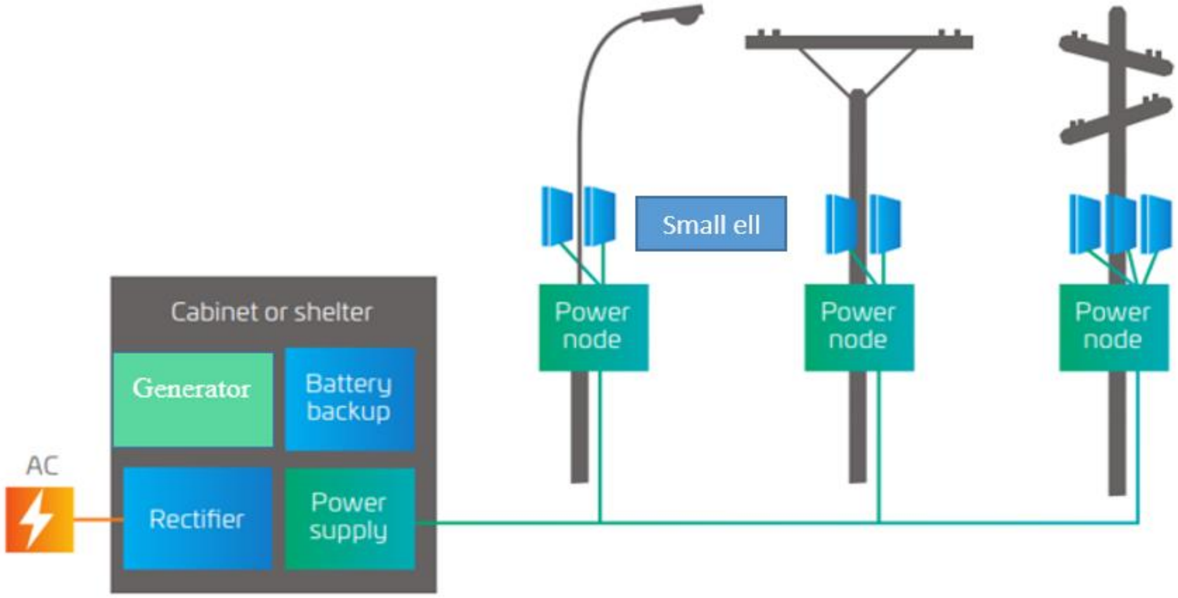


Figure 2-6 Example of small cell power supply [36].

To serve base stations without power interruption, powering each site with battery backup or generator in space-constrained urban locations is a difficult task that needs cooperation between telecom operators and street furniture administrators. Figure 2-6 shows small cells connected with backup generator and battery.

- Power over Ethernet (PoE): The latest PoE standard, IEEE P802.3bt (PoE++) supports up to 71.3 watts per device port for a maximum distance of 100 mts which can be applied for ultra-dense networks [36].

- Distributed power connectivity: It is based on hybrid fiber cabling to provide both power and connectivity from a central location to a cluster of small cells. It can be served from the central office or nearby macro base stations which has access to power and optical network. Simultaneous deployment of data connectivity and power source minimizes the major backhaul challenge during small cell deployment.

Backhaul: Is an intermediate network that includes links between the radio access network and the core network. Generally, backhaul solutions are divided into two categories of wired and wireless solutions. Backhaul selection depends on capacity, deployment density, required data rate, relative cost, electromagnetic interference and the availability of radio spectrum. Digital subscriber line and fiber backhaul are wired solutions that provide high network availability and capacity which need permission from local authorities to undertake a relevant street walk to lay fiber networks.

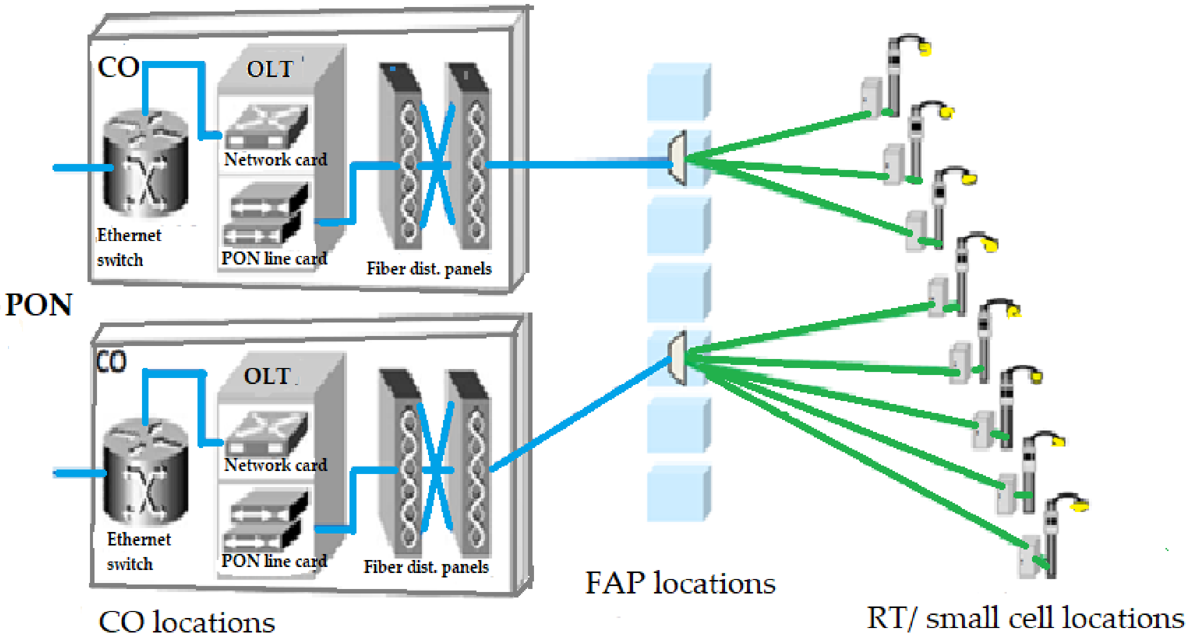


Figure 2-7 Backhaul network architecture [33]

For example, in Kentucky (USA), a guide was issued on fiber planning to communities and utilities on streamlining survey requirements and permit applications and developing pole attachment agreements [34]. Figure 2-7 shows a backhaul network which connects the small cells mounted on streetlamp post to the core network using Passive Optical Network (PON) [33].

The Optical Line Terminal (OLTs) connect with the metro network via the metro terminal equipment co-located at the Central Office (CO). Since the Passive Optical Network (PON) based backhaul network is an overlay on the existing infrastructure, the splitters need to be installed at Fiber Access Points (FAPs) such as in manholes, splice boxes, etc.

The second solution is wireless backhaul which includes millimeter-wave technologies of 60 GHz and 70-80 GHz, microwave technologies between 6 GHz and 60 GHz, sub 6 GHz radio wave technologies. Table 2-2 summarizes the associated throughput and latency of wired and wireless backhaul solutions.

Table 2-2 Performance review of different backhaul solutions [37]

Backhaul type	Backhaul technology	Latency	Throughput
Ideal backhaul	Optical fiber	< 25µs	Up to 10Gbps
Non-ideal backhaul	Digital subscriber line	15-60ms	10-100Mbps
	Wireless	5-35ms	10Mbps-100Gbps

Human exposure to EMF: It has its own impact for peoples near radio frequency which demands to keep standards strictly. ITU recommends that the International Commission on Non-Ionizing Radiation Protection (ICNIRP) limits should be used as discussed in [38].

Table 2-3 Challenges of small cell deployment and recommended solutions [39].

Key challenge	Recommended solutions
Site acquisition	Policymakers should give appropriate rights to operators to use government-owned infrastructure for deployment.
Access costs	Reasonable fees should be requested from operators to deploy small cell radio equipment onto street furniture.
Right of way (ROW) agreement	Standardized ROW usage agreements for fiber and wireless network deployment to reduce the cost and time.
Streamlining the regulatory approval for small cell equipment	Standard industry classifications of equipment with common documentation of compliance and conformity being used when defining related policies.
Radiofrequency compliance	Follow international recommendations for installation classes and provide information [38].

Table 2-3 summarizes the main challenges of small cell planning and deployment with its recommended solutions by Small Cell Forum (SCF). Operators can apply those recommendations in order to overcome small cell deployment challenges. Densification requires posts that can be used for installing base station which can be achieved by using existing street furniture or new standalone pole.

Chapter 3 - Street Furniture Usage for Small Cell Deployment

In previous years, to overcome capacity demand operators used capacity enhancement techniques that involve macro base station deployment on green fields and using building rooftops. Now a day's, densification using macrocells has site acquisition problems or may need an optimum site selection process. In some areas, it may not be affordable to deploy a new site, or the site acquisition cost might be expensive. In order to maximize the cost-benefit of street furniture usage for small cell deployment, it is better to adopt global practices.

3.1 Small Cell Deployment Global Scenario

For successful deployment of small cells, regulators, municipal authorities, site owners, operators and vendors should work jointly. In the USA, to speed-up the rollout of small cells nationwide the Federal Communications Commission (FCC) issued guidelines [39]. For example, during deployment using street furniture, local officials approve or reject within 60 and 90 days for existing and new site requests respectively.

In Europe, the new European Electronic Communication code defines the area for wireless access points and set up nationally consistent rules for streaming the deployment of the coming Fifth Generation (5G) networks. For example, during using existing infrastructure, the rule states easy access and the site rental cost should cover only the administrative costs [39].

In Brazil, small cell deployment is performed on three fronts [40]. The first is responsible for in indoor environments. The second uses a public phone booth. The third work front uses various urban street furniture of the city being with sharing companies. These three task forces are responsible for the deployment of small cells using existing infrastructure for cost-effective site selection until the final equipment installation stage.

3.2 Small Cell Deployment in Ethiopia Context

In Ethiopia, ethio telecom provides mobile service using macro base stations in both rural and urban areas of the country except the lamp site deployed at Hilton hotel. Furthermore, small cells are deployed at Telecom Excellency Academy (TExA) inside the Joint Innovation Center (JIC). Since using only macro base stations to serve the growing demand has site acquisition and rental problems due to this reason it is better to use street furniture for small cell deployment.

To improve the integration between ethio telecom, Ethiopian electric utility and Addis Ababa city road authority federal agreements were signed between those governmental companies. It is better to use this opportunity to reach on collective agreement of using street furniture for small cell deployment. From previous experience, ethio telecom is using Ethiopia Electric Power (EEP) Optical Ground Wire (OPGW) for high-speed transmission of data between cities. From 2019 onwards ethio telecom and EEP agreed with an annual rent of 1000 Birr/km/core which has the advantage to eliminate service outage because of a repeated fiber cut. Furthermore, EEU proposed its existing concrete poles (Appendix II) for optical fiber installation below power lines which minimizes site acquisition problems as well as backhaul problem.

3.3 Techno-economic Analysis of Street Furniture Usage for SCs

The attachment of small cell antennas and associated equipment on street furniture significantly improves the coverage and capacity of cellular networks. Table 3-1 depicts the benefits of street posts usage towards telecom operators, municipality, utility companies and end-users.

Table 3-1 Street post usage benefits

I. Operator benefit [41]	• Infrastructure sharing • Savings in site acquisition, installation and civil work • More capacity at reduced cost per bit • Backhaul can be deployed using fiber or microwave • Fast deployment and easy for maintenance
II. Municipality benefit [42]	• Possible to generate income from site rental • Easy for streetlamp post fault monitoring • Uninterrupted power supply connection
III. Utility benefit [4]	• Possible to generate income from site rental and energy consumption • No need for additional investment to power up the small cells
IV. End-users benefit [10, 4]	• Reduced environmental pollution • Faster data rate at high traffic locations • Longer mobile terminal battery life

In addition to those benefits, a cost-benefit analysis should be studied to assure street furniture usage for small cell deployment.

3.3.1 Cost-Benefit Analysis

Cost-benefit analysis is one of the key methodologies that provide a general picture of the cost structure of a certain technology or system to ensure its feasibility. In today’s cellular network deployment, a large amount of cost is consumed by investment and operating costs which can be attributed to site acquisition, site rental, installation, deployment of a power source and backhaul [43]. To minimize those costs operators must perform proper network planning to find the optimal locations of sites using existing infrastructures or street posts to provide better services at a lower cost.

In this study street furniture such as, streetlamp post, utility concrete pole, nearby building and new standalone pole are used. According to AACRA, new standalone pole costs around 30,800 Birr only to buy the pole as shown in Appendix I.

3.3.2 Cost Estimation and Assumptions

The cost-benefit analysis mainly depends on operational and investment costs [44].

Operational cost: includes the cost of energy (electricity and fuel), site rental, backhaul lease and others. However, this work considers only the cost of energy and site rental because backhaul lease and maintenance costs are common for the type of posts considered in this work. To know the amount of cost needed for energy consumption ethio telecom power calculation is adopted which assumes base stations supplied from commercial power for 20 hours per day and the rest 4 hours from the backup generator which is installed on the central location of street posts. Based on this:

Cost of EEU per month for a single small cell site is calculated as:

$$\mathrm{C}_{EEU/month/site} = P_{sc(kw)}.C_{(E/kwh)}.W_h.W_{d/month} \qquad (3\text{-}1)$$

Where $\mathrm{C}_{EEU/month/site}$ stands for cost of utility power/month for a single site

$P_{sc(kw)}$ small cell power consumption in kW, $C_{(E/kwh)}$ cost of energy/kWh, W_h working hour/day and $W_{d/month}$ is working days/month.

Cost of fuel per month is calculated as:

$$C_{Fuel/month/site} = F_{lt/day}.F_{tarrif}.W_{d/month} \qquad (3\text{-}2)$$

Where $\mathrm{C}_{Fuel/month/site}$ is the cost of fuel/month/site, $F_{lt/day}$ fuel consumption in liter/day, F_{tarrif} fuel tariff/liter and $W_{d/month}$ is the number of working days/month.

Cost of site rental: recently EEU proposed for ethio telecom to use its concrete poles for the deployment of fiber optics cable. According to the proposal, EEU requested 8,039.24 Birr/pole for 25 years which is around 10 Birr/month/pole as shown in Appendix II.

Investment cost: consists of base station equipment costs like, backhaul transmission equipment, Radio Network Controller (RNC), antennas, cables, cost of street post used, site build-out and installation cost. But, the total Capital Expenditure (CAPEX) in this work only considers the cost of selected posts and the cost of a new standalone pole with its installation cost as shown in Table 3-2 because equipment costs are common costs for posts considered in this work.

Table 3-2 Estimated CAPEX and OPEX [45]

No	Site Type	CAPEX type	Estimated CAPEX in Birr	OPEX type	Estimated OPEX in Birr/month
1	Streetlamp post	Site cost	0	Site rental	10.00
				Fuel cost	1,948.00
		Installation		EEU cost	17.00
2	Utility concrete pole	Site cost	0	Site rental	10.00
				Fuel cost	1,948.00
		Installation		EEU cost	17.00
3	Nearby building	Site cost	13,765.00	Site rental	1,000.00
				Fuel cost	1,948.00
		Installation	1,200.00	EEU cost	17.00
4	New standalone pole	Site cost	30,800.00	Site rental	0
				Fuel cost	1,948.00
		Installation	1,200.00	EEU cost	17.00

3.3.3 Exemplary Cost-Benefit Analysis of Small Cell Deployment on Street Posts

Based on the cost estimation and assumptions in Appendix I, Table 3-3 depicts the number of posts selected using MOO simulation to maximize capacity with a minimum number of base stations with their CAPEX and OPEX in Birr. This result is taken from the final simulation to assure the benefits of using existing street furniture rather than deploying new posts.

Table 3-3 Type of selected post with their respective CAPEX and OPEX

Type of post	No. of the selected post	CAPEX in Birr	OPEX in Birr	Total cost in Birr
Streetlamp post	53	0	1,975.00	104,675.00
Utility concrete pole	43	0	1,975.00	84,925.00
Building	8	14,965.00	2,965.00	143,440.00
New standalone pole	13	32,000.00	1,965.00	441,545.00
The total cost needed for small cell deployment for the selected 2x2km				774,585.00

From Figure 3-1 it is shown that using 53 streetlamps costs around 104,675Birr but using 13 new standalone poles (1/4th of streetlamps) costs 441,545Birr which is costly. If we consider all 117 selected small cells to be posted using streetlamp or utility pole, the total cost becomes 231,075Birr, while using new standalone pole costs 3,973,905Birr. Since hybrid post types are considered, the total cost needed is 774,585 Birr which is cheaper compared to using only a new standalone pole.

Therefore, from the cost-benefit analysis, it can be concluded that streetlamp post and utility pole usage for all selected 117 posts reduce the overall deployment cost by 17% compared to the new standalone pole for this exemplary site. The total cost of the new standalone pole for 13 sites consumes around 57% while the cost of streetlamp posts for 53 sites and utility pole for 43 sites consumes only 24% of the total cost.

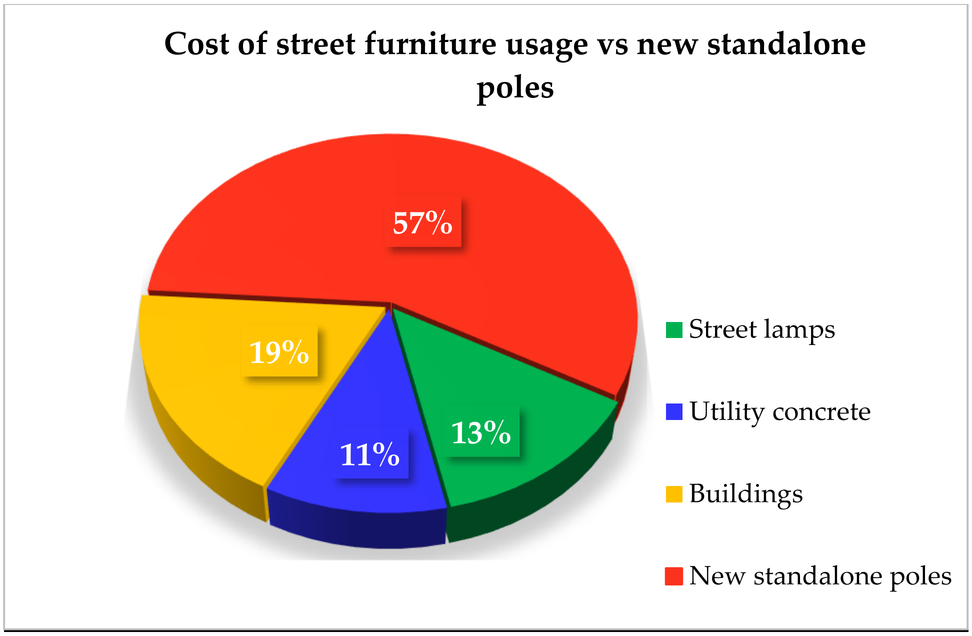


Figure 3-1 Cost of using existing posts versus new poles

This indicates, even if the number of small cells deployed on streetlamp or utility pole and building is 8 times that of new standalone pole the total cost is minimized by 33%. So, to be beneficial from the cost-benefit analysis, mobile network operators should use existing street furniture rather than new posts during small cell deployment to address the growth of capacity demand.

Chapter 4 - Network Planning and Deployment Scenario

4.1 Tools Used for this Study

WinProp is used for network planning of air interfaces and performs propagation modeling and network simulation in rural, urban, indoor, outdoor scenarios. It enables electromagnetic wave propagation simulation and performs wireless network planning [46]. The propagation model is computed by using the dominant path model with an objective of predicting the average received signal power at a given distance from the transmitter and the inconsistency of signal power in proximity to a certain location.

4.2 System Model

In this study, OFDM based multiple access cellular network composed of L base stations with system bandwidth B_{eff} . It is assumed that the coverage area (A) is divided into a small pixel (area elements) with constant received power and SINR. The network geometry is captured by the path loss matrix $G \in R^{AxL}$ (distance-dependent attenuation, antenna gains, and shadowing). Antenna gains can also be integrated within G. The vectors P_{ps} indicate the transmit power at each cell in Pilot Signals (P_S) while P_D indicates data channels. Cell selection process [46, 47] is performed based on the average pilot signal received power at each pixel which can be calculated as $a \in A$ through the following expression:

$$R_{ps}(a,l) = G(a,l)P_{ps}(l)x(l) \tag{4-1}$$

The binary vector $x \in \{0,1\}^L$ indicates whether the l^{th} small cell post is selected or not. $x(l)$ will be 1 if the candidate post is selected as a small cell post else it will be assigned zero. The actual cellular layout is determined by x which is referred to as network topology. The average pilot signal received power at a pixel a from the post l is indicated by $R_{ps}(a,l)$ Thus the a^{th} pixel is served by cell l^* if

$$l^* = \underset{l\in\{1,2,\ldots,L\}}{\arg\max}\ R_{ps(a,l)}$$

The vector $\Psi \in \mathbb{R}^A$ containing the average $SINR$ at each pixel is given by [47]

$$\Psi(a) = \left(\frac{(G(a,l^*)P_D(l^*))}{\left(\sum_{l=1, l\neq l^*}^{L} P_A(l)x(l)G(a,l)) \right) + \sigma^2} \right) \qquad (4\text{-}2)$$

Here σ^2 in (4-2) corresponds to the noise power and the a^{th} pixels are in coverage if the following two conditions are fulfilled:

- The minimum received power of selected candidates within a^{th} pixel should be greater or equal to the minimum power. Minimum received power $R_{ps}(a,l^*) \geq P_{\min}$
- Minimum SINR $\Psi(a) \geq \Psi_{\min}$

The vector $v \in \{0,1\}^A$ describes the coverage. If the previous two coverage criteria are satisfied in pixel a, $v(a)$ becomes 1 else 0. link performance is obtained by means of a non-decreasing function of the SINR. In this thesis work, Shannon's formula has been considered. Hence, the spectral efficiency that can be achieved at each pixel (in coverage) is given by:

$$\eta(a) = \log_2(1+\Psi(a)v(a)[bps/Hz] \qquad (4\text{-}3)$$

Finally, having the spectral efficiency at each pixel we can calculate throughput using the following equation:

$$TP = N_{PRB}BW_{PRB}\min\left(\eta(a), BW_{eff}\log_2\left[1+\frac{SINR}{SINR_{eff}} \right] \right) \qquad (4\text{-}4)$$

4.3 Multiobjective Optimization Problem

Multiobjective optimization is a discipline that focuses on the resolution of problems involving the simultaneous optimization of several conflicting objectives. It is defined by a decision space D, an objective space Z, and $n \geq 2$ objective functions $f_{1,} f_{2,\ldots} f_n$. Each objective function can be either minimized or maximized [47]. Objectives such as cost, energy consumption, number of base stations need to be minimized while maximizing capacity, coverage, quality and network performance.

A Multiobjective (MO) problem with conflicting objectives never has a single optimal solution but a set of optimal solutions. In this thesis work, both network capacity and number of base stations are in conflict, due to this reason MOO is a convenient tool for investigation subset of good solution $l*$ from a set L.

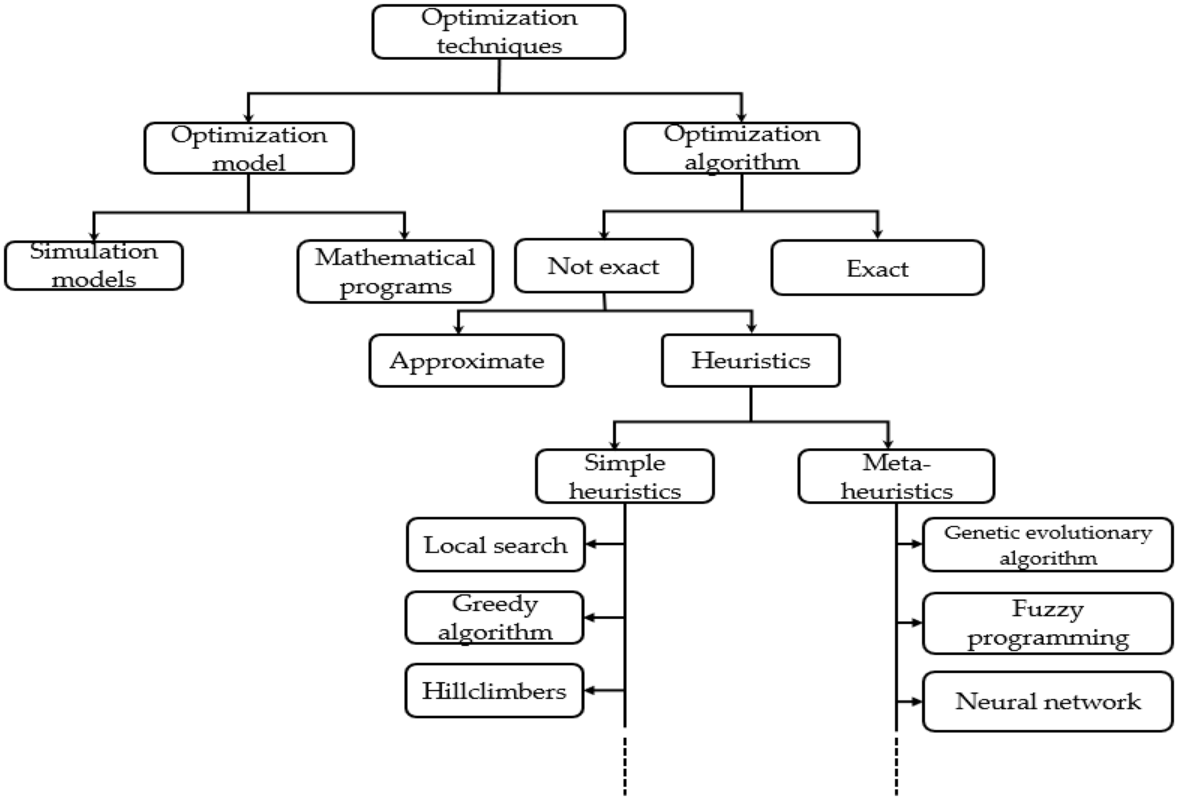


Figure 4-1 Classifications of optimization techniques [45].

Figure 4-1 shows the classification of optimization techniques from a higher level to a lower level. Optimization techniques are classified into the optimization model and optimization algorithm. Optimization models define the optimization problem based on different modeling techniques and classified into the simulation model and mathematical programs. A mathematical program formulates the problem in a mathematical representation. For simple mathematical expression, it is easy to find an analytical solution. For indirect expressions, optimization algorithms are needed to find the optimal objective value and the associated independent variable values [47].

Optimization algorithms are used to solve the optimization problems that are formulated using the optimization models which can be exact or not-exact, as depicted in Figure 4-1. Exact algorithms find a global optimum, but typically don't scale efficiently to large problems. Not-exact algorithms can either be guaranteed or not guaranteed to reach a certain level of solution quality. The former is called approximation algorithms and the latter heuristics.

A heuristic algorithm is classified into simple and meta-heuristics. Simple heuristics are very fast and quickly able to improve upon a given solution but are very prone to get stuck in local optima. Meta-heuristics can be considered to reside at one level higher and attempt to look further than the best solution in a predefined neighborhood. Evolutionary algorithms simultaneously deal with a set of solutions and select Pareto optimal solutions in a single run of the algorithm. Due to this reason, it is suitable for solving MO Problems (MOPs) than mathematical programming.

4.3.1 Genetic Algorithms

Genetic Algorithms (GAs) work based on genetics and evolutionary theory, and they have been successfully used for solving MOPs. GA deals with all sorts of objective functions no matter they are stationary or transient, linear or nonlinear, continuous or

discontinuous. These gave GAs priority in solving MOPs of network planning and optimizations. Recently, the Non-Dominated Sorting Genetic Algorithm (NSGA) has been recommended as the most efficient MO evolutionary algorithm [47].
This NSGA algorithm is based on several layers of classifications of the individuals [20]. Before selection is performed, all non-dominated individuals are classified into one category. To maintain the diversity of the population, these classified individuals are shared with their dummy fitness values. Then this group of classified individuals is ignored, and another layer of non-dominated individuals is considered. The process continues until all individuals in the population are classified. For this technique, the stochastic remainder selection is adopted which can be achieved by NSGA II.

NSGA II consists of three basic features such as it uses an elitist principle, emphasizes non-dominated solutions and uses an explicit diversity preserving mechanism. Using individual ranks builds population and sorts everyone referring to the non-domination level. Before partitioning the new combined pool into fronts uses evolutionary operations to create a new pool of offspring, and then combines the parents and offspring.

Crowding distance to each member will be added to conduct niching. It keeps the population diverse and helps the algorithm to explore the fitness landscape which is currently used in most MOO problems. Figure 4-2 describes the flow diagram of NSGA II starting from population initialization up to the final selection.

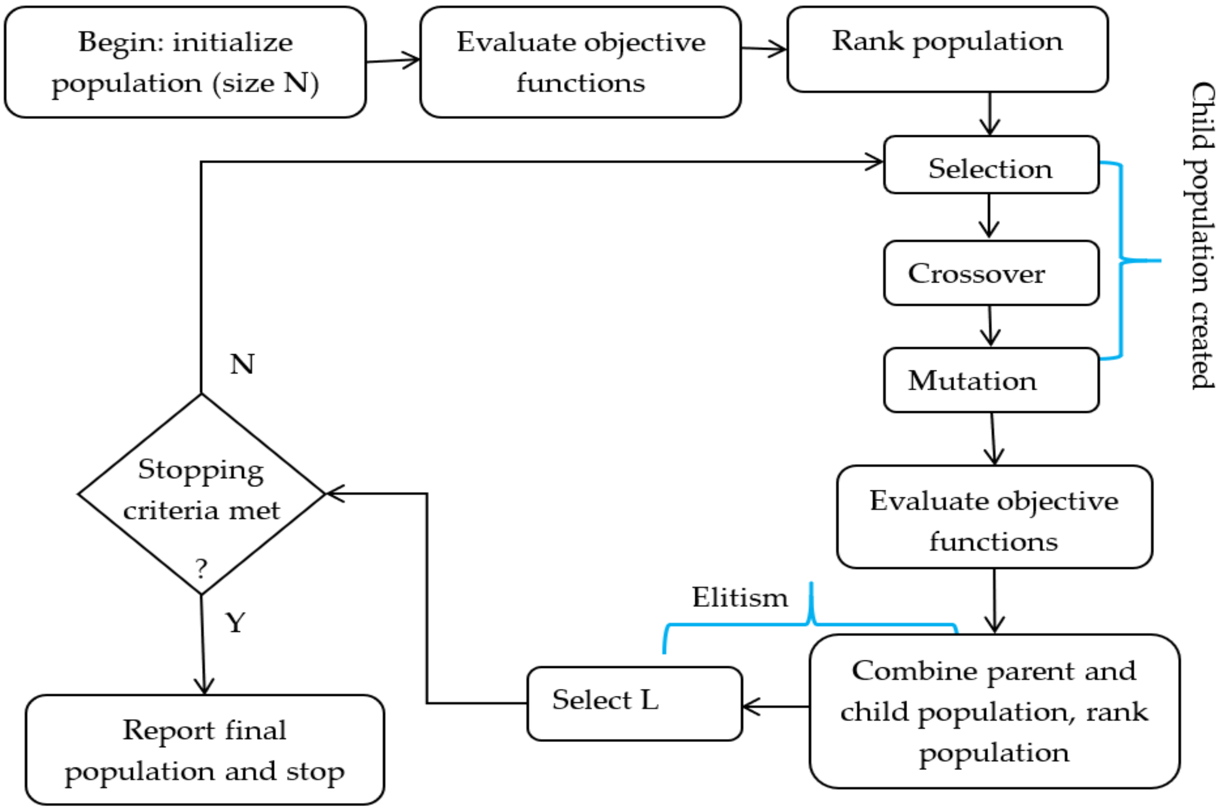


Figure 4-2 Flow chart of NSGA II [45].

4.4 Deployment Scenario and Simulation Approach

I. Deployment scenario

In mobile communication systems, cell planning, availability of base station sites and the service quality at various potential traffic demand areas are needed to be considered [47]. The exact number of cells varies significantly due to several factors, including the topography of the land, the number of obstacles, the number of users, and the traffic pattern in the specified area. Here, the overall deployment scenario and simulation approach which can maximize capacity with a minimum number of base stations will be discussed. Figure 4-3 shows the steps from deployment area identification until optimum topology selection at high level.

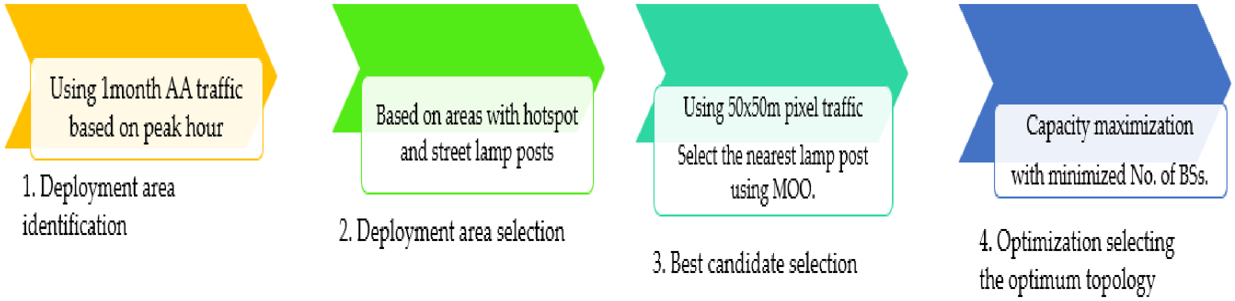


Figure 4-3 Stages from deployment area selection up to optimum topology selection

In order to assure the existence of capacity demand in Addis Ababa, data collection of 2G, 3G and 4G traffic was analyzed as shown in Figure 1-3 (Section 1.1). In this data, it is shown that there is rapid traffic growth in 3G and 4G network while in 2G almost remains the same. To study the traffic distribution for small cell deployment area selection, Addis Ababa's one-month (January 2019) packet switch download traffic is plotted using Map info as shown in Figure 4-4. In the plot, the red colors show cells with hotspot areas while the green color represents low traffic cells. Based on this an outdoor scenario based 2x2km^2 in the Megenagna area was selected which consists of marketplace (Shola Gebeya, Megenagna square) densely populated buildings, cafeterias, schools and residential areas at which potential mobile users found.

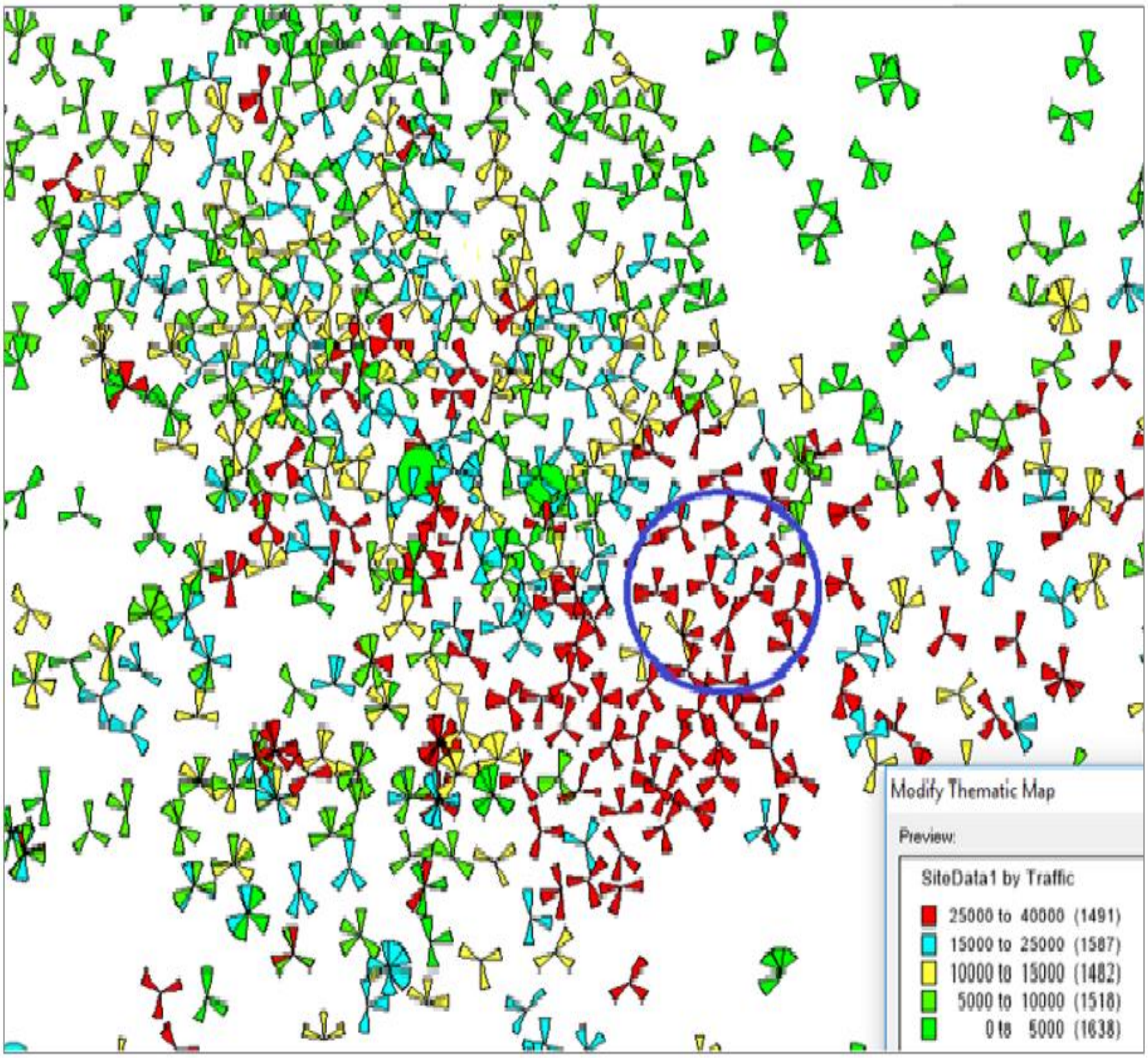


Figure 4-4 Addis Ababa traffic data for Jan. 2019 using Map info

Figure 4-5 shows the selected area with its entire deployed MBSs and possible candidate posts. The selected sites have a real antenna configuration of Kathrein_742212 having a maximum transmit power of 46 dBm. Using this deployment scenario, the path-loss maps for each small cell candidate location and 12 MBSs are generated with the help of cellular network planning tool WinProp.

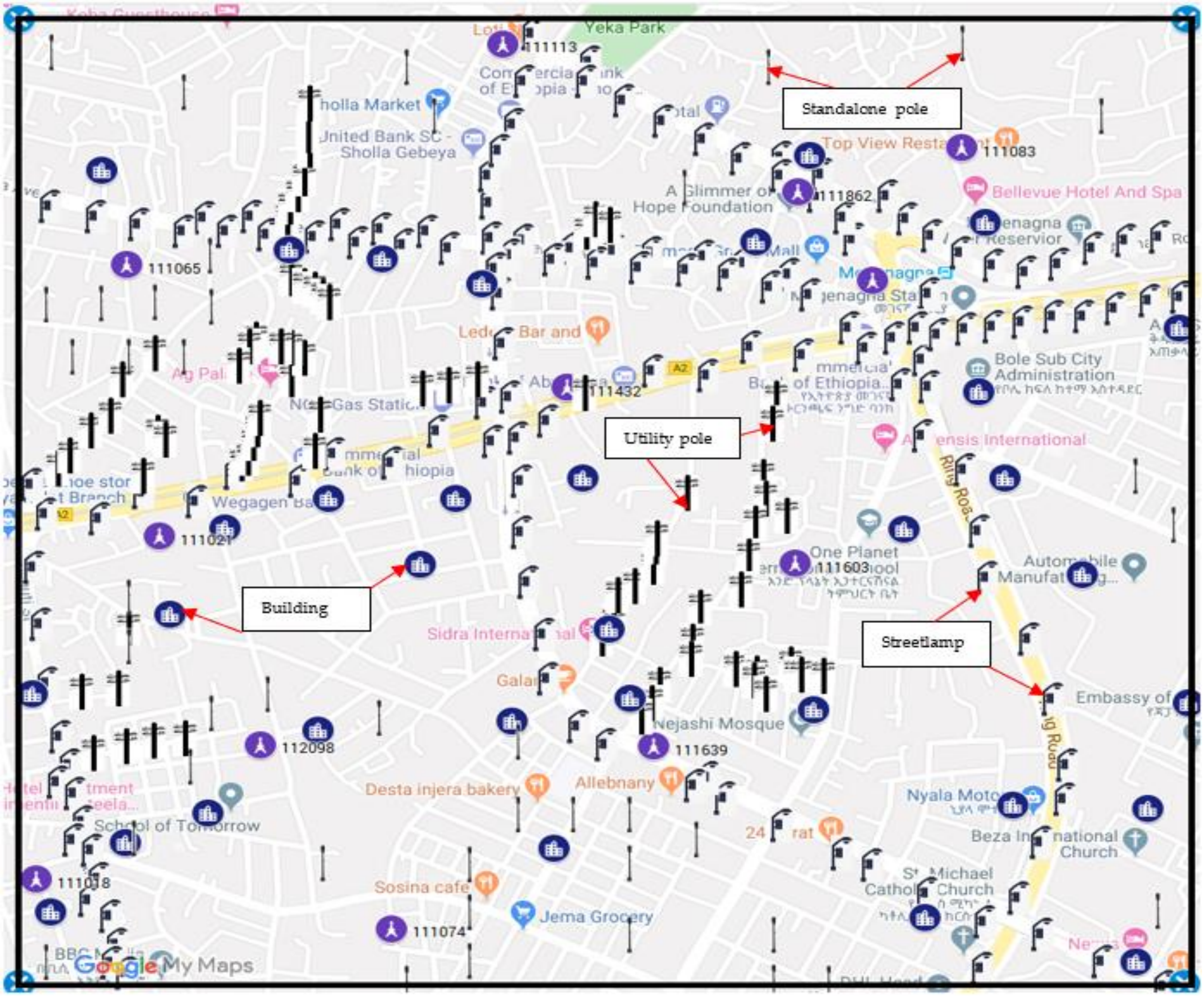


Figure 4-5 Selected area with its entire macro base stations and possible candidate sites.

The next stage is checking the existence of the capacity demand based on served and rejected traffic data. In order to say there is enough capacity on the selected area all the generated traffic from users should be served by the macro sites in their respective area. The overall capacity demand within the selected area was calculated as:

$$PS_{demand} = PS_{served} + PS_{rejected} \ , \tag{4-3}$$

$$RAB_{sucess} = TotalRAB_{att.establiish} - RAB_{failestablish} \ , \tag{4-4}$$

$$PS_{perRAB} = \left(\frac{PS_{traffic}}{RAB_{sucess}} \right), \tag{4-5}$$

The maximum traffic per RAB is found to get the rejected traffic on the selected area.

$$Rejected_{traffic} = \left(Max_{PS.traffic/RAB}\right)\left(RAB_{fail}\right). \tag{4-6}$$

Based on the above equations served and rejected traffic are calculated to make sure the existence of capacity demand. From the analysis result, it is found that the amount of served traffic on the selected area is 67% while the amount of rejected traffic is 33% as shown in Figure 4-6. However, address the customer request efficiently it is better to think for capacity enhancement using small cell deployment in a cost-efficient way.

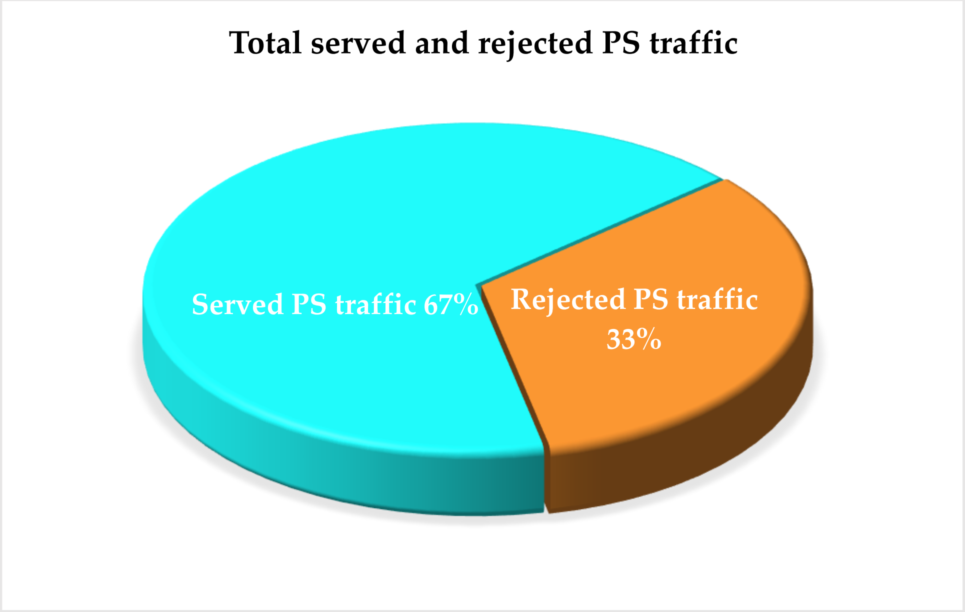


Figure 4-6 Served and rejected traffic of the selected area

After traffic demand analysis, deployment of small cells is performed using existing posts to minimize site acquisition problems in the selected area. It has different types of street posts such as utility concrete poles, streetlamp posts, bus stations, traffic light posts, buildings and new posts. The candidate sites are physically collected by using the Global Positioning System (GPS). Table 4-1 shows the number of collected candidate sites with respect to their types.

Table 4-1 Total collected street posts on the selected area with their respective height

Existing post type	No. of total posts collected using GPS.	Height in meter	No. of selected posts as a final candidate
Streetlamp post	763	9 - 12	143
Utility concrete post	130	9 - 12	81
Buildings	65	6 – 45	33
Traffic light post	10	3 - 5	-
Bus stations	4	3	-
New standalone pole	32	11	42

For this work, based on the existence of hotspot and low Received Signal Code Power (RSCP) a total of 299 candidate sites are selected. Figure 4-7 shows selected hotspot area 50mx50m pixel traffic distribution in Megabyte.

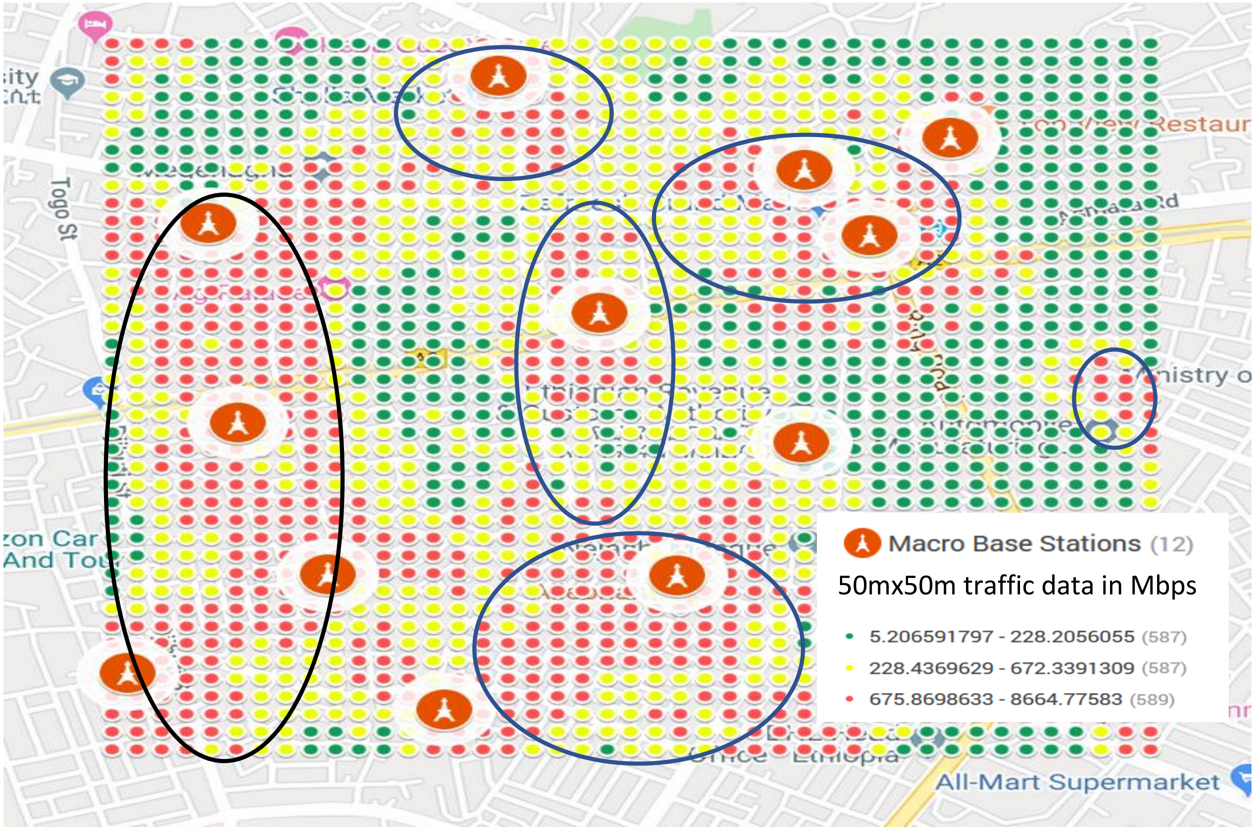


Figure 4-7 Selected area 50mx50m pixel traffic density plot in MegaByte

The small cell base stations are assumed to have a maximum transmit power of 33 dBm, with an Omni-directional antenna located at a height of 10 m. The different options to provide backhaul are assumed to be available from the central office to the location of the candidate sites. Once those maps are available, small cell optimal site selection will be performed using the following simulation approach.

II. Simulation Approach

To investigate the optimum network topology in the selected area, MATLAB is adopted by considering real wireless networks. The real cellular network in this study consists of different parameters which are given in Section 4.6. For a small number of candidates sites, the MATLAB simulator can be run in local computers. However, for more than 100 candidates, to minimize the simulation time it is better to use computer clusters or servers. Thanks to AAiT, the university high-performance computer is used which takes more than one day to come up with optimum topology on the simulation result. During the selection of optimum topology, NSGA-II is used to optimize the location of small cells as discussed in Section 4.3.1. To investigate the performance of street post usage three scenarios are considered.

The first deals with using only street lamp posts for small cell deployment. The second considers, in addition to streetlamp posts nearby building and new standalone poles which can be used for areas without streetlamp posts and buildings. The final category deals in addition to the second candidate posts utility concrete poles which is considered as hybrid topology. In this work, the performance of those categories is evaluated by two performance metrics.

4.5 Performance Metrics

The number of selected posts (f_1) deals with the number of active nodes that have a proportional relation with CAPEX and OPEX for the operators.

$$f_1 = \sum_{l=1}^{L} (x(l)) \tag{4-7}$$

Average network capacity (f_2) corresponds to each network topology x to the expected value of the sum rate. In addition to this, it considers the effect of service demand distribution (Γ). Thus,

$$f_2 = (B_{eff} .A) \sum_{l \in L_x} (| A_l |)^{-1} \sum_{a \in A_l} \eta(a) \Gamma(a) [bps] \tag{4-8}$$

Where, L_x and A_l contain indexes of the active nodes in x and the pixels served by the l^{th} node, respectively. $(A_l)^{-1}$ is the inverse of the number of pixels served by the l^{th} node and $L_x = f_1$. In doing so there are different assumptions and key parameters are taken throughout this study stated in the next section.

4.6 Assumptions and Key Parameters

In the traffic distribution study, there are uniform Spatial Traffic Distribution (STD) and non-uniform STD. In this study, uniform STD is assumed which implies service demand by users is uniformly distributed over the service area 50mx50m. Based on this, during performance investigation of street post usage for small cell deployment, randomly created 335 users are dropped on the network layout. Those users are dropped on the network layout with 1000 snapshots in a static level simulator. The simulation assumptions and parameters are shown in Table 4-2.

Table 4-2 Assumptions and simulation parameters

Parameters	Assumptions/value		
Deployment scenario	Outdoor small cell under overlaid macro network.		
Carrier frequency/Bandwidth	1800/20MHz		
Simulation	Radio propagation modeling (WinProp). Static system-level simulation (MATLAB) with 5m resolution.		
SINR-throughput mapping [49]		For UEs	For small cells
	$SINR_{min}(dB)$	-10	-10
	$SINR_{eff}$	1.8	1.8
	η_{max} (b/s/Hz)	4.4	4.4
	BW_{eff}	0.62	0.62
Macrocells Parameters			
Transmit power	46 dBm		
Antenna height	Taken from the current deployed real network.		
Antenna patterns	Kathrein_742212		
No. of macro sites/cells	12/36		
Small cells candidate parameters			
Lamppost location/height	Deployed at 9, 10, 12 m		
Buildings height	6 to 45 m		
Small cell downlink Omni antenna,	33 dBm transmit power		
Small cell backhauls	Assumed there exists backhaul from CO to small cells.		
UE height	1.5m		
Traffic distribution	Uniform spatial traffic distribution		

Chapter 5 - Simulation Results and Discussion

In this chapter, the performance gain of a street post is evaluated using Genetic algorithm-based MOO simulation for different deployment scenarios such as:

- Small cell deployment using only streetlamp posts
- Small cell deployment using streetlamp, buildings and new standalone poles
- Small cell deployment using streetlamp, utility pole, buildings and new poles

For each deployment scenario, UE throughput (UE TP), SINR and the overall UE TP gain are analyzed by taking the existing macro base stations as a baseline. The optimum topology is selected where there is an increase in capacity while having the same number of small cells or getting the same capacity with a reduced number of small cells.

5.1 Result Using Deployed MBSs with Small Cells on Streetlamp Posts

I. Figure 5-1 shows MOO simulation Pareto plot of selected topologies using only streetlamp post

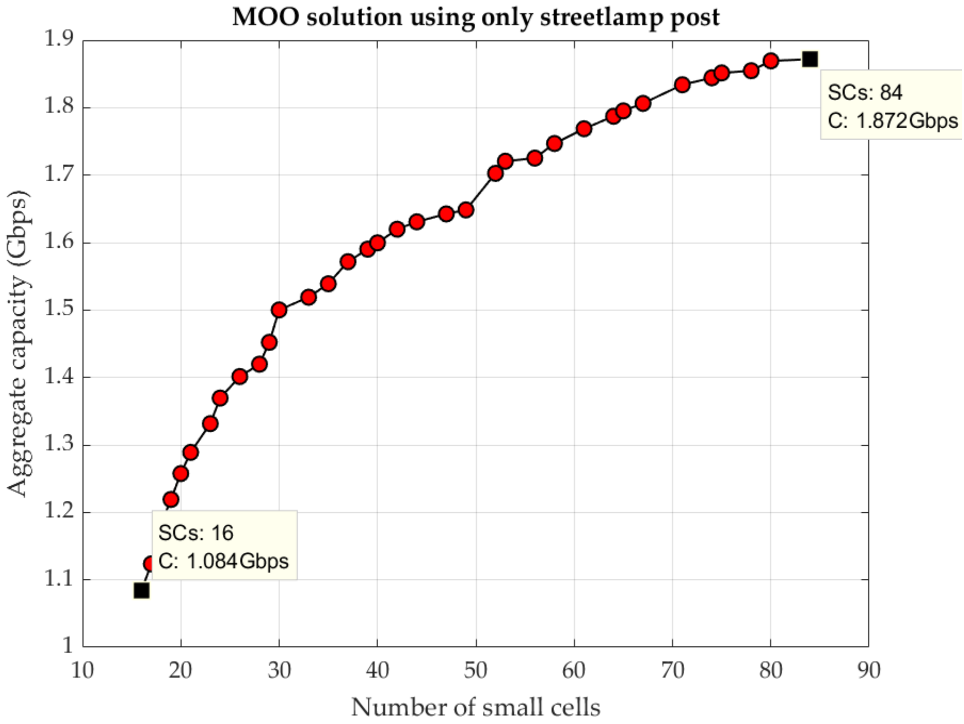
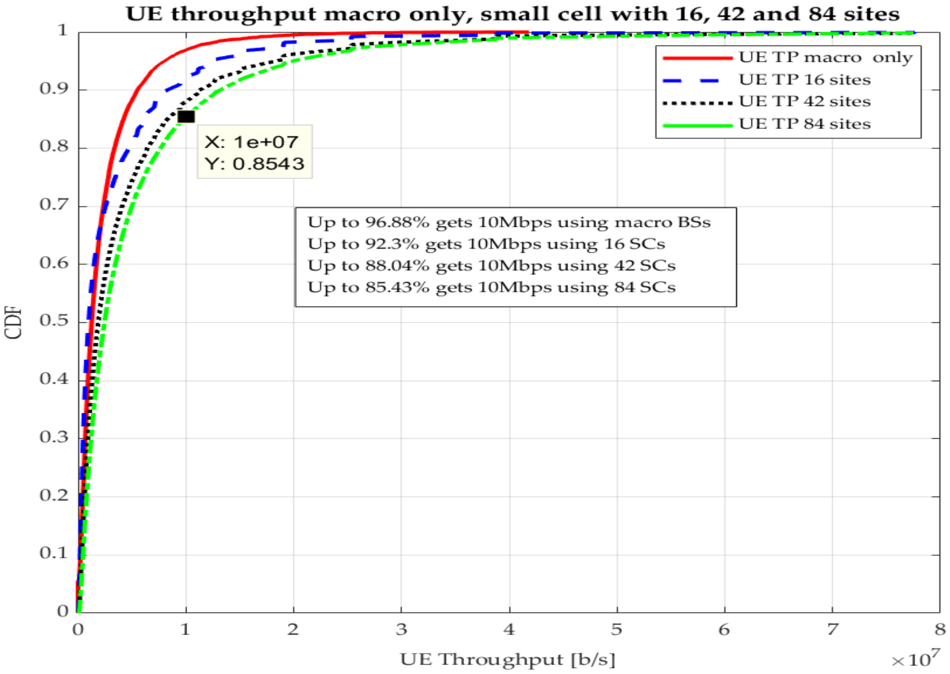


Figure 5-1 Pareto plot using only streetlamp posts

II. UE throughput results using only streetlamp posts



Up to 96.88% gets 10Mbps using macro BSs
Up to 92.3% gets 10Mbps using 16 SCs
Up to 88.04% gets 10Mbps using 42 SCs
Up to 85.43% gets 10Mbps using 84 SCs

Figure 5-2 UE throughput of different topologies

III. SINR results using only streetlamp posts

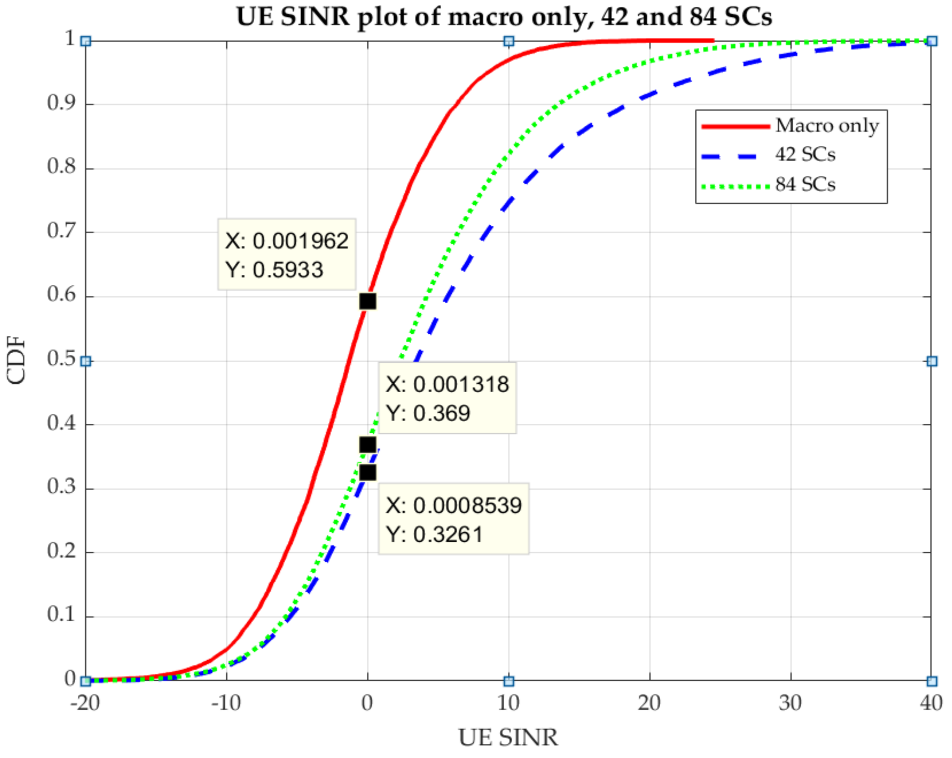


Figure 5-3 UE SINR result

IV. Percentile throughput gain using only streetlamp posts

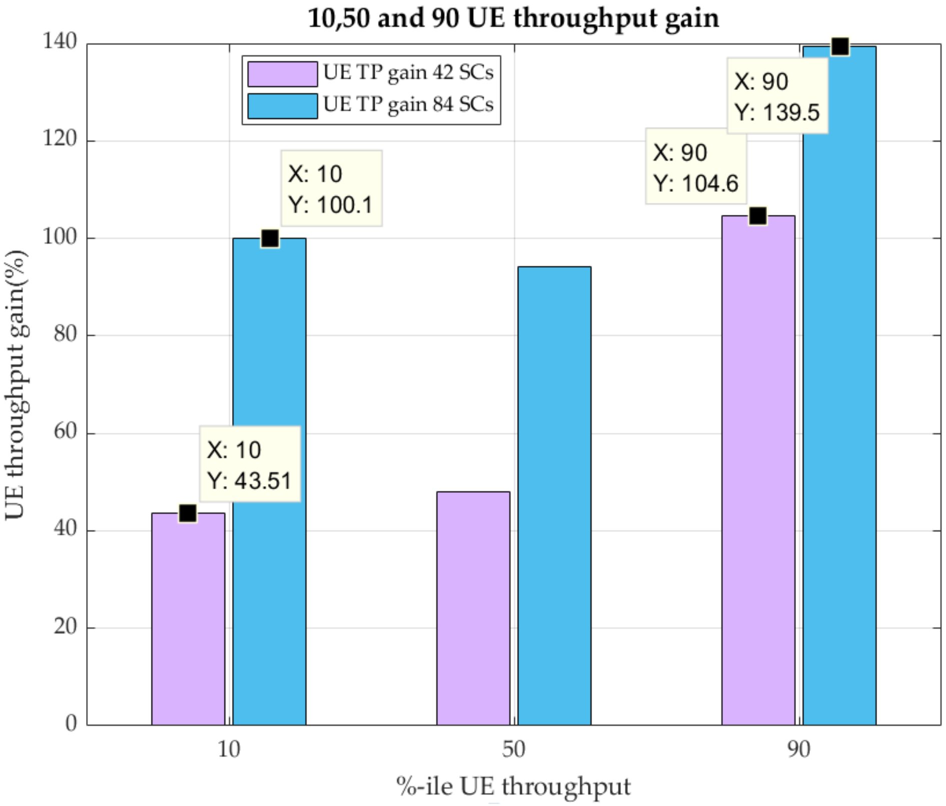


Figure 5-4 UE throughput gains at 10th, 50th and 90th percentile

During this simulation, 143 streetlamp posts are taken as possible candidate sites. The Pareto plot in Figure 5-1 shows that the minimum aggregate capacity is 1.084 Gbps with 16 small cells and 1.872 Gbps using 84 small cells.

UE throughput result in Figure 5-2 indicates the probability of users getting 10 Mbps is around 96.88% while 3.12% of them get more than 10Mbps using existing macro base stations. With SCs having 84 sites, the probability of users getting 10 Mbps is around 85.43% which has an improvement of 11.37% compared to the macro base station.

In Figure 5-3, the probability of users having an SINR value greater than zero is 67.39% for 42 SCs which has around 26.72% gain compared to MBSs whereas for 84 SCs is 63.1%. This indicates a further increase in the number of base stations for a specific area increases the interference between base station which reduces the entire SINR.

Figure 5-4 shows the 10th, 50th and 90th percentile UE TP gain setting MBS as a baseline. At the 10th percentile for 42 small cells, its UE throughput gain is around 43.5% while 84 small cells have 100% gain compared to MBS. This indicates the deployment of small cells using streetlamp posts improves cell edge performance achieved by MBS.

5.2 Result Using Streetlamp Posts, Buildings and New Standalone Poles

I. MOO simulation Pareto plot of selected topologies

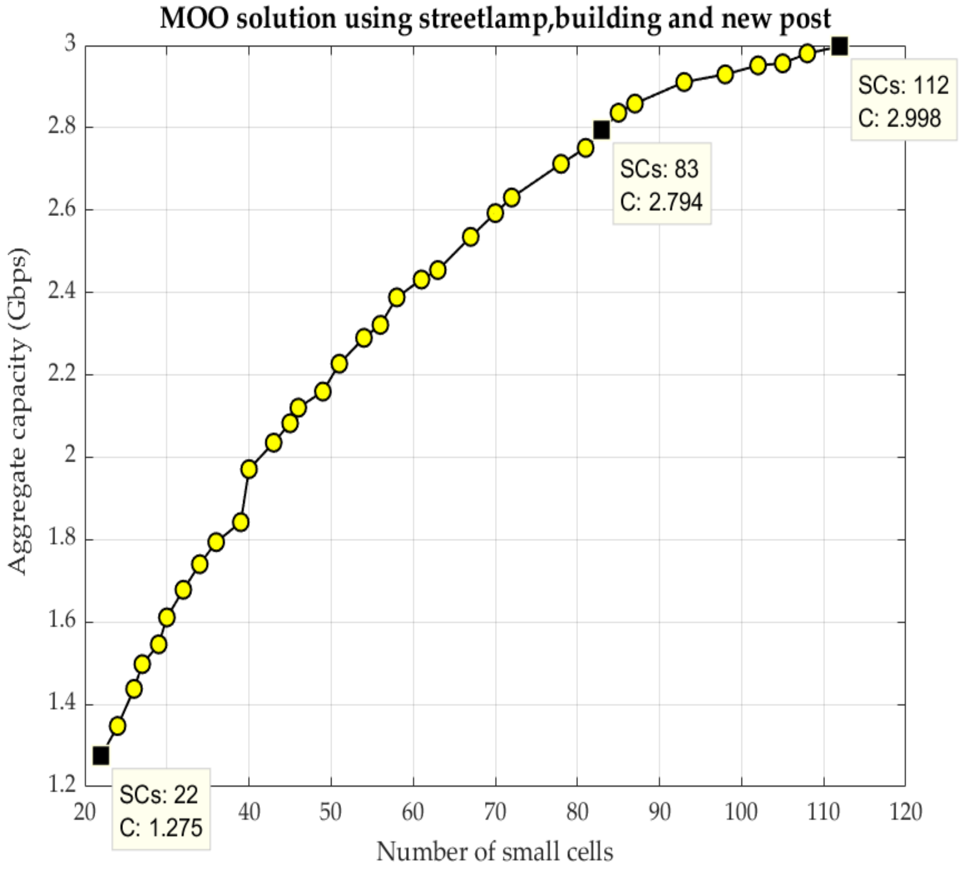


Figure 5-5 Pareto plot of selected small cell topology

II. UE throughput results using streetlamp, building and new standalone pole.

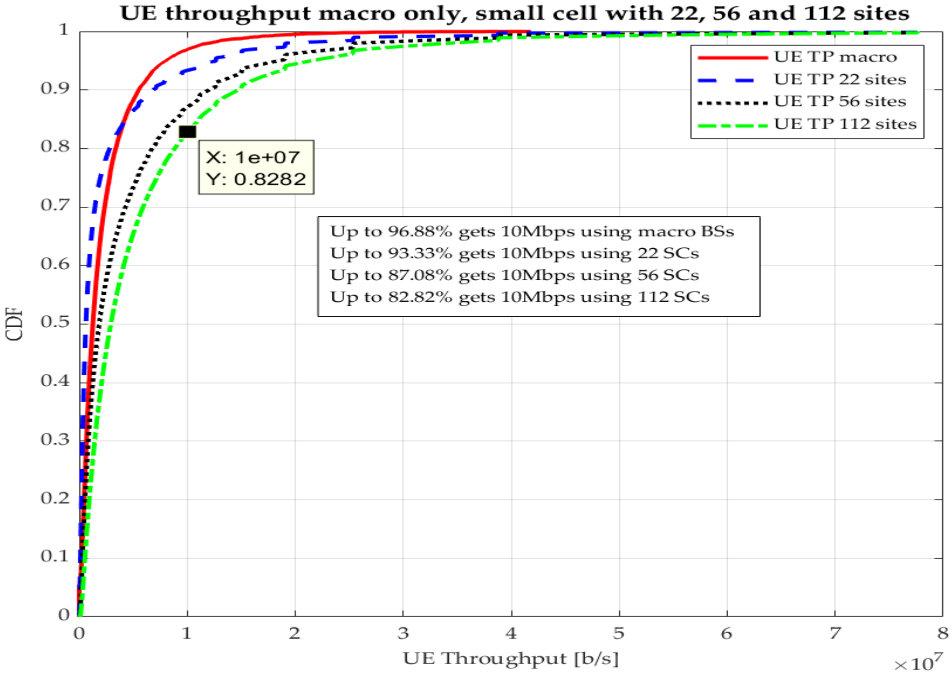


Figure 5-6 UE throughput of different topologies

III. SINR results using streetlamp, building and new standalone pole.

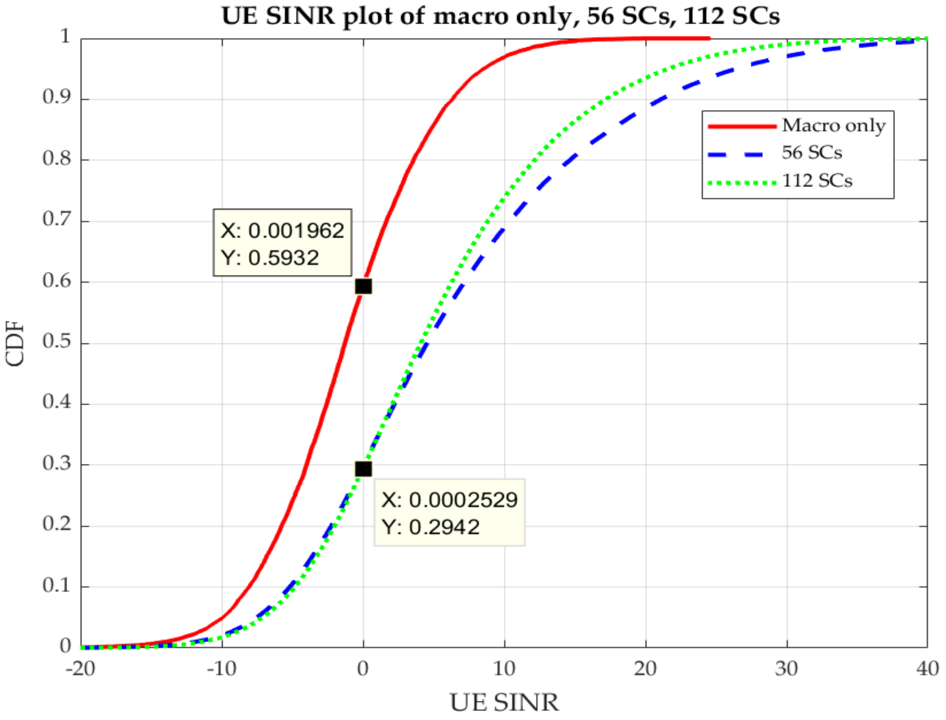


Figure 5-7 UE SINR result

IV. Percentile TP gain for streetlamp, building and new standalone pole.

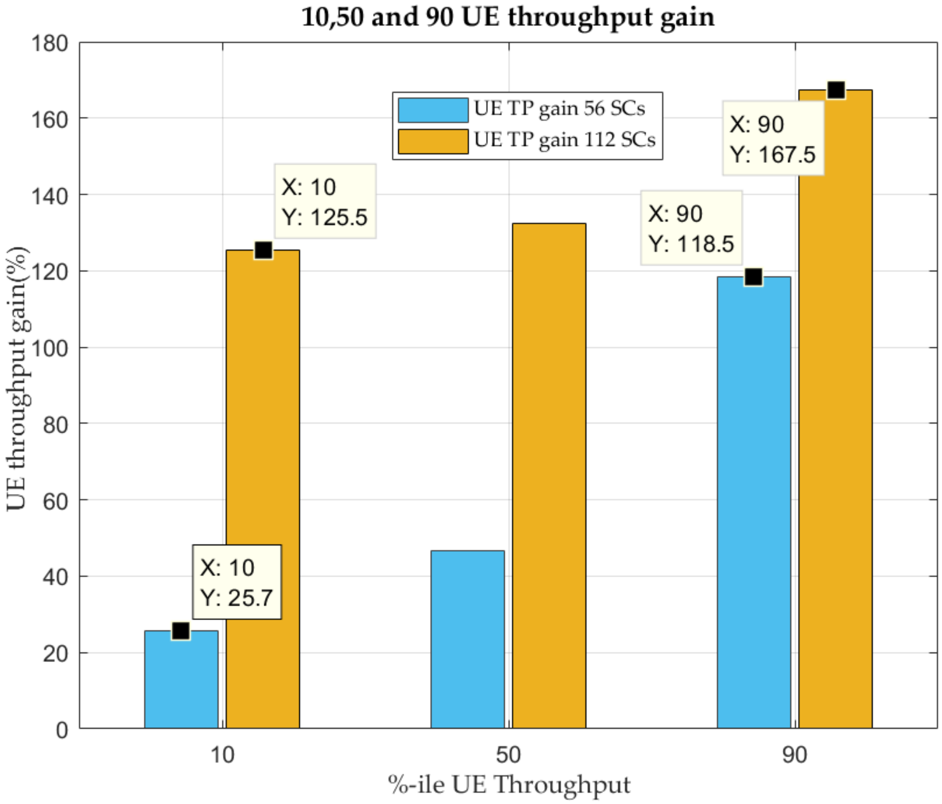


Figure 5-8 UE throughput gains at 10th, 50th and 90th percentile

In this scenario streetlamp posts, nearby buildings and new standalone poles are considered. It consists of 143 streetlamp posts, 33 buildings, 42 new poles and a totally 218 candidate posts. The Pareto plot in Figure 5-5 shows the minimum aggregate capacity is 1.275 Gbps with 22 small cells while the maximum is 2.998 Gbps using 112 small cells.

In Figure 5-6, the UE TP result indicates, the probability of users getting 10 Mbps with 112 SCs is around 82.82% while 17.18% of them get more than 10Mbps which has an improvement of 14.06% compared to the MBSs.

In Figure 5-7, the probability of users having an SINR value greater than zero is 70.58% for 56 SCs which has around 29.9% gain compared to MBSs.

From Figure 5-8, UE TP gain at 10th percentile using 56 small cells is around 25.7% while using 112 small cells has 125% gain compared to macro base stations, while 82.82% for 112 SCs. This further increase in base stations increases the interference between them which decreases the SINR value that affects the overall network performance.

5.3 Result Using Streetlamp, Utility, Buildings and New Standalone Pole

I. MOO simulation Pareto plot of streetlamp, utility, building and new pole

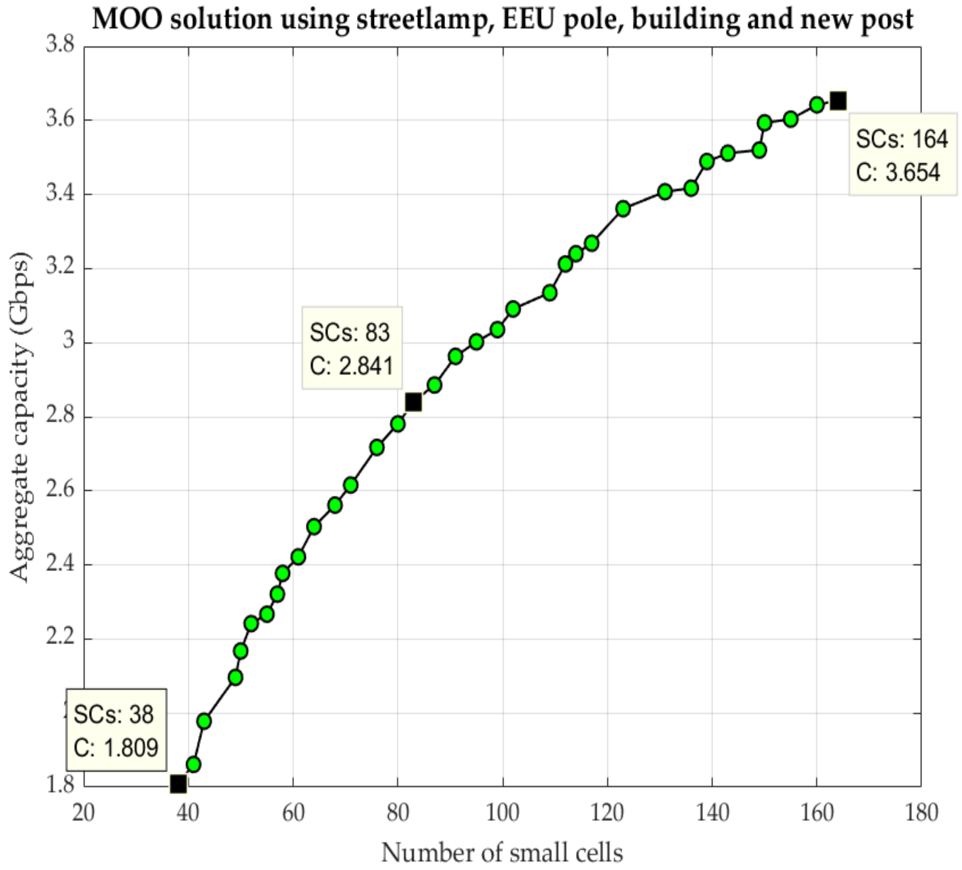
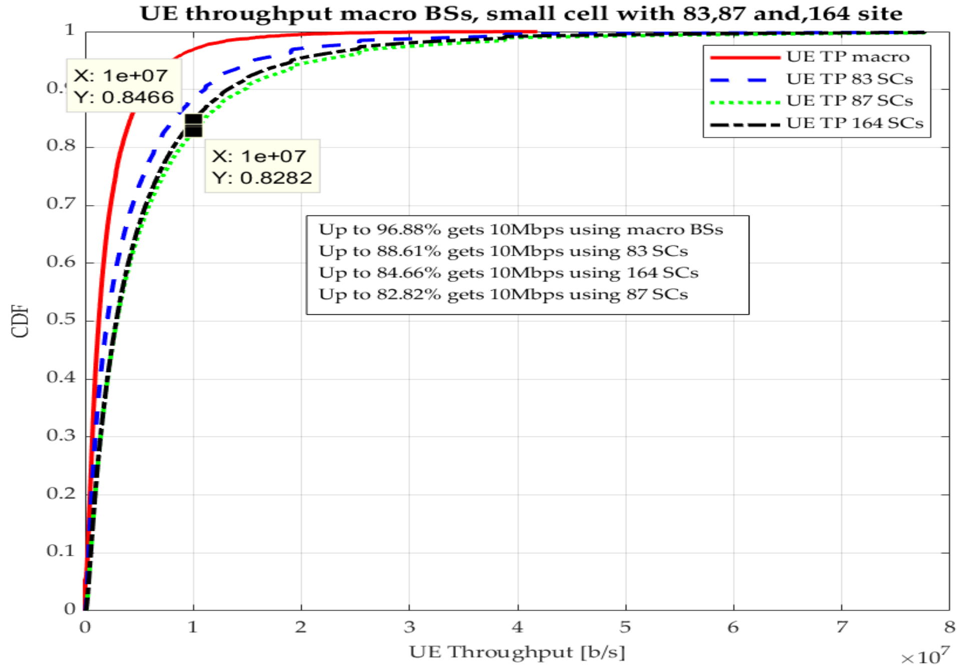


Figure 5-9 Pareto plot using streetlamp, utility, building and new standalone pole

II. UE throughput results using streetlamp, utility, building and new standalone pole



Up to 96.88% gets 10Mbps using macro BSs
Up to 88.61% gets 10Mbps using 83 SCs
Up to 84.66% gets 10Mbps using 164 SCs
Up to 82.82% gets 10Mbps using 87 SCs

Figure 5-10 UE throughput for hybrid topology

III. SINR results using streetlamp, utility, building and new standalone pole

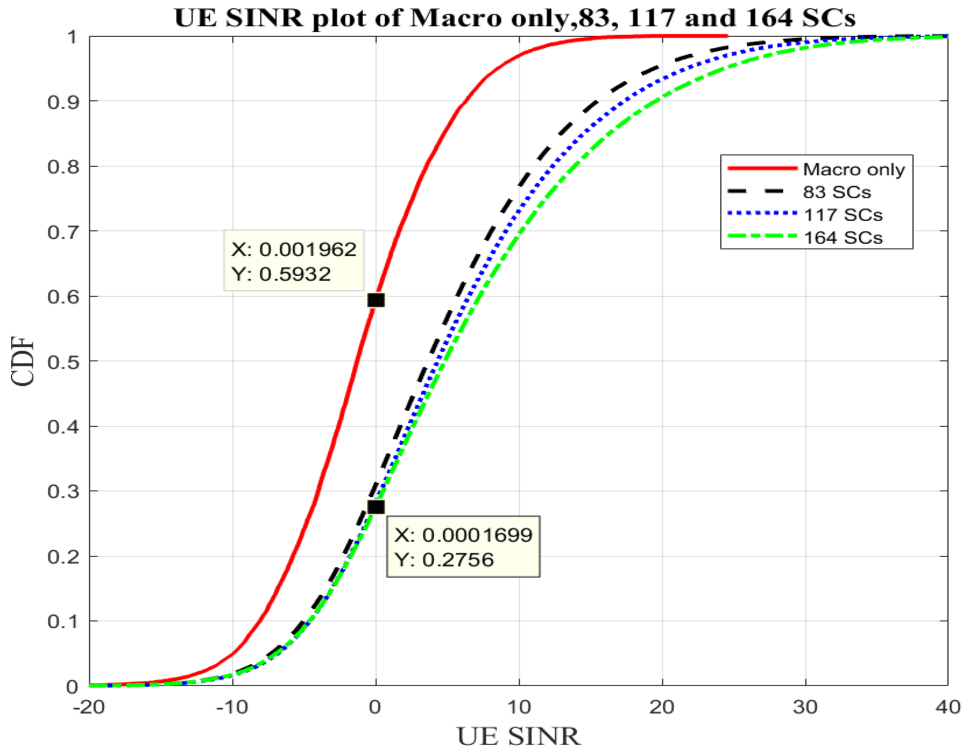


Figure 5-11 UE SINR result

IV. Percentile TP gain using streetlamp, utility, building and new standalone pole

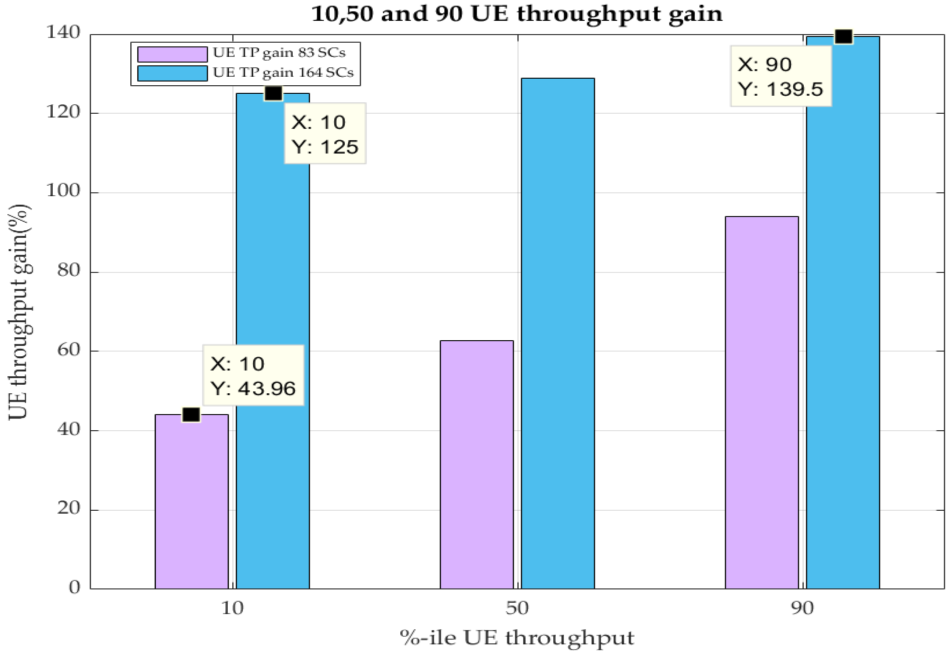


Figure 5-12 UE throughput gains at 10th, 50th and 90th percentile

The final simulation in this study deals with hybrid post usage of 143 streetlamp posts, 33 buildings, 42 new posts and 81 utility concrete poles with a total number of 299 candidate posts. The Pareto plot in Figure 5-9 shows the minimum aggregate capacity is 1.809 Gbps with 38 SCs while the maximum is 3.654 Gbps using 164 SCs.

UE throughput results in Figure 5-10 indicates the probability of users getting 10 Mbps with 164 SCs is around 84.66% while 12.22% of them get more than 10Mbps with an improvement of 12.21% compared to the MBSs. But topology with 87 SCs has an improvement of 14.06% than MBSs which shows the need for proper topology selection.

In Figure 5-11, the probability of users having an SINR value greater than zero is 72.44% for 164 SCs which has around 31.76% gain compared to MBSs.

Figure 5-12 shows at 10th percentile UE TP gain using 83 SCs is around 43.96 while using 164 SCs has 125% gain compared to MBSs.

Finally, from the given candidates the following street furniture are selected for small cell deployment for Megenagna area 2x2 km^2 as shown in Table 5-1.

Table 5-1 Types and number of selected street posts

Type of post	No. of candidates	No. of selected post
Streetlamp post	143	53
Utility concrete pole	81	43
Building	33	8
New standalone pole	42	13

Figure 5-13 shows the final location of selected hybrid small cell posts with streetlamp, utility, building and new standalone pole.

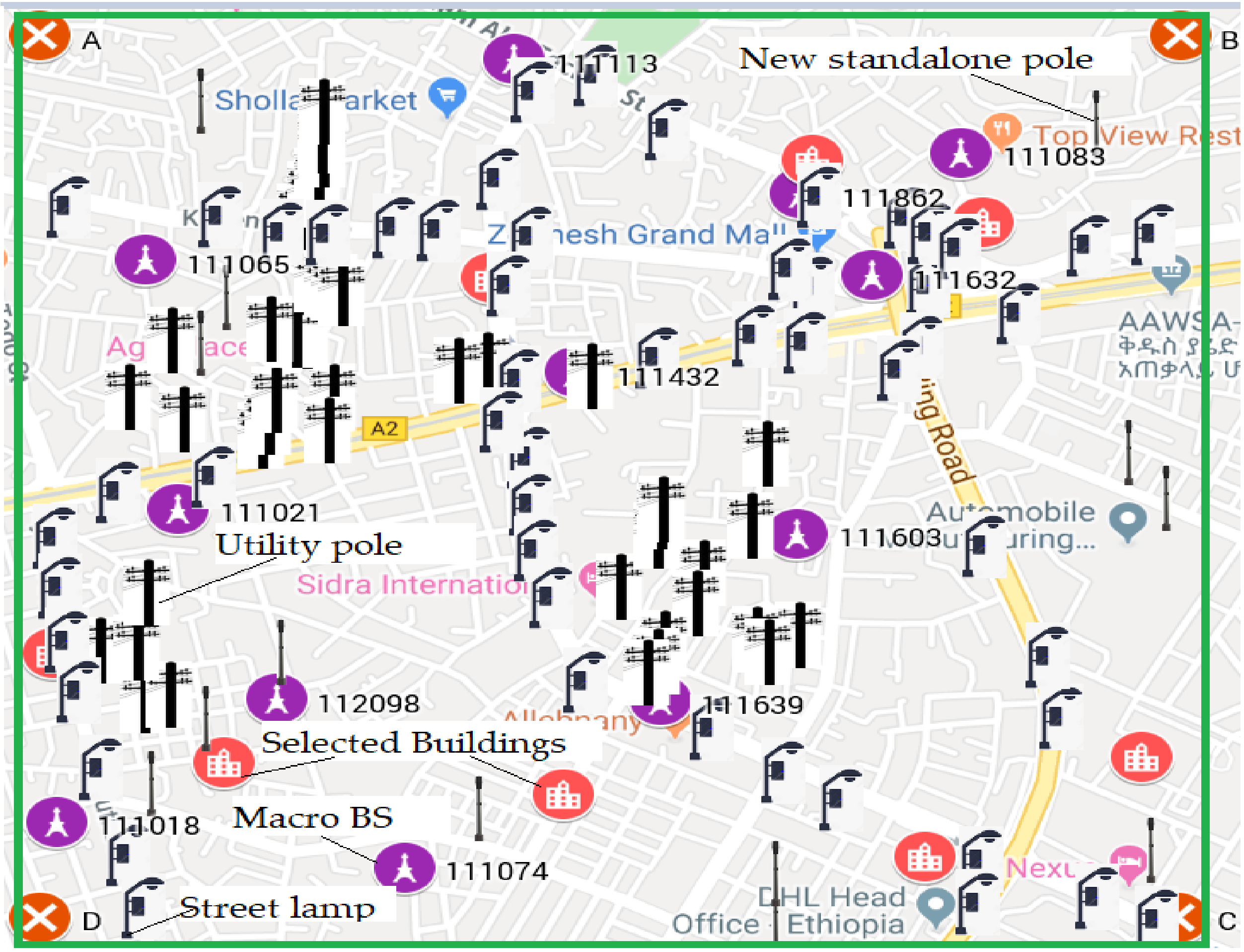


Figure 5-13 Final selected hybrid existing posts for small cell deployment

From MOO simulation result all scenarios are summarized as follows. As shown in the summarized Pareto plot of Figure 5-14, the maximum capacity achieved using the existing 12 MBSs with 36 cells is 145.5 Mbps. However, using (only streetlamp posts with 84 small cells) and using (streetlamp, building and new post with 112 small cells) has a maximum capacity of 1.872 Gbps and 2.998Gbps respectively. Furthermore, hybrid of all posts provides a capacity of 3.654Gbps with 164 small cells which have 25% capacity gain compared to the existing macro base stations.

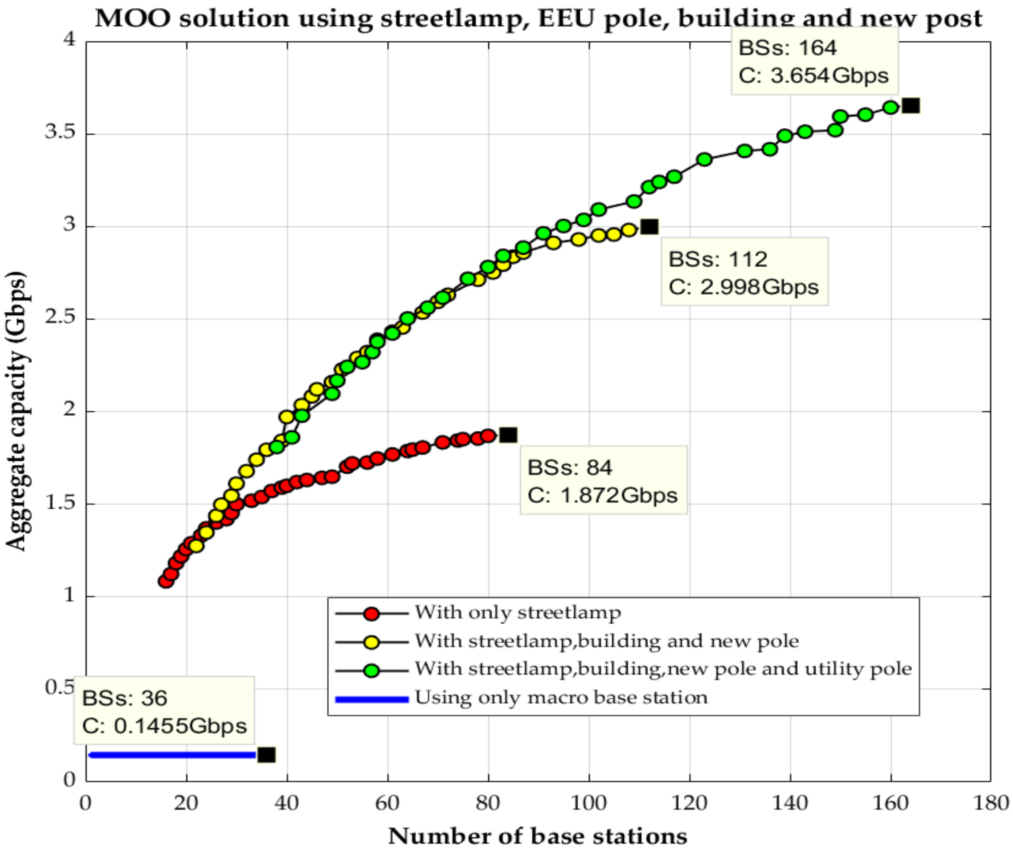


Figure 5-14 Pareto plot for hybrid usage of all posts

Optimization can be achieved from using the same number of small cells that provide improved capacity or providing the same amount of capacity with a minimized number of base stations. For example, using only streetlamp posts the maximum capacity achieved is 1.8Gbps with 84 SCs while using hybrid it becomes 2.841Gbps with the same number of SCs as shown in Figure 5-15.

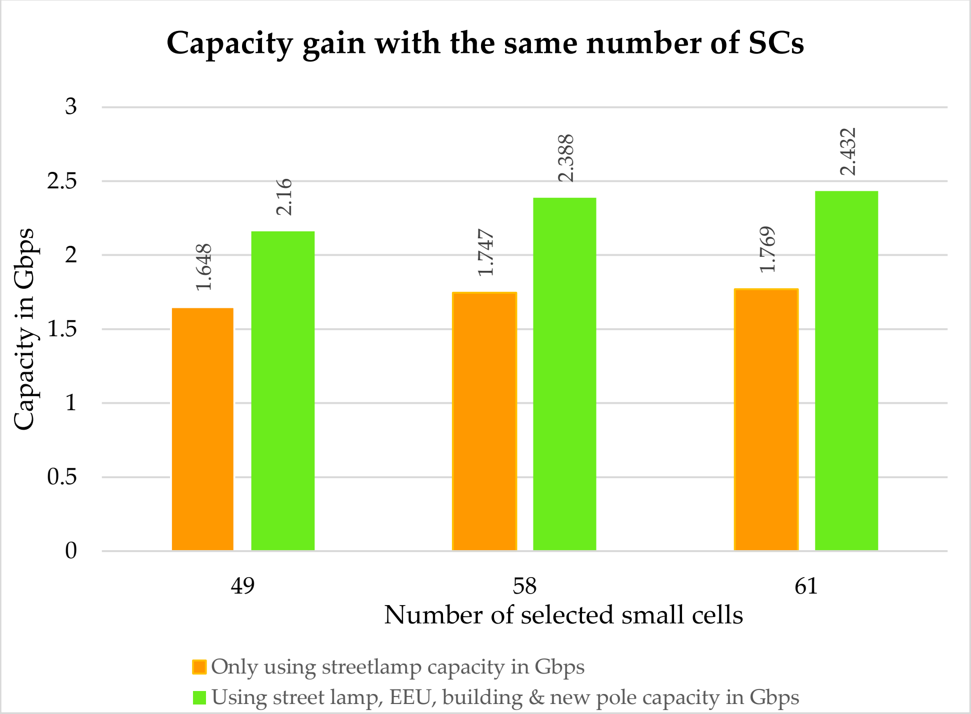


Figure 5-15 Capacity gain for different topologies with the same number of small cells

Using multiobjective optimization in small cell base station planning help us in order to find the optimum topology which maximizes the network capacity without affecting the number of base station or vice versa as shown in Figure 5-15.

Chapter 6 - Conclusion and Future Work

6.1 Conclusion

The limited network resource enforces mobile network operators to study capacity and performance improvement techniques to provide better service for their customers. This study has sought performance investigation of street furniture usage for small cell deployment for selected Megenagna area in Addis Ababa. To maximize network performance, it needs the optimal placement of small cells from candidate sites in the selected area.

The simulation result indicates when only streetlamp posts are considered as a candidate the maximum capacity achieved was 1.872 Gbps with 84 small cells. However, at the final simulation using a hybrid of street furniture, the capacity is improved to 2.841 Gbps with 83 number of small cells. This indicates that using the same number of small cells the possibility of achieving better performance which minimizes operational and investment costs.

In most literature during cellular network deployment cost reduction can be achieved by reducing the number of base stations without affecting the required capacity, in addition to this, in this thesis using a street lamp or utility pole for small cell deployment has 17% cost reduction per pole than using new standalone pole for mobile network operators.

To conclude, using street furniture for small cell deployment has a remarkable capital and operational cost reduction while maximizing the capacity of the network. In addition to this, it enables utility companies to generate revenue from rental fees which encourages mobile network operators to use existing posts rather than new posts.

6.2 Future Work

In this study, the main target was on using street furniture for small cell deployment in a cost-efficient way. In doing so, it needs wired or wireless backhaul which connects the small cells with the central office.

The potential future works can be:

- Cost-effective backhaul network design for small cell deployment during street post usage.
- Rules and regulations to be applied in using street furniture for small cell deployment should be studied in the case of ethio telecom based on global practice.
- In the case of multi-operator, having individual network equipment maximizes site acquisition problems which needs infrastructure sharing between operators that can be future work.

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Appendix I

Table A-1 consists of possible small cell candidate pole types with their respective cost in Birr and height in meter as per source from AACRA and EEU planning and design department.

Table A- 1 Possible candidate pole types with their respective cost and height

No.	Pole type	Unit	Cost in Birr	Height	Ref.
1	Double arm octagonal steel streetlamp posts	pcs	29,700.00	12 mt	[45]
2	Octagonal steel streetlamp posts double-arm at top and at 1/2 of height	pcs	30,800.00	12 mt	
3	Single arm octagonal steel streetlamp posts	pcs	28,500.00	12 mt	
4	Single arm octagonal steel streetlamp posts	pcs	25,200.00	10 mt	
5	Single arm octagonal steel streetlamp posts	pcs	22,100.00	9 mt	
6	Concrete pole	pcs	8,708.45	12 mt	[5]
7	Concrete pole	pcs	7,982.75	11 mt	
8	Impregnated wooden pole	pcs	2,623.44	12 mt	
9	Impregnated wooden pole	pcs	2,429.22	11 mt	
10	Impregnated wooden pole	pcs	1,962.19	9 mt	

Appendix II

Table A-2 Summary of cost-sharing by ET for medium voltage (MV) and low voltage (LV) EEU networks under Addis Ababa distribution rehabilitation & upgrading project (AADRUP).

Table A- 2 Summery of utility pole cost-sharing

No.	**Item description**	**Quantity**	**Make ready cost (Birr)**	**ET annual rent rate (Birr)**	**Ethio telecom cost-sharing in (Birr)**
1	Standard MV concrete pole 12mt	1	5,186.61	114.105	8,039.24
2	Rocky soil MV concrete pole 12mt	1	5,746.57	126.424	8,907.17
3	Standard LV concrete pole 10mt	1	5,004.14	110.091	7,756.41
4	Rocky soil MV concrete pole 10mt	1	5,564.10	122.410	8,624.35

1. NB. Make ready cost: ethio telecom will pay a one-time upfront fee for any "make ready" work required by EEU to make a pole ready to allow telecommunications attachments.
2. $$Total\ ET\ cost\ sharing\ for\ 25\ years\ charge\ rate\ (Birr) = makeready\ cost\ (onetime\ cost) + ((ET\ annual\ rent)\ (25\ years)).$$