



Addis Ababa University
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Communication Engineering Graduate Program

***Techno-Economic Analysis of 5G Hybrid Deployment of Sub
6GHz and mmWave Band: The Case of Bole area, Addis
Ababa, Ethiopia***

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ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
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ABSTRACT

As wireless communication demand increases, fourth-generation (4G) networks are becoming insufficient. Fifth-generation (5G) networks address this challenge by offering higher data rates, lower latency, and improved Quality of Experience (QoE). Key enabling technologies include Massive Multiple-Input Multiple-Output (Massive MIMO), millimeter-wave (mmWave) communication, and device-to-device communication. In Ethiopia, Ethio Telecom has launched the deployment of 5G services using the sub-6 GHz (3.5 GHz) band, It will eventually be expanded to mmWave (28 GHz).

The aims of this thesis is to analyze the techno-economic feasibility of a hybrid 5G deployment in the Bole area of Addis Ababa, combining sub-6 GHz (3.5 GHz) macro cells with mmWave (28 GHz) micro cells through carrier aggregation. This analysis uses data from Ethio Telecom, literature, and (3rd Generation Partnership Project) 3GPP specifications. Execute network dimensioning and apply a modified version of the Techno Economic Results from the Advanced Communications Technology and Services (TERA) tool for cost and revenue modeling, and a five-year financial analysis using a 10% discount rate.

The analysis shows that the hybrid 5G deployment model is both technically feasible and economically viable. Key financial indicators include a payback period of 4.48 years, a positive Net Present Value (NPV) of ETB 193.98 million, and an Internal Rate of Return (IRR) of 30%, which exceeds the assumed discount rate. These findings support the strategic adoption of hybrid 5G networks to meet Ethiopia's growing connectivity needs.

Key Words: 5G New Radio, Sub 6GHz, mmWave, QoS, TERA, Techno-economic Analysis

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List of Abbreviations

3GPP	Third-Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GC	5G core
AA	Addis Ababa
AAU	Active Antenna Unit
AR	Augmented Reality
ACTS	Advanced Communication Technologies and Services
ARPU	Average Revenue per User
CA	Carrier aggregation
CAPEX	Capital expenditure
CF	Cash Flow
CPS	Cyber-Physical System
D2D	Device to Device
DCF	Discounted Cash Flow
DL	Down Link
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
gNB	Next-Generation Node B
HetNet	Heterogeneous Network
IMT-2020	International Mobile Telecommunications-2020
IoT	Internet of Thing
ISP	Internet Service Providers
IRR	Internal Rate of Return
LTE	Long Term Evolution
Mbps	Mega bits per second
ms	milliseconds
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
mMTC	Massive Machine Type Communication
NR	New Radio

NG-RAN	Next Generation Radio Access Network
NOMA	Non-Orthogonal Multiple Access
NR-CA	NR Carrier aggregation
NR-DC	NR-NR Dual Connectivity
NSA	Non-Standalone
NPV	Net Present Value
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational expenditure
OAM	Operational and Maintenance Cost
PBP	Payback Period
PPP	Poisson point process
QoS	Quality of Service
QoE	Quality of experience
RAN	Radio Access Network
RAT	Radio Access Technologies
ROI	Return on Investment
SA	Standalone
TEA	Techno Economic Analysis
TERA	Techno Economic Results from ACTS
TCO	Total Cost of Ownership
URLLC	Low Latency Communications
UL	Up Link
UE	User Equipment
VR	Virtual Reality

Chapter 1: Introduction

1.1 Background

Mobile Internet and Internet of Things (IoT) are two important factors that will help fifth-generation (5G) communications grow. Experts create use cases to demonstrate the necessity of new technologies whenever they are introduced. Similar to previous generations, the International Telecommunication Union (ITU) has created a use case diagram for 5G, which includes Ultra-Reliable and Low Latency Communications (URLLC), Massive Machine Type Communications (mMTC), and Enhanced Mobile Broadband (eMBB) [2, 3]. It's a triangular map that assigns an application category to each corner and then graphs specific applications (eHealth services, automotive driving, augmented reality (AR)/virtual reality (VR), cyber-Physical Systems (CPS), and soon.) within the triangle based on the extent to which they share the characteristics of each category [3].

- Enhanced Mobile Broadband (eMBB):- This use case provides greater data bandwidth which helps developing AR/VR, UltraHD streaming video, and many more.
- Massive machine type communications (mMTC):- This use case supports to improve large implementation of IoT. mMTC deployment handles of a huge number of devices.
- Ultra-Reliable Low-Latency Communications (URLLC):-This use case supports remote medical surgery, public protection, disaster relief, transportation safety, etc[39].

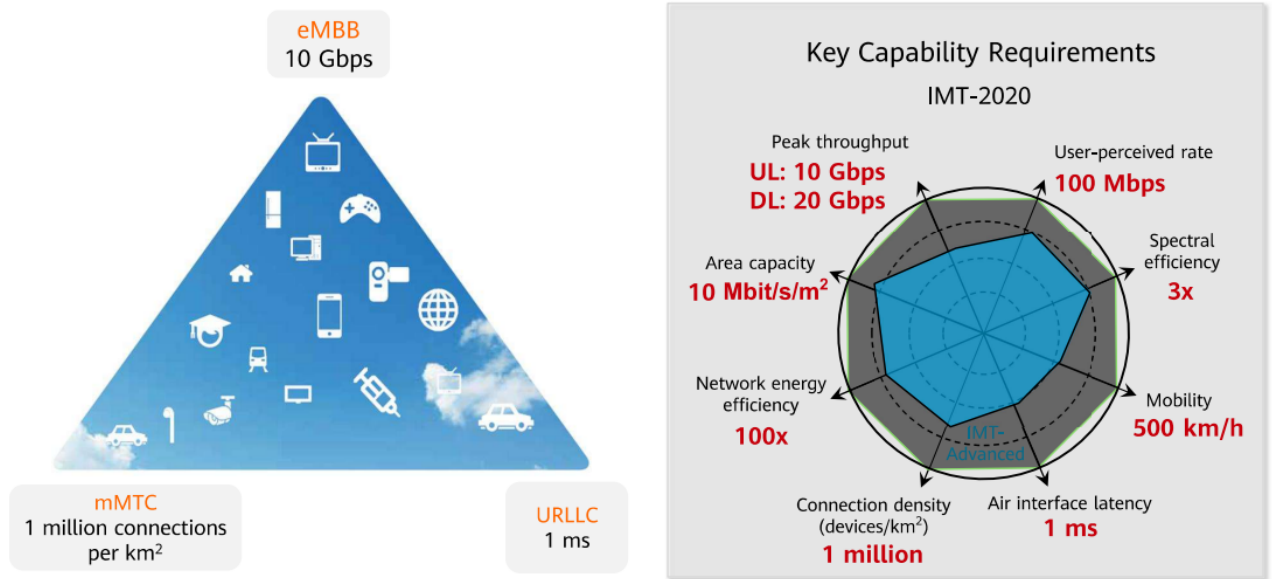


Figure 1.1: Summary of 5G Uses Case [15]

1.2 Statement of the Problem

The telecommunications sector is rapidly evolving, with increasing demand for faster, more reliable mobile services. In Ethiopia also, mobile data usage is growing due to the data-driven applications and widespread adoption of smartphones. In response, Ethio Telecom has launched 5G services, primarily using the sub-6 GHz (3.5 GHz) frequency band in none stand alone (NSA) deployment option, it will expand into mmWave (28 GHz) in the future.

However, there is currently a lack of detailed local studies evaluating the technical and economic impact of deploying a hybrid 5G network, one that combines sub-6 GHz macro cells with mmWave micro cells. This absence of techno-economic evaluation could lead to inefficient investments, higher operational costs, and reduced network performance in high-demand areas like Bole, Addis Ababa when deploy this hybrid network. Therefore,

a structured study is needed to assess whether a hybrid 5G approach is a viable and cost-effective solution for meeting Ethiopia's growing connectivity needs.

1.3 Objectives

1.3.1 General Objective

To provide the technical and economic analysis of deploying 5G networks in the hybrid frequency of sub 6GHz (3.5GHz) and mm wave (28GHz) band in the bole area, Addis Ababa, Ethiopia.

1.3.2 Specific objectives

The following particular tasks help to achieve the above general objective:-

- To study the fundamental concepts and architecture of 5G network systems.
- To examine the deployment of 5G networks using 3.5 GHz (sub 6 GHz) and 28 GHz (mm-wave) frequency bands through literature, standards, and current technologies.
- To assess the technical feasibility of deploying 5G hybrid networks in the Bole, Addis Ababa, using a hybrid frequency approach that combines sub-6 GHz and mmWave bands.
- To develop a financial model that assesses the economic viability of 5G deployment using the hybrid frequency bands.

1.4 Methodology

In order to accomplish the objective within the allotted time, the procedure can be broken down into different stages.

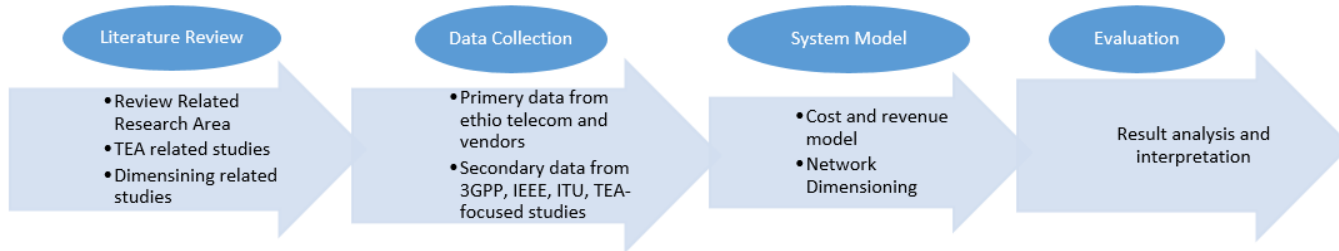


Figure 1.2: Proposed Methodologies.

Started with a literature review, which examined existing research on 5G deployment strategies, techno-economic analysis (TEA) models, and network design methodologies. This phase provided a foundational understanding of relevant technologies, modeling tools, and deployment scenarios.

Both primary and secondary sources were used to obtain data after the literature review. Ethio Telecom and the vendor Huawei provided the primary data, while 3GPP standards, IEEE papers, ITU publications, and earlier TEA-focused research provided the secondary data. The information gathered included market trends, cost projections, and technical aspects required for precise modeling.

A system model was then developed for a hybrid 5G network architecture combining 3.6GHz (sub-6) macro cells and 28GHz (mm-Wave) micro cells. This model incorporated propagation modeling, radio network dimensioning, and financial modeling of capital expenditure (CAPEX), operational expenditure (OPEX), and projected revenue. A modified

version of the TERA model was applied to align the analysis with the specific objectives of the study. Network simulations were performed using Atoll software, a widely used tool for radio planning and optimization.

Lastly, the Total Cost of Ownership (TCO) was determined, economic viability was evaluated using metrics like Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period, and sensitivity analysis was performed to gauge how reliable the findings were.

1.5 Literature Review

In the 5G network technology, sub 6GHz and mmWave band is now attractive and large attention from both academic and industry sector. There are different types of research investigated the performance of the sub 6GHz and mmWave band scenarios. Below is a brief summary of some of the studies that have been done on hybrid or coexisting circumstances and are connected to this topic.

T. Kebebew [1] examines 5G sub-band (3.5 GHz) and 5G mmWave (26 GHz) frequencies to assess coverage, capacity, and cost performance of 5G mobile radio networks. The WinProp simulation program is used for the analysis, which assesses each band's performance under practical deployment situations. The outcomes demonstrate that the sub-band provides improved coverage reachability, mostly as a result of its enhanced propagation properties and obstacle-piercing capabilities. The mmWave band, on the other hand, has a notable capacity advantage, providing faster data rates and the potential to accommodate more connected devices. Nevertheless, this advantage is counterbalanced by its drawbacks, which include a reduced range and increased vulnerability to signal ob-

struction. According to the cost analysis, the 5G sub-band (3.5 GHz) offers better cost performance in the short term because of reduced initial deployment costs, which makes it more appropriate for quick deployment. On the other hand, the 5G mmWave (26 GHz) spectrum exhibits greater long-term cost efficiency and may provide higher returns as technology and infrastructure advance. Analysis of the coexistence of both frequencies is missed in this study.

The study in [2] contributes valuable insights into the performance evaluation and design optimization of Sub-6GHz-mmWave cellular networks that are integrated, particularly in traffic hotspot scenarios. The combination of analytical modeling and simulation results provides a comprehensive understanding of the network behavior and can aid in the development of efficient deployment strategies for future cellular networks. By modeling Sub-6GHz base stations as a Poisson point process (PPP) and mmWave small cells as a Poisson cluster process in traffic hotspots, the analytical framework captures the spatial distribution and deployment characteristics of the two types of base stations in the integrated network. This modeling approach enables the analysis of network performance metrics and the evaluation of coverage and quality of service in different network scenarios, particularly in high-traffic hotspot areas. In this paper analysis is missing the cost which is economic implication.

In [10], a comparison is made between network planning for 5G NR (New Radio) in mid-band (2.6 GHz) and high-band (26 GHz). The study simulates network coverage in Jababeka Industrial Estate using Mentum Planet 7.3 software. Higher data rates at 26 GHz as opposed to 2.6 GHz demonstrate that the LOS scenario outperforms the NLOS scenario. You can use this information to better understand how various frequency bands

affect the coverage and data capacity of a network in a particular location, such as Jababeka Industrial Estate. However, it does not specifically address the coexistence of frequency's and cost performance analysis.

The study [8] focuses on the n78 band (3.3-3.8GHz TDD) in Australia and examines the performance analysis of 5G networks in both sub-6GHz and mmwave bands. For the initial rollout, it recommends utilising LTE cell planning techniques on this 5G spectrum and co-locating 5G NR on already-existing LTE base stations. The study provides a link budget, coverage forecasts, and trial measurements for a 5G NR trial at 3.5GHz. The results show coverage comparable to LTE networks, with beam shaping or power tweaks allowing for customization. Although it mentions spectrum support for 600MHz to mmwave bands, it also points out that higher frequencies require special planning because they enhance bandwidth but also cause penetration losses. In this paper analysis is missing the cost which is economic implication.

For 5G networks, Y. Ayenew [21] discusses the issues of cost, awareness, and compatibility with current technologies. They carried out a thorough techno-economic analysis that included cost modeling, network dimensioning, market predictions, and a five-year economic feasibility assessment utilizing a modified TERA model in the context of Ethiopian Telecom. Factors including 5G application services, deployment alternatives, operating frequencies, and market potential have a significant impact on network capacity, coverage, and site needs, the study emphasizes. These elements are crucial to the network's financial sustainability, as seen by the analysis's impressive payback period of only 3.3 years and significant net present value (NPV) of 1,812,120,611.60. In this paper analysis is considered single frequency band and it missed the hybrid frequency band.

1.6 Scope and Limitations

1.6.1 Scope

The coexistence of the sub-6 GHz (3.5 GHz) and mmWave (28 GHz) bands is the main subject of this thesis, which examines the techno-economic viability of implementing 5G hybrid technology in Bole, Addis Ababa, Ethiopia's.

1.6.2 Limitations

Here is the Limitation of this thesis

- Focused on specifically on the area of Bole and may not be generalizable to other places in Ethiopia.
- The analysis will primarily consider the technical and economic aspects of 5G deployment and may not take into account social, cultural, or environmental factors.
- Its limited by the availability of data on 5G technology in the Bole area, as well as by constraints related to time and resources.
- Not address the potential cybersecurity risks associated with 5G technology deployment.

1.7 Contributions

This thesis contributes to the 5G hybrid network planning by developing and applying a tailored Techno-Economic Analysis framework to assess the feasibility of deploying 5G technology in the Bole area of Addis Ababa, Ethiopia. It offers a comparative evaluation

of dual-band deployment using sub-6 GHz (3.5 GHz) and mmWave (28 GHz) frequencies, providing practical insights into their coexistence. By focusing on a localized case study, the research reflects the unique infrastructural, regulatory, and socio-economic conditions of the region, making it a valuable reference for similar urban areas in developing countries. Additionally, the thesis includes simulation-based performance evaluations, analyzing key metrics such as coverage and capacity to validate the proposed deployment strategies.

1.8 Thesis outline

There are six chapters in this thesis. Chapter 1 Introduces the study, reviewing relevant literature, outlining the problem statement, defining the objectives, describing the methodology, and clarifying the scope, limitations, and key contributions. Chapter 2 explains the core concepts of 5G New Radio (NR) technology, including its architecture, air interface, and radio resource management. Chapter 3 introduces the Techno-Economic Analysis (TEA) framework and the modeling techniques used. Chapter 4 focuses on the deployment strategy and network dimensioning for 5G in the study area. Chapter 5 presents the key findings of the study, including results from the TEA model and simulation outcomes. It provides a detailed interpretation of the data, highlighting the financial and technical feasibility of deploying 5G in the Bole area, along with a comparative evaluation of performance metrics such as coverage and capacity. Finally, Chapter 6 summarizes the conclusions and offers recommendations for future research.

Chapter 2: Introduction to 5G Technology

2.1 Background

The Third Generation Partnership Project (3GPP), whose primary goal is to address a range of scenarios anticipated in the future evolution of mobile technologies, launched the significant development known as 5G New Radio (5G NR), which represents the fifth generation of wireless access technologies. In contrast to 4G, 5G offers a number of remarkable advantages. It meets the growing demand for data-intensive applications by supporting extraordinarily wide transmission bandwidths through the use of higher frequency bands, allowing for extraordinarily high data rates [13].

In terms of system capacity, there are three main techniques for 5G communication. This means that the use of massive MIMO for the first time to improve the spectral efficiency of the system is made; mm wave spectrum is used to increase the system bandwidth; and multi-layer and ultra dense networks are used to increase the spatial reuse of spectrum. Systems using massive antenna arrays to serve multiple users are called Massive MIMO systems. Massive MIMO systems can overcome the severe loss of mm wave signals, provide wireless backhaul and suppress interference in multi-layer and dense networks [15].

2.1.1 5G Deployment Scenarios

The deployment scenarios for 5G NR are predicated on the type of core either a 5G signaling core or an evolved packet core and the various radio access technologies (RATs). The 3GPP specifications released in December 2017 outline the various phases in which the new 5G standard will be implemented. Fourth generation (4G) long-term evolution (LTE) is already in use over the world. The anchor carrier will be used as the initial connection carrier when most operators first implement 5G NR in coexistence with LTE in order to do so more swiftly and economically. Later on, the technology will be implemented as a stand-alone RAT after it has reached maturity and all 3GPP specifications have been approved [15]

- **Non-standalone (NSA):**- a hybrid network combining 5G NR and 4G LTE technology. NSA networks can provide some benefits of 5G, such as enhanced speed and capacity, but lack ultra-low latency and other 5G-specific capabilities. NSA networks are easier to deploy and operate than SA networks, making them an ideal choice for first deployments [22].
- **Standalone (SA):**- a standalone 5G network that does not rely on any other network technology, including 4G. SA networks can provide 5G features, like faster speeds, more capacity, and lower latency. SA networks require more difficult deployment and management than non-standalone networks [22].

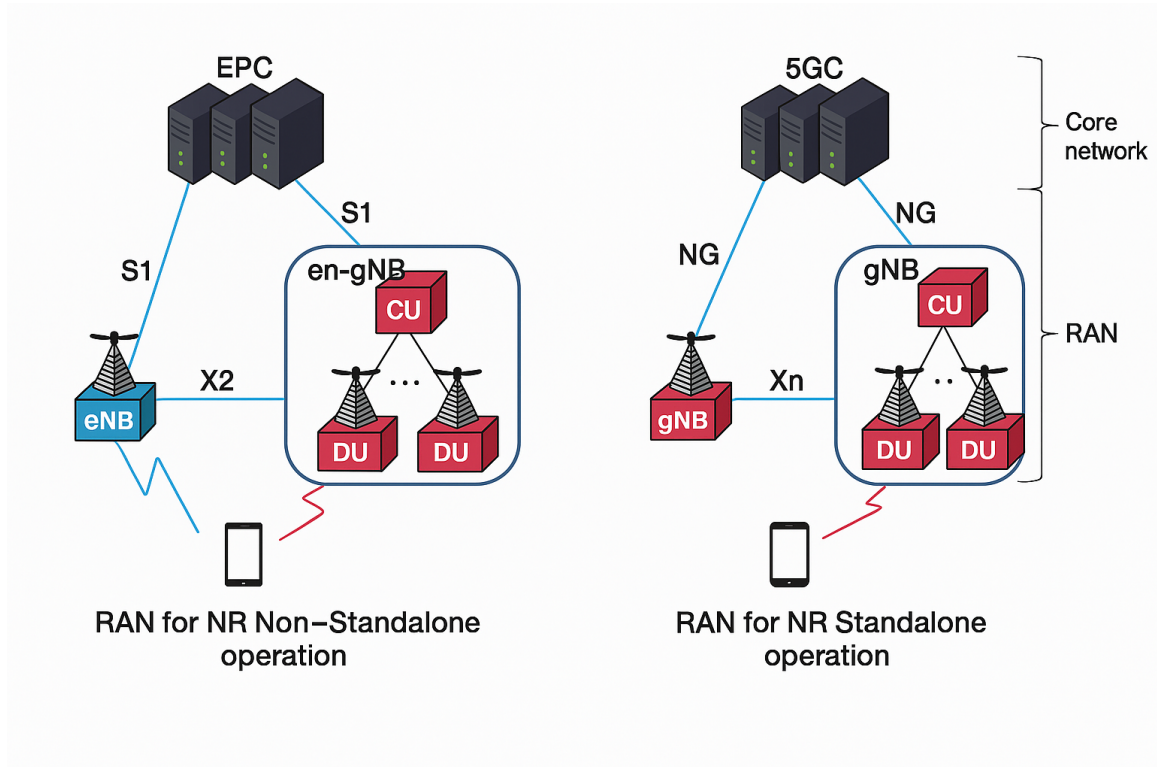


Figure 2.1: 5G Radio Access Network Standardization [1]

2.1.2 5G Radio Network Architecture

Figure 2.2 shows the 5G NR network architecture, which consists of multiple pieces that work together to provide improved wireless connection. Here's an outline of essential concepts related to 5G architecture.

- **User Equipment (UE):** refers to the devices used by end users to connect to the 5G network. This category comprises smartphones, tablets, IoT devices, and other mobile devices that use gNBs to benefit from 5G infrastructure capabilities [1].
- **Next-Generation evolved NodeB (Ng-eNB):** This term might refer to an evolved version of the evolved NodeB (LTE eNB) that includes certain 5G capabilities [12].
- **New Radio - Radio Access Network (NR-RAN):** The system includes gNBs

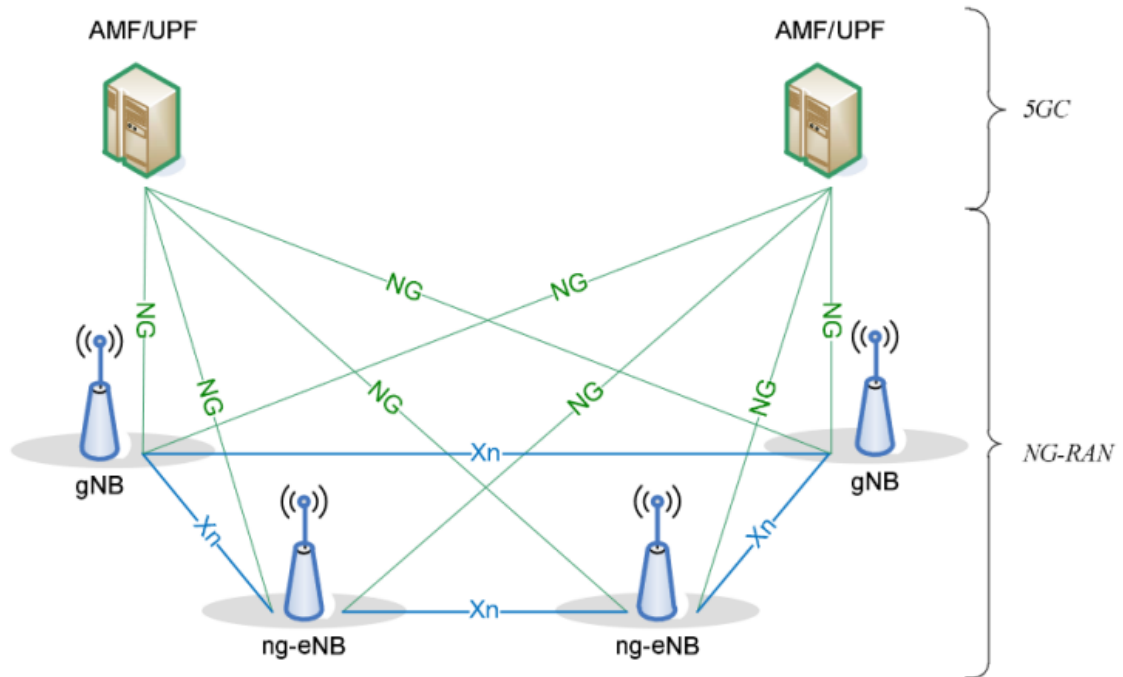


Figure 2.2: 5G Overall Architecture [27]

that provide radio access for UEs and connect to the 5G Core (5GC) network. The NR-RAN allows fast wireless connection and supports advanced 5G technology [12].

- 5G Core (5GC):** The 5G Core (5GC) network is a key component of the 5G architecture, offering increased network capabilities. The new core network features separate control and user planes, network slicing, support for many use cases, and enhanced scalability compared to prior versions [1].
- Access and Mobility Management Function (AMF) / User Plane Function (UPF):** The AMF is a critical component of the 5G Core (5GC) network. It manages access and mobility, including session management, mobility handling, and connection setup for UEs. The UPF efficiently routes and forwards data packets [12].
- Next-Gen NodeB (gNB):** a key component of the 5G Radio Access Network (NR-

RAN). The enhanced base station communicates directly with User Equipment (UE) [1].

- **Xn Interface - Control Plane:** In the control plane, the Xn interface joins nearby gNBs to coordinate radio resources, handle handovers, and exchange control signals. This interface is crucial for ensuring efficient mobility, resource allocation, and network management [12].
- **Xn Interface - User Plane:** The Xn interface in the user plane allows for seamless data transmission between nearby Next-Gen NodeBs in the 5G Radio Access Network (NR-RAN). This interface optimizes user experience during handovers and efficiently allocates resources across neighboring cells [1].
- **Next Generation User Plane (NG-U):** In the 5G architecture, NG-U is the next-generation user plane. The system prioritizes efficient routing, low latency, and fast data transmission to serve various current applications and services [12].
- **Next Generation Control Plane (NG-C):** is the next version of the control plane in 5G architecture. It provides extensive network functionalities for control and management, including network slicing, support for multiple use cases, and efficient resource allocation [1].
- **Evolved Packet Core (EPC):** is the core network architecture used in 4G LTE networks. In 5G, the 5G Core (5GC) is employed. The EPC can be used in non-standalone mode when paired with current LTE networks, while the 5GC is designed for standalone 5G operation [1].

2.1.3 5G Frequency Band and Spectrum

5G uses various frequency bands. The most commonly used band is the low band (below 7GHz) with frequency division duplex (FDD). The lower frequency allows for broader coverage. However, capacity is restricted [23]. The mid-band below 7GHz with time division duplex (TDD) is ideal for 5G deployments. It has higher bandwidth and capacity than the low band. However, uplink coverage is lower compared to low band [23]. High-band or millimeter wave (above 24GHz) provides high peak speeds and minimal latency, but has reduced uplink coverage compared to mid- and low-bands [23].

5G's flexible numerology allows for a variety of deployment scenarios, including massive cells with sub-1GHz carrier frequencies and mmWave deployments with significant spectrum licenses. Tables 2.1 and 2.2 show that this adaptable numerology supports sub-carrier spacing (SCS) from 15kHz to 240kHz with varied slot lengths. LTE has a fixed 15kHz subcarrier spacing and a slot duration of 1 ms [18].

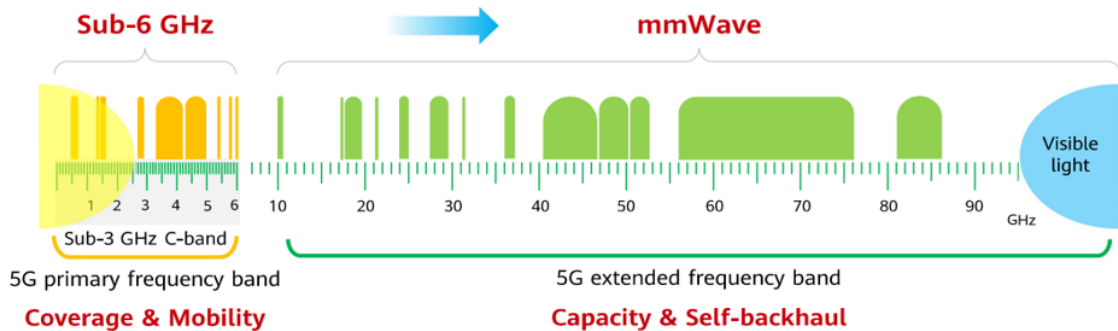


Figure 2.3: 5G full-spectrum access [23]

Table 2.1: 3GPP defines 5G frequency ranges [18].

Frequency Range Name	Corresponding range
FR1	410 MHz – 7125 MHz
FR2	24250 MHz – 52600 MHz

Table 2.2: 5G frequency bands [18].

Frequency Band	Duplex mode	Numerology	Sub carrier spacing (SCS)	Slot Length
FR1 Low Band	FDD	0	15KHz	1ms
FR1 Mid Band	TDD	1	30KHz	500us
FR2 High Band	TDD	3	120KHz	125us

2.1.4 Characteristics of Sub-6 GHz and mm-wave Bands

Main Characteristics of Sub-6 GHz

- **Better Penetration:** - penetrates walls and other impediments more effectively.
- **Network Architecture:** - The network architecture includes both non-standalone (NSA) and standalone (SA) architectures.
- **Better Coverage:** - Cover more than higher frequency bands.
- **Lower Latency:** -Lower latency compared to 4G allows for faster response times for applications like online gaming and video conferencing.
- **High speeds:** - While slower than mm-Wave, much quicker than 4G
- **Lower deployment costs:** - It is affordable for network operators.
- **Increased capacity:** - Supports more devices and data simultaneously than prior generations.

Main Characteristics of mm-wave Bands

- **High Speed:** - Provides average data transmission speeds of up to 1.6 Gbps, with peak rates reaching 20 Gbps.
- **Higher Spectral Efficiency:** - Provides the maximum spectral efficiency among existing bands.
- **Low Latency:** - Provides low latency (1ms) makes it suitable for real-time applications such as online gaming, augmented reality, and driverless vehicles.
- **Short Range:** - The nature of mmWave communications limits coverage to shorter distances than lower frequency bands.
- **High Capacity:** - Supports a high density of linked devices, making it ideal for crowded metropolitan areas and Internet of Things (IoT) applications.
- **Network Architecture:** - It employs Massive Multiple Input Multiple Output (MIMO) and beamforming antennas.
- **High Bandwidth:** - Allows for the transmission of huge amounts of data, which increases network speeds and capacity over wide bandwidths [18].

2.2 Carrier Aggregation in 5G Technology

Carrier aggregation combines numerous carrier frequencies in the same or other bands to increase bandwidth and match peak data rates. Carrier Aggregation in 5G can expand coverage and increase network capacity. Carrier aggregation have three categories:

- **Carrier aggregation intra-band contiguous:** This includes mixing multiple carriers in the same frequency band.
- **Non-contiguous intra-band carrier aggregation:** refers to the combination of multiple carriers in the same frequency band, separated by another carrier.
- **Carrier Aggregation inter-band non-contiguous:** Non-contiguous carrier aggregation allows for transmission over many frequency bands. This is the most common use case for CA. However, using several transceivers in the UE leads to higher costs and power consumption. Figure 2.4 shows three methods of carrier aggregation.[24]

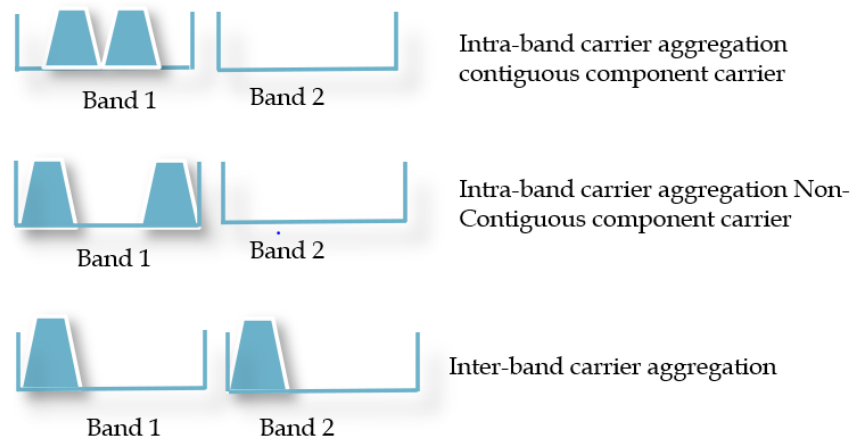


Figure 2.4: Carrier Aggregation Type [24]

2.2.1 Operating bands for CA between FR1 and FR2

5G NR carrier aggregation operates within the bands described in Table 2.4. The band combinations consist of at least one FR1 and one FR2 working band. Mid band frequency is 3.5GHz (NR Operating Band n78), while mmwave frequency is 28GHz (NR Operating Band n257) [13].

Table 2.3: Band combinations for inter-band NR CA between FR1 and FR2 [18].

NR CA Band	NR Band
CA_n8-n258	n8, n257
CA_n71-n257 ¹	n71, n257
CA_n77-n257 ¹	n77, n257
CA_n78-n257 ¹	n78, n257
CA_n79-n257 ¹	n79, n257
NOTE 1: Applicable for UE supporting inter-band carrier aggregation with mandatory simultaneous Rx/Tx capability.	

2.2.2 Advantages of Carrier Aggregation in 5G

The concept of carrier aggregation improves network capacity in different ways, some of which are given below.

- **Increased Bandwidth:** Aggregating several carriers leads to increased bandwidth for data transfer. This enables faster data rates and better network performance, particularly for applications that require high throughput.
- **Flexible Resource Allocation:** Carrier aggregation allows for efficient deployment of radio resources by dynamically distributing carriers to users based on their individual needs. This optimizes spectrum utilization and increases network capacity.
- **Better Spectrum Efficiency:** Combining carriers from multiple frequency bands improves spectrum efficiency. It maximizes underused frequency bands and optimizes spectrum resources.
- **Improved User Experience:** Carrier aggregation enhances user experience by enabling faster data rates and improved network capacity. It enables quicker down-

load and upload speeds, smoother video streaming, and improved performance for bandwidth-intensive applications.

- **Support for Multiple Use Cases:** Carrier aggregation supports a variety of use cases and services with different bandwidth requirements. It supports simultaneous transmission of many data streams, including voice, video, and data, for a smooth user experience.
- **Efficient Carrier Management:** Carrier aggregation allows for efficient management of carriers by dynamically adding or releasing them based on network circumstances and user demand. This adaptability optimizes resource allocation and makes efficient use of available carriers.
- **Reduced latency:** Carrier aggregation reduces latency by merging various frequency bands. This can improve the performance of real-time applications, like video streaming and gaming [24].

Chapter 3: **Techno-economic Analysis**

3.1 Introduction to Techno-economic Analysis

Techno-economic analysis (TEA) is a method for determining the economic feasibility of multi-functional systems. The evaluation and modeling are future-oriented, employing and combining many techniques from the broad field of future-oriented technology analysis (FTA), including cost-benefit analysis, scenarios, trend analysis, expert opinion, and quantitative modeling [1].

The term techno-economics was first used in telecommunications during the European research program Research into Advanced Communications for Europe (RACE) from 1985 to 1995. Early techno-economic modeling work was done in projects like as RACE 1014 ATMOSPHERIC and RACE 1044, where potential scenarios and techniques for evolving to broadband systems were studied [20]. Later, the RACE 2087, Tool for Introduction Scenarios and Techno-economic Studies for the Access Network (TITAN) project created a methodology and a tool for assessing the techno-economic viability of new narrow band and broadband services and access networks [83]. Since the late 1990s, many European research initiatives have used and expanded on the methodology and tools developed in the early studies, as indicated in Table 3.1 [20].

Table 3.1: TEA models and their use cases [20].

TEA Model	Use Case	Example
Techno-Economic Results from ACTS (TERA)	When comparing broadband radio and satellite systems, it's important to consider fixed and wireless technologies (e.g., 2G, 3G, and LTE) for multimedia broadband services.	Fixed WiMAX vs. ADSL
Techno-economics of IP Optimized Networks and Services (TONIC)	New business models for providing IP-based mobile services (competitive scenario). Mobile IP service provisioning for 3G mobile and fixed networks.	Feasibility study, broadband over cable TV network
Techno-economics of integrated Communication Systems and Services (ECOSYS)	Emerging mobile telecommunication projects involve technology, services, and business.	Virtual service operator, TV on mobile, broadband service on fixed WiMAX
Universal Techno-Economic Model (UTEM)	Our universal, adaptable, scalable, and generalizable techno-economic evaluation tool enables agile decision-making across many domains, taking into account all market players' viewpoints, under a specific license of use. [31]	Any access technology in any configuration

3.2 Techno-economic Result from ACTS Framework

Techno-economic The Advanced Communication Technology and Service (ACTS) Framework (TERA) combines technical, market, economic, and cost factors to evaluate major network parts [18]. TERA was created under the European Union's Advanced Communications Technologies and Services (ACTS) program during the fourth framework program for scientific research and development. Figure 3.1 illustrates the TERA framework for techno-economic evaluations, which require market, technology, and general economic inputs [20]. The analysis generates revenues, costs, and investments, as well as profits, cash flows, and other economic variables. In the TERA architecture, an investment is always analyzed for a user-defined time period. The services to be offered, as well as their market

penetration over the research period, must be defined. The revenues for each year are computed by combining annual market penetration and ARPU data. Network architectures for providing services must also be defined. This necessitates network planning skills and is usually done outside of the TERA framework[20].

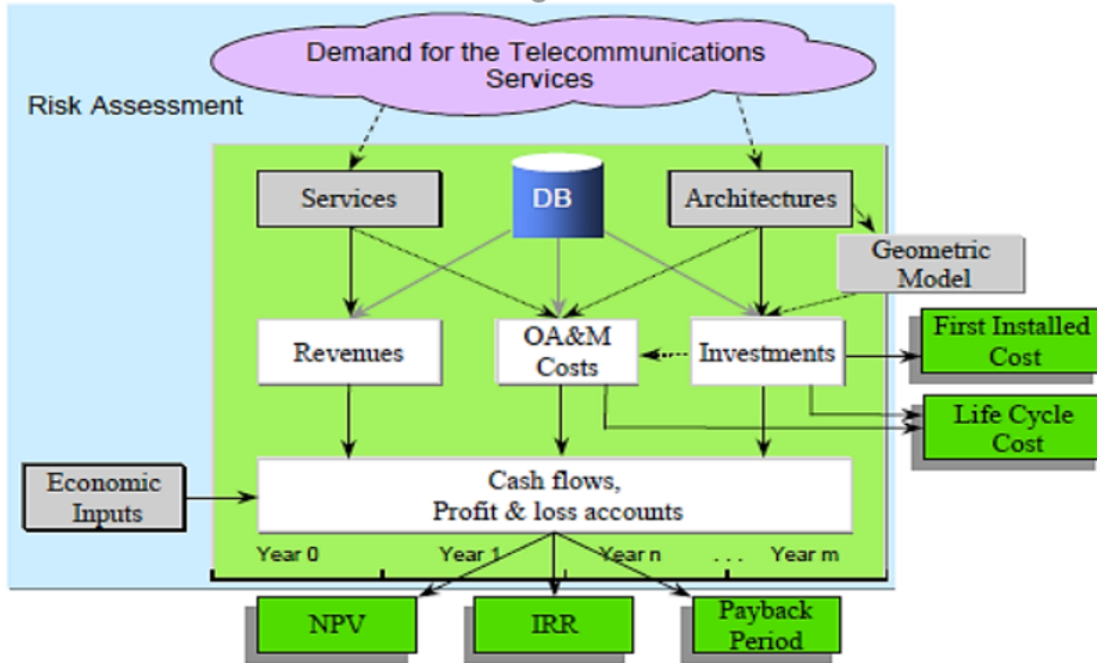


Figure 3.1: TERA Framework for TEA [20,21]

The TERA model integrates a cost database for calculating network component costs. The network design, shopping list, and cost database provide annual investment estimates. Typically, investments are spaced out across the study term. The operation, administration, and maintenance (OA&M) expenditures cover repair components, repair work, and administration. The TERA program calculates the first two automatically using user-defined parameters, but the last one must be explicitly entered into the model. The project's life-cycle costs are calculated by combining investment and operating and maintenance expenditures. The TERA model calculates profitability, cash flows, and basic economic

metrics like NPV, IRR, and payback period by factoring in revenues, investments, OA&M expenses, and discount rates. Profits are evaluated based on sales, investment, and technological market share. Retained cash flows are calculated as the difference between life-cycle costs and revenues, minus taxes. The cash balance represents the cumulative cash flow for each year of the study period. The model also calculates the project's net present value, IRR, and payback period [20].

3.2.1 Cost Modeling

Every financial model includes various particular costs. Analytically, there are two types of expenditures: capital (CAPEX) and operational (OPEX). CAPEX refers to all upfront costs associated with network implementation. Expenses for network construction include equipment, sites, and other associated costs. OPEX refers to expenses related to the system's daily operations, management, and coordination. The Total Cost of Ownership (TCO) is the total cost of acquiring a technology, including CAPEX and OPEX [25].

Capital Expenditure (CAPEX) and Operational Expenditure (OPEX)

Capital Expenditure (CAPEX) refers to the initial investment required for the deployment of a network, encompassing costs related to equipment, infrastructure, and upgrades. These expenses are derived from the outcomes of network dimensioning, a process that identifies the quantity of network equipment necessary to implement a 5G network [1].

CAPEX formula is:

$$CAPEX(i) = \sum M_j(i) \cdot C_i \cdot capex(1 + P_j capex)^{i-1} \quad (3.1)$$

Where:

- j is the key element or component type of the CAPEX,
- $M_j(i)$ is the number of j type elements purchased in year i ,
- C_j capex is the per unit investment cost for each asset j in the first year,
- P_j capex is yearly price trends, and
- CAPEX(i) is the investment in year.

The key components of the 5G Carrier Aggregation (CA) network are organized into five main categories: equipment costs, site construction expenses, installation fees, core expenditures, and commercial power costs. This framework is based on cost data acquired from vendor databases, industry price catalogs, and Ethio Telecom project paperwork relating to the development of 5G in Addis Ababa. Additionally, relevant literature on 5G network cost modeling is considered.

OPEX refers to the expense of deploying a network for business operations [25]. OPEX costs are often modeled with the number of required network elements as inputs. This covers costs for maintenance, operation, site renting, and energy use.

OPEX formula is:

$$OPEX(i) = \sum N_j(i) \cdot C_i \cdot Opex(1 + P_j Opex)^{i-1} \quad (3.2)$$

Where:

- j is customer-driven and network-driven costs,

- $N_j(i)$ is the number of item j type elements operated during year i ,
- C_j opex is the per unit operating cost for each asset j in the first year,
- P_j opex is yearly price trends, and
- $OPEX(i)$ is the operational expenses in year i .

Total Cost of Ownership (TCO)

TCO refers to the total cost of investing in, operating, and maintaining a network over its lifetime. It can be calculated using the general formula shown below.

$$TCO = CAPEX + OPEX \quad (3.3)$$

Where:

- TCO is the total cost ownership of the network,
- CAPEX is capital expenditures and
- OPEX is operation expenditures.

3.2.2 Revenue Modeling

A revenue model determines how much an operator would charge clients for a service, taking into account subscriber count, ARPU, and 5G network market share [1].

The revenue can be calculated by:

$$R_T = N_S \cdot ARPU \cdot M_S \quad (3.4)$$

$$ARPU = \frac{\text{Total Revenue}}{\text{Total Number of Users}} \quad (3.5)$$

Where:

- R_T is the total revenue generated,
- N_S is the predicted number of subscribers,
- ARPU is the average revenue per user, and
- M_S is the 5G network market share.

3.2.3 TERA Evaluation Method

TEA relies heavily on determining project profitability. This study used Cash Flow (CF) and Discounted Cash Flow (DCF) for techno-economic evaluation, as well as NPV, IRR, and PBP to assess project profitability [25].

1. Cash Flow (CF) and Discounted Cash Flow (DCF)

The term CF refers to the total amount of cash received and dispensed during the study period. The costs and revenue model outputs can be mathematically described using the formula [25].

$$CF = \sum_{i=1}^T (R_T - C_T)_i \quad (3.6)$$

Where:

- CF is the cash flow,
- C_T Total cost of the network (TCO), and

- R_T total revenue,
- T is the study period.

The discounted cash flow approach (DCF) uses a discounted rate to calculate the present value of a company's future cash flows, yielding a current estimate of its fair value [25]. DCF is mathematically modeled, as seen by the formula below.

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \dots + \frac{CF_i}{(1+r)^i} \quad (3.7)$$

Where:

- DCF is discounted cash flow and CF is the cash flow for the given year,
- CF_1 is the first year CF and CF_2 is the second year CF,
- CF_i is the CF for additional years,
- i is study period, and r stands for discounted rate.

2. Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP)

Net Present Value (NPV)

The NPV is the difference between the present value of cash inflows (e.g. revenue, loan) and outflows (e.g. expenses, investments) over a particular period. NPV is a capital budgeting and investment planning tool that evaluates the profitability of various network deployment scenarios. Overall, projects with a positive NPV are valuable. With a negative

NPV are not [20, 25]. The NPV is determined using the formula shown below.

$$NPV = \sum_{i=1}^T \frac{CF_i}{(1+r)^i} \quad (3.8)$$

Where:

- NPV is Net Present Value,
- T is the study period,
- CF_i is the cash flow occurring at time i, and
- r is the discount rate.

Internal Rate of Return (IRR)

The IRR is a measure used in financial research to determine the profitability of potential investments. In a discounted cash flow analysis, the discount rate of the NPV for all cash flows is set to zero. This means that the present value of the cash flow stream equals the investment's initial value [20,25]. The IRR can be calculated using the following formula:

$$NPV = \sum_{i=0}^T \frac{CF_i}{(1+IRR)^i} \quad (3.9)$$

Where:

- NPV is Net Present Value,
- T is total number of study period,

- IRR is Internal Rate of Return, and
- CF is cash flow.

According to the IRR concept, the higher the IRR, the more desirable deployment, and it is deemed the best and would be implemented first.

Payback Period (PBP)

PBP is the time it takes for an investment to reach its breakeven point. Shorter payback periods imply more appealing investments, while longer payback periods indicate less desired ones [20, 25]. The PBP can be represented numerically as follows:

$$PBP = LP + \left[\frac{CCF}{CF} \right] \quad (3.10)$$

Where:

- PBP is the Payback period,
- LP is the last period of negative cumulative CF,
- CCF is value of cumulative CF at the end of LP, and
- CF is the total CF after LP.

3. Sensitivity Analysis

Sensitivity analysis determines how much change in input values for a specific variable impacts the outcome. The results can be shown using a sensitivity analysis graph with a tornado diagram, and the sensitivity of each input is reflected by the change or variation

in output within the normal value to investigate how changing input assumptions affects prediction [20,25].

3.3 Network Dimensioning

Network dimensioning involves calculating the optimal capacity and resources needed for a telecom network to function efficiently and effectively. The analysis considers elements such as user count, service types, traffic patterns, growth projections, and technical improvements. The purpose is to guarantee that the network can manage the anticipated traffic without causing congestion or service disruptions. This approach identifies the minimum resources needed to perform services at a certain area. When designing a radio cellular network, important factors to consider are coverage area, frequency band, bandwidth allocation, MIMO architecture, population density, and traffic distribution [10].

In order to determine how many radio stations are needed to achieve coverage and capacity requirements, coverage and capacity planning are crucial elements in the network dimensioning process. In order to properly evaluate network loading, this procedure also entails analyzing the traffic profile, which includes data rates and coverage metrics.

3.3.1 5G Coverage Dimensioning

Radio Link Budget (RLB) computations, which are necessary to ascertain path loss for both Downlink (DL) and Uplink (UL) radio links, are the first step in the coverage dimensioning process. The maximum allowable signal attenuation, or path loss, between the User Equipment (UE) and the gNodeB antennas is evaluated by these link budget computations.

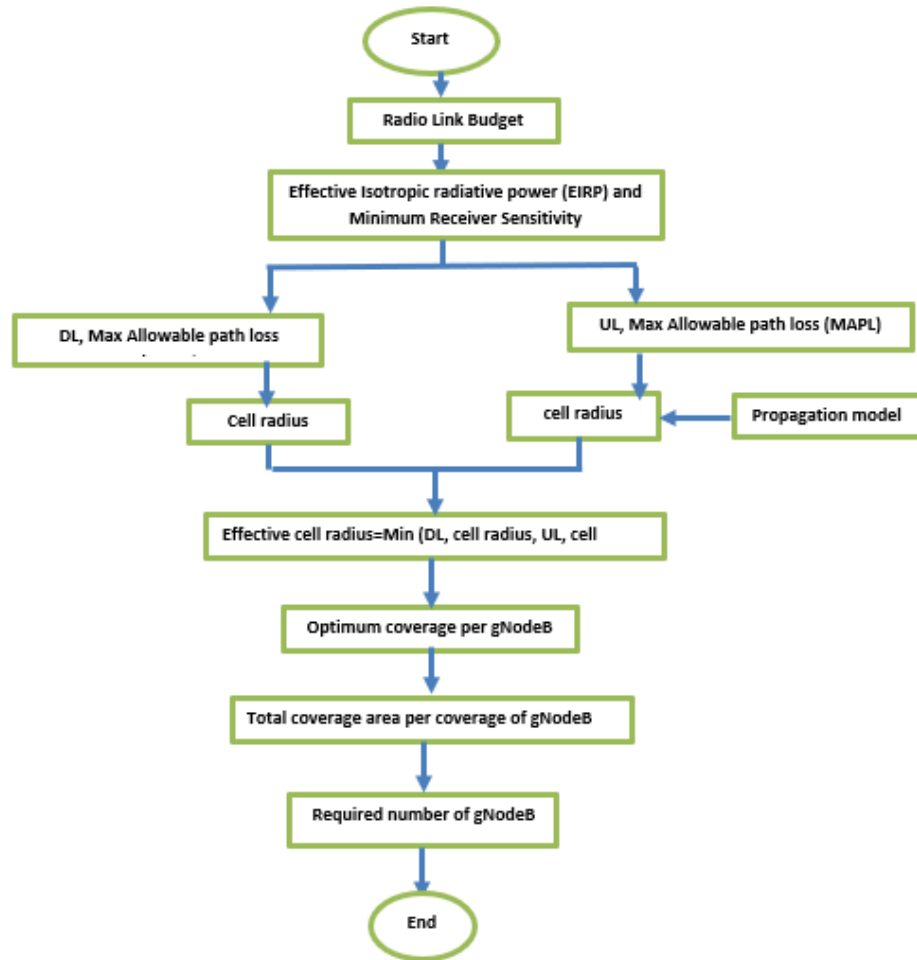


Figure 3.2: 5G CA Coverage Dimensioning Flow Chart.

By considering existing ethio telecom 5G network data, smart infrastructure, digital economy and E-Commerce, the selected area of this study is around bole 4 km² area of a techno-economic analysis of a 5G carrier aggregation network in Addis Ababa.

Radio Link Budget

For both uplink and downlink communications across the air interface, the maximum attenuation received between the mobile antenna from UE and the antennas from gNodeB is known as the maximum allowable path loss (MAPL). gNodeB antennas for both uplink

and downlink connections across the air interface. The losses between UE and gNodeB as well as the information needed to determine the link budget are taken into consideration when calculating the coverage. The following describes a number of parameters that were used to estimate the radio link budget.

Propagation Model

In network planning, propagation models are essential, particularly for feasibility studies and early deployments. Effective wireless communication system dimensioning and design require a thorough understanding of these paradigms. They can be broadly divided into three categories: stochastic, deterministic, and empirical models [1].

- Empirical models are those that are exclusively grounded in measurements and observations. The primary goal of these models is to predict path loss.
- Deterministic models: These models calculate the received signal power at a given point using the principles governing the propagation of electromagnetic waves.
- Although stochastic models are the least accurate, they use the least amount of environmental data and require a lot less computing resources to produce predictions. Additionally, it uses a number of random variables to model the environment.

Empirical propagation models, such as the Stanford University Interim (SUI) model, the Cooperation of Scientific and Technical Research (COST)-231 Hata model, the Okumura-Hata model, and the 3GPP TR 38.901 model, are available for 3.5 GHz frequency range. Use the Alpha-Beta-Gamma (ABG) Model, Close-In (CI) Free Space Reference Distance

Model, and 3GPP TR 38.901 Model for the 5G mmwave (26GHz) to help evaluate coverage and capacity in scenarios where direct line-of-sight and blockage events have a major impact on signal propagation.

Operating Frequency and Bandwidth

The operational frequency band and bandwidth are the two basic inputs considered while dimensioning coverage. The operating frequency band was chosen based on 3GPP Release 15 recommendations for deploying 5G New Radio (5G NR). The 5G network uses large MIMO, Time Division Duplex (TDD), and available channels and bandwidth to boost peak, average, and cell edge throughput [8].

Table 3.2: Selected frequency bands and Bandwidth for this thesis.

Frequency band (GHz)	Morphology	Bandwidth	Mode
C band (3.5)	Urban	100MHz	TDD
mmWave band (28)	Urban	200MHz	TDD
Carrier Aggregation (CA)	Urban	300MHz	TDD

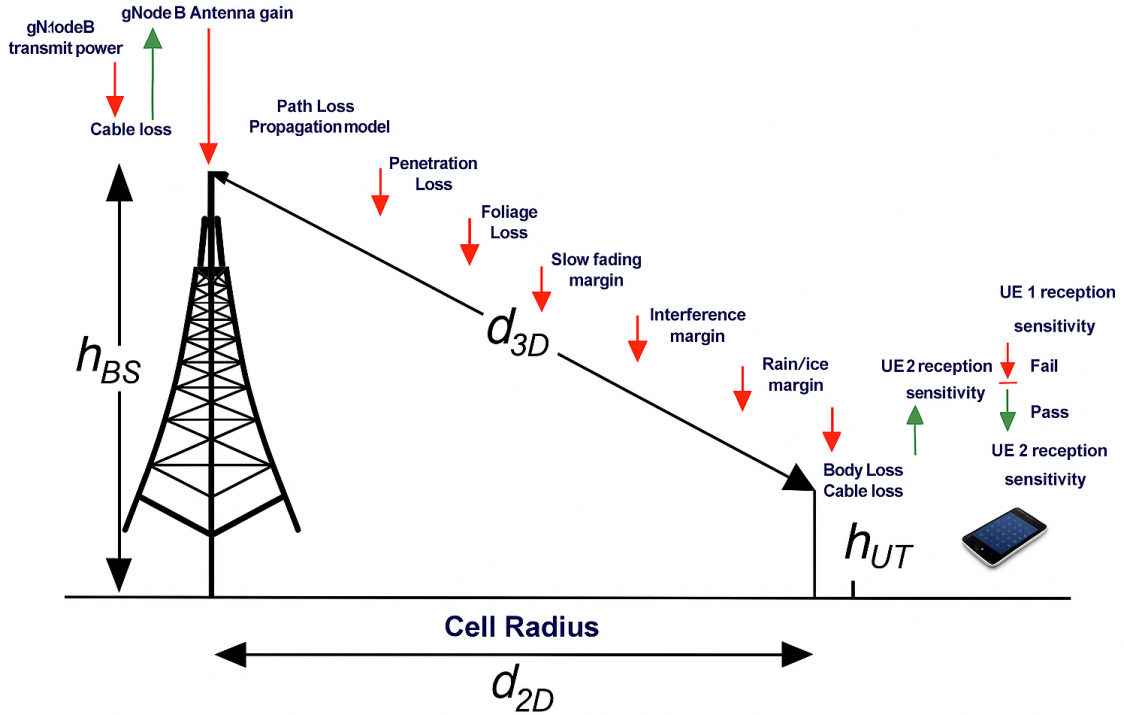


Figure 3.3: 5G Link Budget factors[14].

gNodeB Transmitter Power: Refers to the transmitter's maximum transmission power per branch, typically 49dBm [10].

gNodeB Antenna Gain: Related to the antenna size and beam width of horizontal or vertical antenna layouts, respectively. The antenna gains and beam width are determined by the type of clutter and the amount of coverage needed [10]. A low gain antenna (15-17dBi) can be used in dense urban and urban clutter locations, whilst a high gain antenna (18-20dBi) can be used to enhance Radio Frequency (RF) coverage in rural areas and roads [26].

UE Maximum Total Transmitter Power: The transmission power of a UE is determined by its power class [26].

Loss: This includes cable and body loss at both the gNodeB and UE. Cable loss values

for gNodeB range from 1-6 dB based on cable length. Holding the UE close to the user's head causes body loss of approximately 2-3 dB in practical planning [12].

Effective Isotropic Radiated Power (EIRP): Refers to the amount of power sent in the intended direction, taking into account the gain of the transmitter antenna and losses in transmission cables and connectors. This can be determined using the formula below. [12]

$$EIPR = P_{Tx} + G_{Tx} - \sum Total Tx losses \quad (3.11)$$

Where:

- P_{Tx} is the transmitter power (dBm),
- G_{Tx} is the transmitter antenna gain (dBi),
- Total Tx losses include cable and additional losses on the transmitter side (dB).

Cell Edge User Throughput: It is the minimum net single-UE target throughput required at the cell edge. Typically, the network operator will offer this parameter based on the services required at the cell edge.

Thermal Noise: Thermal noise is a loss induced by temperature (heat). It can be stated as

$$N = K_B T B \quad (3.12)$$

where:

- $K_B = 1.38066 \times 10^{-23}$ J/K (Boltzmann constant)

- $T = 290$ K (absolute temperature)
- B is channel bandwidth

Noise Figure: The ratio of SINR at the receiver input end to SINR at the receiver output end is used to evaluate the receiver's performance. The normal noise figure ranges from 6 to 8 decibels [10].

Signal to Interference Noise Ratio (SINR): Value is determined by the receiver design, which is based on system-level simulation results. Thus, the SINR parameter is dependent on vendor specifics [26].

Receiver Sensitivity: It expresses the minimum signal strength necessary for decoding by the gNodeB or UE receiver in the absence of interference.

$$R_s = N_F + \text{SINR} + N \quad (3.13)$$

where:

- R_s is the receiver sensitivity (dBm),
- N_F is the noise figure (dB),
- SINR is the signal-to-interference-noise ratio (dB),
- N is the thermal noise (dB).

Slow/Shadow Fading Margin: It is the fading induced by blocking a natural feature. The standard deviation of slow fading determines the slow fading difference, whereas location changes create shadow fading. Depending on the type of congestion, the slow fading

standard deviation ranges from 5 to 12 dB [26].

Penetration Loss: Refers to the fading of radio signals between indoor terminals and gNodeBs due to building obstructions. This is based on the building type and clutter category in the targeted coverage region.

Table 3.3: penetration losses based on the Clutter type of area [26].

Clutter type	Penetration loss (dB)	Typical values	Standard deviation of slow fading (dB)
Dense urban	19-25	19	10
Urban	15-18	15	8
Suburban	10-14	11	6
Rural	5-8	8	6

Maximum Allowable Path Loss (MAPL): Propagation models can determine the number of gNodeB sites needed to cover the target area, allowing for the estimation of the maximum cell range [26]. The maximum allowable path loss formula is

$$\text{MAPL} = \text{EIRP} - R_s - PL - S_m - I_m + G_R \quad (3.14)$$

where:

- MAPL is the Maximum Allowable Path Loss (dB),
- EIRP is the Effective Isotropic Radiated Power (dBm),
- R_s is the receiver sensitivity (dBm),
- PL is the path loss (dB),
- S_m is the signal margin (dB),

- I_m is the interference margin (dB),
- G_R is the receiver gain (dB).

Site Count based on coverage

After calculating MAPL in both UL and DL, the cell radius is determined using the appropriate propagation model. Network design studies typically use a hexagonal model for site coverage and layout [26]. Site configurations can be omni-directional, bi-sector, or tri-sector, as illustrated in the figure 3.4.

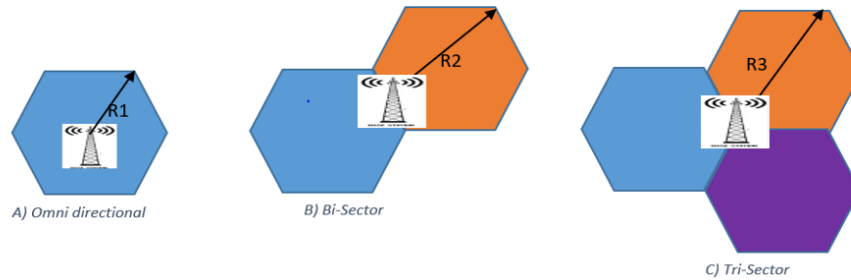


Figure 3.4: Different types of site arrangements [26]

The gNodeB area is calculated as follows depending on site configurations as shown in Figure 3.5

For omni-directional coverage, the area SA can be expressed as:

$$gNB(\text{Area} [\text{km}^2]) = 3 \cdot \sqrt{3} \cdot [R_1]^2 [\text{km}^2] \quad (3.15)$$

For bi-sector coverage, the area SA can be expressed as:

$$gNB(\text{Area} [\text{km}^2]) = \sqrt{3} \cdot [R_2]^2 [\text{km}^2] \quad (3.16)$$

For tri-sector coverage, the area SA can be expressed as:

$$gNB(\text{Area} [\text{km}^2]) = \frac{9}{8}\sqrt{3} \cdot [R_3]^2 [\text{km}^2] \quad (3.17)$$

where:

- gNB is gNodeB area (km^2),
- R_1, R_2, R_3 is radius of the cell (km).

Finally, the coverage-based site count is determined as follows:

$$N_{gNB} = \frac{Total_{SA}}{gNB_{Area}} \quad (3.18)$$

where:

- T_{NS} is the total number of sites,
- $Total_{SA}$ is the target selected coverage area,
- gNB_{Area} is the gNodeB area.

3.3.2 5G Capacity Dimensioning

Capacity dimensioning is utilized to estimate the resources needed to accommodate a specific level of offered traffic while maintaining a desired QoS, throughput, or blocking probability. In the case of 5G carrier aggregation network, capacity dimensioning is influenced by factors such as the required data plan for each user, the modulation scheme, coding techniques, and the available bandwidth and Signal-to-Interference-plus-Noise Ratio (SINR) within the cell.

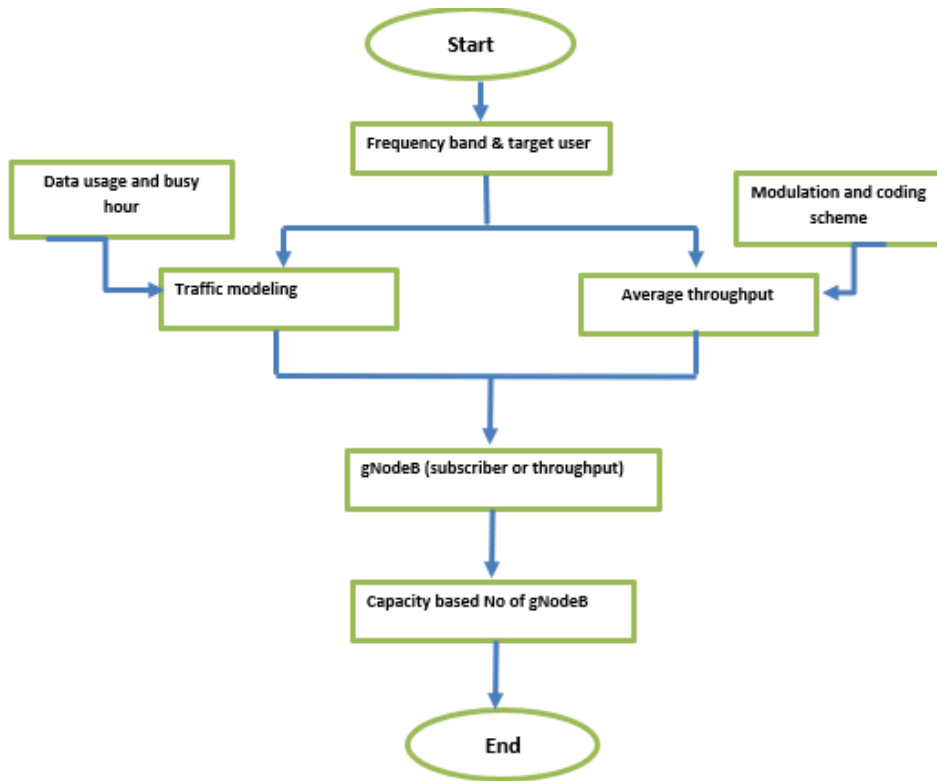


Figure 3.5: 5G CA Capacity Dimensioning Flow Chart.

Traffic Demand Analysis

Analyze expected traffic patterns, including peak and average data usage, user density, and application types. This helps estimate the network’s overall traffic load. The traffic model aims to describe average subscriber behavior during busy hours. Because traffic is not evenly dispersed throughout the day, a site’s capacity should be calculated using BH [10].

The average throughput at BH (in Kbps):

$$A_{BH} = \frac{M \times 8}{D \times T} \times R \quad (3.19)$$

where:

- M (Monthly service package) is the total data in bytes,
- The factor 8 bit/byte converts bytes to bits,
- (D) Number of days is the total number of days in the month,
- (T) Time in seconds is the total time considered,
- (R) Busy hour ratio is the bandwidth/handoff ratio.

Network Capacity Analysis

Base station maximum throughput (measured in Mbps or Gbps) is a key quality parameter that reflects the transfer rate of standard, non-redundant data. Capacity planning is to estimate the number of sites needed to meet capacity requirements. Network operators analyze expected traffic and average cell throughput to determine capacity-based site counts.

The aggregate throughput is modeled using the 3GPP TS 38.306 standard for 5G NR networks. The maximum data transfer rate for DL and UL can be estimated using the formula below.[27]

$$R_{\text{Data}} = 10^{-6} \cdot \sum_{j=1}^J (v_{\text{Layers}}(j) \cdot Q_m(j) \cdot f(j) \cdot R_{\text{max}} \cdot N_{\text{PRB}}^{\text{BW}}(j, \mu) \cdot 0.12 \cdot T_s^\mu \cdot (1 - OH(j))) \quad (3.20)$$

Where:

- R_{Data} is data rate (in Mbps)
- 10^{-6} - to express in Mbps.

- j - this represents the number of aggregated component carriers in a band or band combination, with a maximum value of j up to 16.
- $v_{\text{Layers}}(j)$ - the maximum number of MIMO layers, which can be up to 8 in DL and 4 in UL.
- $Q_m(j)$ - modulation type: QPSK (2), 16QAM (4), 64QAM (6), and 256QAM (8).
- $f(j)$ - the scaling factor for medium and high mobility can be 0.4, 0.75, 0.8, or 1.
- R_{max} - the value is defined by the 3GPP 38.212 and 3GPP 38.214 encoding types. In Low Density Parity Check (LDPC), the highest number is 948/1024.
- $N_{\text{PRB}}^{\text{BW}}(j, \mu)$ - the maximum number of assigned Physical Resource Blocks (PRB) in bandwidth per subcarrier spacing.
- T_s^μ - indicates the average duration of an OFDM symbol in a frame. The value μ (i) is a regular cyclic prefix. $T_s^\mu = \frac{10^{-3}}{14 \cdot 2^\mu} = 3.577 \times 10^{-5}$
- $OH(j)$ - overhead representation of the control channel. The normal DL and UL values for FR1 are 0.14 and 0.08, respectively, while for FR2, they are 0.18 and 0.10.

Site Counts based on capacity

To calculate the capacity-based site count, use the formula below after considering traffic and capacity requirements.

$$N_{\text{sub}}^{\text{gNodeB}} = \frac{C_{\text{site}}^{\text{DL, UL}}}{T_{\text{sub}}^{\text{BH}}} \quad (3.21)$$

Where:

- $(N_{\text{sub}}^{\text{gNodeB}})$ is the maximum number of subscribers per gNodeB (downlink, uplink).
- $(C_{\text{site}}^{\text{DL, UL}})$ is the aggregate capacity throughput per site (downlink, uplink).
- $(T_{\text{sub}}^{\text{BH}})$ is the average throughput per subscriber at busy hour (BH).

Finally, to determine the number of gNodeBs needed to support the entire number of subscribers, use the following formula:

$$N_{\text{sites}}^{\text{DL, UL}} = \frac{N_{\text{sub}}}{N_{\text{site}}^{\text{site}}} \quad (3.22)$$

Where:

- $(N_{\text{sites}}^{\text{DL, UL}})$ is the capacity-based site count (downlink, uplink).
- (N_{sub}) is the total number of subscribers.
- $(N_{\text{site}}^{\text{site}})$ is the maximum number of subscribers per site (downlink, uplink).

Chapter 4: **Implemented TERA Model and Techno-**

Economic Analysis

4.1 Area Selection and Deployment Option

Based on existing Ethio Telecom data and location behavior, the digital economy, e-commerce, and smart infrastructure, the selected area around Bole is ideal for a comprehensive site survey of 5G mobile radio networks. This survey will cover the frequency bands of the sub-band (3.5GHz) and 5G mm-wave (28GHz). The chosen site is a rectangular zone measuring 2km by 2km in front of the Skylight Hotel, which is a 4 square kilometers area, ensuring precise site selection. This location is a dynamic example of urban connectivity needs.

The site's proximity to the international airport, Millennium Hall, and embassies makes it more relevant and significant, offering valuable data and insights. This site assessment provides useful insights into the interplay of coverage, capacity, and cost performance in both frequency scenarios.



Figure 4.1: Bole (red) within Addis Ababa and Selected area with existing 5G base station.

For the techno-economic analysis of 5G hybrid deployment in the Bole area of Addis Ababa, Ethiopia, several deployment scenarios are considered, focusing on infrastructure and cell types.

Applicable Infrastructure

- **NSA:- 5G Using Existing Infrastructure including core and transmission.**
Ethiotelecom reuse 2G, 3G, and 4G assets, including towers, power equipment, and core. Upgrades to current sites are cost-effective, while new resources are carefully explored for future sites.

Cell Types

- **Macro Cell Deployment (Sub-6 GHz)**
 - **Infrastructure:-** Requires fewer, larger base stations with extensive coverage areas.
 - **Cell Type:-** Macro cells, which provide broad coverage and are suitable for areas with moderate user density.
 - **Use Case:-** Ideal for general urban coverage, ensuring connectivity across larger

areas.

- **Micro Cell Deployment (mm-Wave)**

- **Infrastructure:-** Involves a higher density of smaller base stations due to the limited range of mm-wave frequencies.

- **Cell Type:-** Small cells offer high capacity and are designed for dense urban environments.

- **Use Case:-** Best for hotspots like stadiums, airports, and commercial centers where high data rates and low latency are crucial.

- **Hybrid Deployment**

- **Infrastructure:-** Combines macro and small cells by carrier aggregation method to leverage the strengths of both sub-6 GHz and mm-wave frequencies.

- **Cell Type:-** A mix of macro and small cells to provide comprehensive coverage and capacity.

- **Use Case:-** Suitable for areas with mixed user density and varied connectivity needs, such as the Bole area with its mix of residential, commercial, and institutional buildings.

4.2 Network Dimensioning

4.2.1 Coverage Dimensioning

Coverage planning identifies the number of sites needed to service a certain area and ensures effective network coverage for users. It considers both the radio link budget and the propagation model. Radio Link Budget Calculations are used to estimate the maximum

signal attenuation or path loss between UE and gNodeB antennas.

Radio Link Budget

The radio link budget specifies transmitter power levels, system losses and gains, and calculates downlink and uplink attenuation between the UE and the gNodeB antenna, also known as the Maximum Allowable Pathloss Value (MAPL). This MAPL is utilized in the propagation model to calculate cell radius. The study examines O2O downlinking with Line of Sight (LOS) utilizing UMa for mid-band (3.5GHz) and UMi for mmWave (28GHz) link budgets.

Table 4.1: Macro cell and Micro cell specifications.

General Parameters	Units	Downlink/Uplink	Downlink/Uplink
Morphology		Urban	
Cell edge probability of coverage		90-95%	
User environment		Indoor, Outdoor	
Frequency Band		n78	n257
Frequency	GHz	3.5	28
Frequency Range	MHz	3300–3800	26,500–29,500
Cell Type		Macro cell	Micro cell
Duplex Band		TDD	TDD
Data channel type		PDSCH	PUSCH
Bandwidth	MHz	100	200
Subcarrier Spacing	(KHz/MHz)	30	120
Max number of RB	KHz	273	264
PRB size	KHz	360	1440

The values of each parameters that used for calculation of maximum allowable pathloss (MAPL) are as shown on the below table.

gNodeB Transmitter and UE receiver Characteristics

Table 4.2: 5G sub-band(3.5GHz) and mmwave (28GHz) Radio link budget.

General Parameters	Units	Formula	Downlink/Uplink for 3.5GHz	Downlink/Uplink for 28GHz
Cell edge rate	Mbps		50/10	100/25
Transmit Power	dBm	A	49/49	36/36
Transmit Antenna Gain	dBi	B	14/14	32/32
Transmitter Cable and connector Loss	dB	C	2/2	2/2
EIRP	dBm	A+B+C	61/61	76/76
UE Gain	dBi	D	0/0	10/10
Penetration Loss	dB	E	22/22	34/34
Foliage Loss	dB	F	12/12	17/17
Body Block Loss	dB	G	3/3	3/3
Interference Margin	dB	H	6/6	1/0.5
Rain/Ice Margin	dB	I	0/0	3/3
Slow Fading Margin	dB	J	4/8	2/4
Temperature	Kelvin	K	293/293	293/293
Thermal Noise	dB	L	-123.93/-123.93	-117.91/-117.91
Noise figure UE	dB	M	9/9	7/7
Demodulation threshold SNR	dB	N	-1.1/-1.1	-1.1/-1.1
RBL = $10 \log_{10}(\text{SCQ})$	dB	O	35.15/35.15	35.01/35.01
Receiver noise floor	dBm	M+L	-114.93/-114.93	-110.91/-110.91
SINR	linear	$2^{\left(\frac{\text{Data rate}}{\text{BW}}\right)-1}$	0.41/0.07	0.41/0.07
SINR	dB	$10*\log(\text{SINR})$	-3.83/-11.44	-3.83/-11.44
Receiver sensitivity	dBm	L+M+SINR	-118.76/-126.37	-110.91/-119.19
MAPL	dB	A + B - C + D - E - F - G - H - I - J - M - N - O	98.71/102.32	106.94/109.94

Propagation Models

This thesis follows the 3GPP 38.901 standard for network planning and uses two frequencies: 3.5GHz sub 6GHz and 28GHz mm-Wave band. Thus, two propagation models are utilized: Urban Macro (UMa) and Urban Micro (UMi). The path loss model for the Urban Macro (UMa) cell is shown in Equation [28].

$$”PL_{UMa}[\text{dB}] = \max(PL_{UMa-LOS}, PL'_{UMa-NLOS}) \quad \text{for } 10 \text{ m} \leq d_{2D} \leq 5 \text{ km}” \quad (4.1)$$

where

$$”PL'_{UMa-NLOS} = 13.54 + 39.08 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) - 0.6(h_{UE} - 1.5)” \quad (4.2)$$

and

$$”PL_{UMa-LOS} = \begin{cases} 28 + 22 \log_{10}(d_{3D}) + 20 \log_{10}(f_{c,UMa}) & \text{for } 10 \text{ m} \leq d_{2D} \leq d'_{BP} \\ 28 + 40 \log_{10}(d_{3D}) + 20 \log_{10}(f_{c,UMa}) - \\ 9 \log_{10}((d'_{BP})^2 + (h_{BS} - h_{UE})^2) & \text{for } d'_{BP} \leq d_{2D} \leq 5 \text{ km} \end{cases}” \quad (4.3)$$

The minimum radius for UMa-LOS is calculated using,

$$\text{Radius}_{UMa-LOS} = 10^{\left(\frac{\text{MAP}_{UMa-LOS} - 28 - 20 \log_{10}(f_{c,UMa})}{22}\right)} \quad (4.4)$$

where

- d_{3D} is the 3D distance between transmitter and UE, calculated by $d_{3D} = \sqrt{d_{2D}^2 + (h_{BS} - h_{UE})^2}$

- d_{2D} is the 2D distance between the transmitter and UE
- f_c is the operating center frequency in GHz
- d'_{BP} is the break point, which calculated by $d'_{BP} = 4h'_{BS} \times h'_{UE} \times f_c \times 10^9 / c$

Similarly, The path loss for an Urban Micro (UMi) cell according to 3GPP TR-38.901 specifications [28] is as follows,

$${}^{\text{''}}\text{PL}_{\text{UMi}}[\text{dB}] = \max(\text{PL}_{\text{UMi-LOS}}, \text{PL}'_{\text{UMi-NLOS}}) \quad \text{for } 10 \text{ m} \leq d_{2D} \leq 5 \text{ km}{}^{\text{''}} \quad (4.5)$$

where

$${}^{\text{''}}\text{PL}'_{\text{UMi-NLOS}}[\text{dB}] = 22.4 + 35.3 \log_{10}(d_{3D}) + 21.3 \log_{10}(f_{c,\text{UMi}}) - 0.3(h_{UE} - 1.5){}^{\text{''}} \quad (4.6)$$

and

$${}^{\text{''}}\text{PL}_{\text{UMi-LOS}}[\text{dB}] = \begin{cases} 32.4 + 21 \log_{10}(d_{3D}) + 20 \log_{10}(f_{c,\text{UMi}}) & \text{for } 10 \text{ m} \leq d_{2D} \leq d'_{BP} \\ 32.4 + 40 \log_{10}(d_{3D}) + 20 \log_{10}(f_{c,\text{UMi}}) - \\ 9.5 \log_{10}((d'_{BP})^2 + (h_{BS} - h_{UE})^2) & \text{for } d'_{BP} \leq d_{2D} \leq 5 \text{ km} \end{cases}{}^{\text{''}} \quad (4.7)$$

The minimum radius for UMi-LOS is calculated using,

$$\text{Radius}_{\text{UMi-LOS}} = 10^{\left(\frac{\text{MAPL}_{\text{UMi-LOS}} - 32.4 - 20 \log_{10}(f_{c,\text{UMi}})}{21}\right)} \quad (4.8)$$

Table 4.3: Macro cell and Micro cell requirements calculations

General Parameters	Units	Downlink/Uplink	Downlink/Uplink
Calculated MAPL	dB	98.71/102.32	106.94/109.94
gNodeB antenna height	m	25/25	10/10
UE antenna height	m	1.5/1.5	1.5/1.5
d'_{BP}	m	560/560	1680/1680
d_{3D}	m	524.01/764.8	148.46/206.28
d_{2D}	Km	0.5235/0.7644	0.1466/0.2049
Total selected area	Km ²	4/4	4/4
gNB Area	Km ²	0.534/1.1387	0.0419/0.0818

To perform a link budget analysis using Equ (3.14), we need to find the Maximum Allowable Path Loss (MAPL) for both macrocell and microcell in the downlink and uplink. The MAPL values are 98.71 dBm and 106.94 dBm for the downlink, and 102.32 dB and 109.94 dB for the uplink. Using Equation (4.4) and (4.8), the 3D cell radius for the downlink and uplink is calculated. For the macrocell, the downlink radius is 524.01 m, and the uplink radius is 764.8 m. For the microcell, the downlink radius is 148.46 m, and the uplink radius is 206.28m.

Finally, using Equation ($d_{3D} = \sqrt{d_{2D}^2 + (h_{BS} - h_{UE})^2}$), the 2D cell radius for the downlink and uplink is determined. For the macrocell, the downlink radius is 0.5235 km, and the uplink radius is 0.7644 km. For the microcell, the downlink radius is 0.1466 km, and the uplink radius is 0.2049 km.

After calculating cell radius for both frequency then calculate cell area that have three sector by using equation of $gNB_{Area} = \frac{9}{8}\sqrt{3} \cdot [d_{2D}]^2 [km^2]$, the total number of micro and

macro cell is calculated as (3.18),

$$N_{\text{Mcov}}(DL) = \frac{\text{Total}_{\text{SA}}}{gNB_{\text{Mcell}}} = \frac{4}{0.534} = 7.49 \approx 8gNodeB$$

$$N_{\text{Mcov}}(UL) = \frac{\text{Total}_{\text{SA}}}{gNB_{\text{Mcell}}} = \frac{4}{1.1387} = 3.51 \approx 4gNodeB$$

$$N_{\text{mcov}}(DL) = \frac{\text{Total}_{\text{SA}}}{gNB_{\text{mcell}}} = \frac{4}{0.0419} = 95.53 \approx 96gNodeB$$

$$N_{\text{mcov}}(UL) = \frac{\text{Total}_{\text{SA}}}{gNB_{\text{mcell}}} = \frac{4}{0.0818} = 48.87 \approx 96 = 49gNodeB$$

4.2.2 Capacity Dimensioning

To compute the number of gNBs required for capacity dimensioning, we consider the busy hours and traffic patterns of Ethiopian telecom consumers. In addition, we use the number of 5G subscribers and geographical deployment area behavior.

Here's the step:

Step 1: The total number of subscribers

The number of subscribers determines the number of sites needed to meet capacity. Subscriber forecasting is a critical process to do before beginning network planning to build a network capable of accommodating future subscriber growth. Understanding the social and economic aspects that impact subscriber numbers is crucial for forecasting future trends.

Population density is the number of people living in a specific area of one square kilometer. Addis Abeba's population is projected to reach 5,956,680 in 2025, with a density of 527/km² in 2025. This yields a population density of around 5,165 people per square

kilometer [35]. This study uses the following assumptions to emphasize the importance of all factors in successful network capacity planning.

- Assume 80% expected mobile subscriber's (5.5% market share of safari and others are under age) and 60% of total population is 5G users in 2025.

$$5G_{EMS} = TP \times T_{EMS} \times \left(\frac{5G_{EMS}(\%)}{100} \right) \times SA[1] \quad (4.9)$$

where

- $5G_{EMS}$ refers to the expected number of 5G mobile subscribers.
- TP is the total population.
- T_{EMS} is total expected Mobile Subscriber
- SA is selected study area

$$5G_{EMS} = 5165 \times 0.8 \times 0.6 \times 4 = 9916.8 \approx 9917 \text{ subscribers}$$

Step 2: Determine the average total throughput per subscriber during busy hours (BH)

As stated in the table, Ethio Telecom divides its customer into three levels based on data usage: Gold, Silver, and Bronze. The organization determines four peak hours each day, namely from 10 a.m. to 12 p.m. and 8 p.m. to 10 p.m., for a total of four busy hours in a 24-hour period[21].

Table 4.4: Ethio-telecom classifies customers based on their data usage.

Types of customers	Traffic Usage in GB/Month/User	Usage ratio of the services (%)	Traffic ratio of a busy hour (BH) to a whole day (%)
Gold	25	60	16.67%
Silver	20	25	
Bronze	10	15	

To compute average total throughput per subscriber during Busy Hour (BH), use equation (3.19).

$$\text{Gold Av.thrput at BH (DL, UL)} = \frac{25 \times 10^9 \times 8 \text{ bit/byte}}{30 \times 3600} \times 16.667\% = 308.704 \text{ Kbps}$$

$$\text{Silver Av.thrput at BH (DL, UL)} = \frac{20 \times 10^9 \times 8 \text{ bit/byte}}{30 \times 3600} \times 16.667\% = 246.963 \text{ Kbps}$$

$$\text{Bronze Av.thrput at BH (DL, UL)} = \frac{10 \times 10^9 \times 8 \text{ bit/byte}}{30 \times 3600} \times 16.667\% = 123.481 \text{ Kbps}$$

$$\text{Total Av.thrput per sub at BH} = \sum (\text{Av.thrput per sub at BH (Kbps)} \times \text{usage ratio of the service})$$

$$\text{Total Average throughput at BH} = (308.704 \times 0.6) + (246.963 \times 0.25) + (123.481 \times 0.15) = 253.14 \text{ Kbps}$$

Step 3. Determine 5G new radio aggregate throughput.

Using the 3GPP TS 38.306 version 16.1.0 Release 16 technical standard formula (3.20). The table below shows the values needed to determine aggregate throughput.

Table 4.5: Parameters used to calculate the throughputs for 5G New radio.

parameter	3.5GHz DL/UL	28GHz DL/UL	CA 3.5GHz and 28GHz DL/UL
Bandwidth (MHz)	100	200	300
Subcarrier Spacing (KHz)	30	120	30 and 120
Sub-carrier per RB	12	12	12
Component Carrier	1	1	2
Modulation Order	DL 8/UL 6	DL 8/UL 6	DL 8/UL 6
Number of Layer	2	2	2
Scaling Factor	0.5	0.5	0.5
Max. code rate (Rmax)	948/1024	948/1024	948/1024
Overhead	0.14/0.8	0.18/0.1	0.14/0.8 and 0.18/0.1
Numerology(μ)	1	3	1 and 3
Number of RB	273	264	546
Average OFDM symbol duration (Ts)	3.577×10^{-5}	3.577×10^{-5}	3.577×10^{-5}

For 3.5GHz Frequency Band

$$\begin{aligned}
 R_{\text{DataDL}} &= 10^{-6} \times 1 \times 2 \times 8 \times 0.5 \times \left(\frac{948}{1024} \right) \times (273 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.14)) \\
 &= 584.25 \text{Mbps}
 \end{aligned}$$

$$\begin{aligned}
 R_{\text{DataUL}} &= 10^{-6} \times 1 \times 2 \times 6 \times 0.5 \times \left(\frac{948}{1024} \right) \times (273 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.08)) \\
 &= 468.76 \text{Mbps}
 \end{aligned}$$

Maximum number of subscriber per gNodeB downlink and uplink for 3.5GHz fre-

quency is calculated by using equation (3.22)

$$N_{\max \text{ sub DL}}^{\text{gNodeB}} = \frac{584.25\text{Mbps}}{253.14\text{Kbps}} = 2309\text{subscriber}$$

$$N_{\max \text{ sub UL}}^{\text{gNodeB}} = \frac{468.76\text{Mbps}}{253.14\text{Kbps}} = 1852\text{subscriber}$$

Finally, the number of gNodeB required according with capacity dimensioning frequency calculated by (3.23)

$$N_{\text{sites}}^{\text{DL}} = \frac{9917}{2309} = 4.29 \approx 5\text{gNodeB}$$

$$N_{\text{sites}}^{\text{UL}} = \frac{9917}{1852} = 5.35 \approx 6\text{gNodeB}$$

For 28GHz Frequency Band

$$\begin{aligned} R_{\text{DataDL}} &= 10^{-6} \times 1 \times 2 \times 8 \times 0.5 \times \left(\frac{948}{1024} \right) \times (264 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.18)) \\ &= 2154.84\text{Mbps} \end{aligned}$$

$$\begin{aligned} R_{\text{DataUL}} &= 10^{-6} \times 1 \times 2 \times 6 \times 0.5 \times \left(\frac{948}{1024} \right) \times (264 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.1)) \\ &= 1773.80\text{Mbps} \end{aligned}$$

Maximum number of subscriber per gNodeB downlink and uplink for 28GHz fre-

quency is calculated by using equation (3.22)

$$N_{\max \text{ sub DL}}^{\text{gNodeB}} = \frac{2154.84\text{Mbps}}{253.14\text{Kbps}} = 8513\text{subscriber}$$

$$N_{\max \text{ sub UL}}^{\text{gNodeB}} = \frac{1773.80\text{Mbps}}{253.14\text{Kbps}} = 7002\text{subscriber}$$

Finally, the number of gNodeB required according with capacity dimensioning frequency calculated by (3.23)

$$N_{\text{sites}}^{\text{DL}} = \frac{9917}{8513} = 1.16 \approx 2\text{gNodeB}$$

$$N_{\text{sites}}^{\text{UL}} = \frac{9917}{7002} = 1.41 \approx 2\text{gNodeB}$$

For CA of 3.5GHz and 28GHz Frequency Band

$$\begin{aligned} R_{\text{DataDL}} &= 10^{-6} \times 1 \times 2 \times 8 \times 0.5 \times \left(\frac{948}{1024} \right) \times (264 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.18)) \\ &\quad + 1 \times 2 \times 8 \times 0.5 \times \left(\frac{948}{1024} \right) \times (273 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.14)) \\ &= 2844.21\text{Mbps} \end{aligned}$$

$$\begin{aligned} R_{\text{DataUL}} &= 10^{-6} \times 1 \times 2 \times 6 \times 0.5 \times \left(\frac{948}{1024} \right) \times (264 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.1)) \\ &\quad + 1 \times 2 \times 6 \times 0.5 \times \left(\frac{948}{1024} \right) \times (273 \times 12) \times (14 \times 2^1 \div 10^{-3} \times (1 - 0.08)) \\ &= 2281.98\text{Mbps} \end{aligned}$$

Maximum number of subscriber per gNodeB downlink and uplink for 28GHz frequency is calculated by using equation (3.22)

$$N_{\max \text{ sub DL}}^{\text{gNodeB}} = \frac{2844.21\text{Mbps}}{253.14\text{Kbps}} = 11236.1\text{subscriber}$$

$$N_{\max \text{ sub UL}}^{\text{gNodeB}} = \frac{2281.98\text{Mbps}}{253.14\text{Kbps}} = 9015\text{subscriber}$$

Finally, the number of gNodeB required according with capacity dimensioning frequency calculated by (3.23)

$$N_{\text{sites}}^{\text{DL}} = \frac{9917}{11236.1} = 0.88 \approx 1\text{gNodeB}$$

$$N_{\text{sites}}^{\text{UL}} = \frac{9917}{9015} = 1.10 \approx 2\text{gNodeB}$$

Table 4.6: Numbers of gNodeB's in capacity and coverage-based sites count for target area.

Dimensioning	Coverage DL	Coverage UL	Capacity DL	Capacity UL
Calculated value of gNodeB's for 3.5GHz	8	4	5	6
Calculated value of gNodeB's for 28GHz	96	49	2	2
Calculated value of gNodeB's for CA			1	2

This planning focuses on coverage, with the CA method raising data rate further. The 3.5GHz frequency is the primary cell due to its wider coverage area than the 28GHz frequency. In this situation, the secondary cell operates at 28GHz. As a result, eight sites were utilized in this study to conduct CA techno economic analysis.

4.3 Implemented TERA Model

In chapter three, we examined various techno-economic evaluation models and their applications. The ACTS (Advanced Communication Telecom Services) framework (TERA) is a popular tool for doing techno-economic analysis in the telecom industry. TERA combines technical, market, economic, and cost information for key network components to enable techno-economic analysis.

Among the available models, TERA, used in this thesis, stands out for its comprehensiveness. It evaluates the economic viability of various deployment strategies by considering both technical parameters and economic factors, enabling a thorough assessment of costs, revenues, and return on investment across different scenarios. For this study, the original TERA model has been modified to incorporate specific evaluation criteria that emphasize both technical and economic benefits.

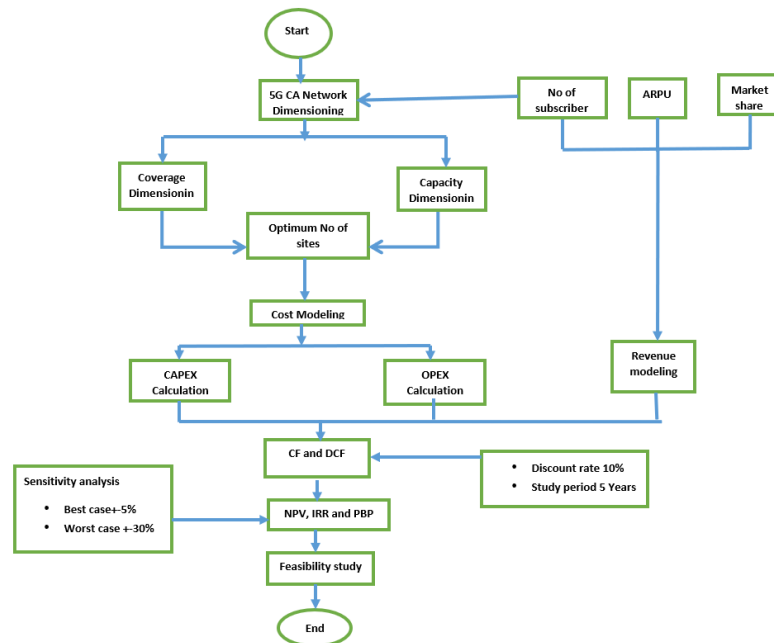


Figure 4.2: Modified TERA model

4.4 Market Analysis

Marketing study is crucial for successfully integrating technology and economics in deploying 5G hybrid networks. This analysis helps evaluate the feasibility and success of 5G hybrid installation in the Bole area of Addis Ababa, Ethiopia.

The population of Addis Abeba is expected to reach 5,956,680 by 2025. Addis Ababa’s population was 392,000 in 1950. Addis Abeba has increased by 253,050 in the last year, reflecting a 4.44% annual change. These population estimates and projections are from the most recent edition of the UN World Urbanization Prospects. These estimates cover Addis Abeba’s urban agglomeration, which includes both the city itself and its surrounding suburbs [35]. The city is a growing metropolitan hub in Ethiopia, with security issues in other regions. The jobs available in Addis Abeba, the availability of good drinking water and plumbing, and the numerous stores and enterprises assure that growth will continue to be steady in this capital city well into the future.

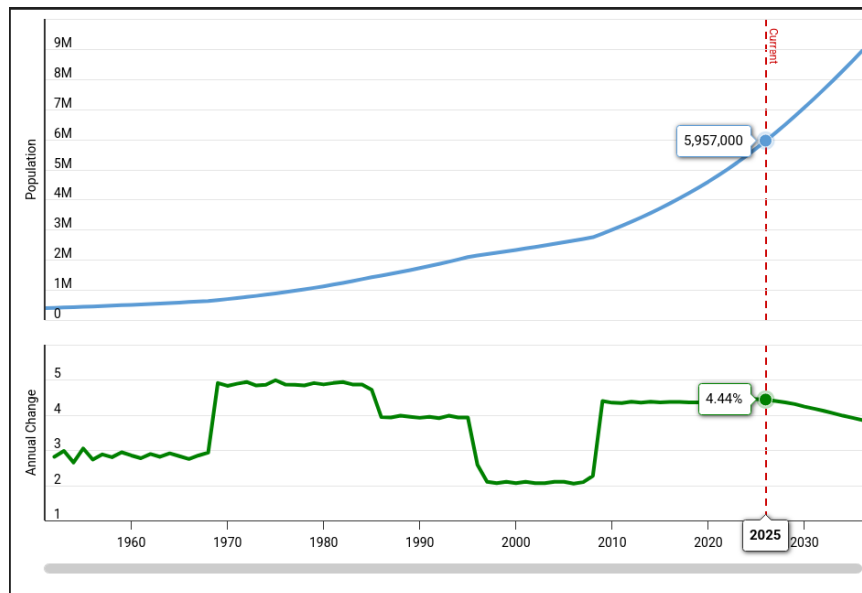


Figure 4.3: Addis Ababa Populations [35]

Between 2020 and 2024, the Ethiopian mobile market experienced a 70.5% increase in users, from 48.6 million in June 2020 to 82.9 million in June 2024.. Until October 2022, the Company was Ethiopia's sole telecommunications operator. It is now the leading player, with 78.3 million subscribers and 94.5% market share as of June 30, 2024.

By June 30, 2024, the Ethiopian mobile market had 82.9 million subscribers, against an estimated population of 128.1 million. This equates to a market penetration rate of 64.7%. The large unaddressed market, along with Ethiopia's growing youthful population, presents substantial opportunities for expanding telecommunication operations in the country.

Continued adoption of smartphones, which is forecast to reach 89.0% by 2030, in tandem with the expansion of the 4G and 5G network coverage's will drive uptake of data services and in turn, is expected to drive growth in income from this segment. The Company began its 5G network in May 2022, beginning in Addis Abeba and eventually expanding to chosen locations. The key strategic goal of this deployment was to improve the service quality of network technologies, with 5G technology promising to accommodate up to 100 times more connected devices per unit area than 4G LTE. The Company believes that the rollout of 4G LTE and 5G is critical to Ethiopia's digitalization, allowing consumers to enjoy innovative products such as the Company's tele engage, web hosting, smart education (U learning), and One Office, which benefit from improved speed, lower latency, and increased capacity.

Addis Ababa covers 527 km² with a populations density of around 5,165 people per km². The Bole area, is a fast-growing hub with high internet demand. Considering the city's 2025 population projection of 5,956,680 and assuming 80% market share with 60% 5G

adoption, the estimated number of 5G subscribers in Bole for 4 km² area is approximately 9,917.

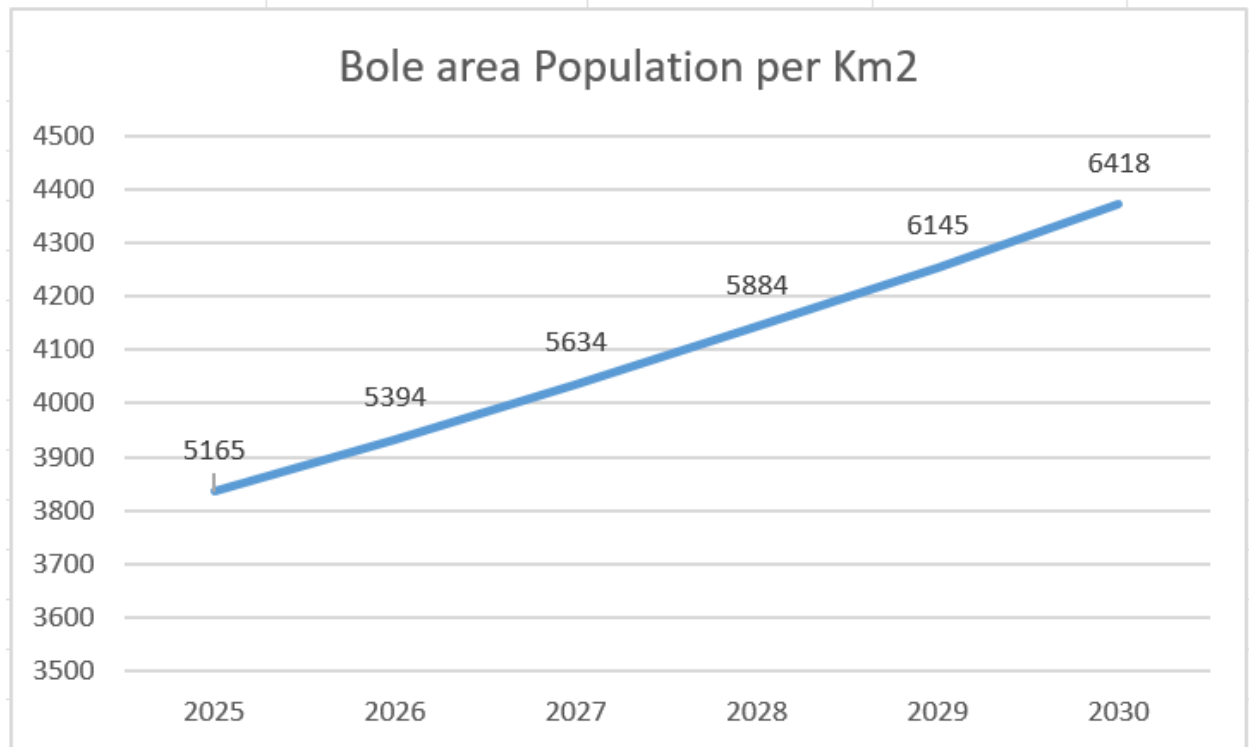


Figure 4.4: Forecast Populations per Km², Addis Ababa city.

4.5 Economic Analysis

Market and technical assessments serve as the foundation for economic analysis. It focuses mostly on cost and revenue modeling. Cost modeling includes CAPEX and OPEX estimations, as well as TCO.

4.5.1 CAPEX OPEX, and TCO Estimation

CAPEX and OPEX are important factors in network planning and financial management. CAPEX refers to initial network investments, whereas OPEX covers continuing costs for smooth operation. Accurate data collection and analysis for both CAPEX and

OPEX are critical for effective network planning, budgeting, and financial sustainability.

The below table lists are some key items that are typically included in the CAPEX and OPEX cost for 5G hybrid network deployment. For upgrading existing BS and deploying new BS are collected from ethio telecom’s actual 5G deployed network but the equipment cost are based on industry estimates and expert opinions, the cost of a 5G network with carrier aggregation capability across 3.5GHz and 28GHz can be 1.5 to 2 times higher than a non-aggregated 3.5GHz network, in this thesis we consider the equipment cost is 1.5 times the deployed 5G network[24].

Table 4.7: CAPEX of gNodeB components.[36]

No.	Component	Description	CA of 3.5GHz and 28GHz (NSA) in ETB
1	Spectrum Acquisition (for 28GHz)	The cost of acquiring the necessary spectrum licenses for 28GHz bands to aggregate.	92,732,210
2	Equipment cost for all RAN, Back haul with Software and Licensing	This includes the cost of upgrading or installing new base stations, antennas, and other network equipment to support carrier aggregation.	129,980,768.07
3	Service Cost (Design, Installation, Testing and validation)	Labor costs for the Design, installation, configuration, Testing and validation of new equipment and technologies.	4,808,138.96
4	Site Acquisition and Preparation	The costs of acquiring new sites or preparing existing ones to support the additional equipment needed for carrier aggregation.	601,301
Total			228,122,418

Estimating operational costs for a project may be more uncertain than capital expenses. This thesis mostly on annual OPEX data from the 2024 operational cost reports. We reference research [1] and [21] to understand the operational expenses of 5G technology,

which are expected to increase by 10% annually. We also discuss cost distribution.

Table 4.8: OPEX of gNodeB components [1&2].

No.	Component	Description	Distribution	CA of 3.5GHz and 28GHz (NSA) in ETB
1	Maintenance and Repairs	Regular maintenance and any necessary repairs to keep the network infrastructure in optimal condition.	30%	73,676
2	Rental Costs	Costs for sites where network equipment is installed.	5%	12,279
3	Labor Costs	Salaries and benefits for technical and operational staff responsible for network management and maintenance.	11%	27,015
4	Software Licensing and Updates	Ongoing costs for software updates and license renewals to ensure the network remains up-to-date and secure.	10%	24,559
5	Energy Costs	Electricity and other energy costs required to power the network equipment.	12%	29,471
6	Customer Support	Costs associated with providing customer support services, including technical support teams.	5%	12,279
7	Insurance	Insurance premiums to cover network infrastructure and operations.	5%	12,279
8	Marketing and Sales	Expenses for promoting services and acquiring customers	17%	41,750
9	General Administration		5%	12,279
Total			100%	245,588

The total cost of ownership (TCO) is the sum of the two costs, which can be calculated using Eq. 3.3. These cost estimates cover the initial year's CAPEX and OPEX for the study period.

$$TCO = 228,122,418 + 245,588 = 228,368,005ETB$$

4.5.2 Revenue Modelling

Revenue forecasting can be based on service user numbers and operator rating policies.

Revenue can be estimated using the formula 3.5.

$$R = N_{\text{Sub}} \times \text{ARPU} \quad (4.10)$$

Where:

- R is total Revenue
- N_{sub} is the overall number of subscribers.
- $ARPU$ is the annual revenue generated by each user.

According to the annual report and prospectus document, ethio telecom had an average of 22.0 million, 24.6 million, and 37.1 million mobile broadband subscribers in 2022, 2023, and 2024, respectively. The average revenue per user (ARPU) for these years was 48.5 ETB, 53.5 ETB, and 42.5 ETB, respectively. Then revenue for mobile broad band 12827, 15808 and 18909 million ETB on 2022, 2023, and 2024 respectively [30].

For mobile broadband in 2023, the ARPU for 4G and 5G technologies were 50.8 ETB and 159 ETB, respectively. In 2024, the ARPU for 4G and 5G technologies increased to 78 ETB and 214.6 ETB, respectively and projected to 2030 by the rate of 35% if its flow this trend in the future.

Chapter 5: Results and Discussion

This chapter presents the study's findings and their implications for the thesis objectives indicated in Chapter 1. The findings are organized based on the major ideas derived from data analysis.

5.1 Economic Analysis

This study analyzes three years of Ethio Telecom's ARPU statistics. Using historical trends, a linear regression model predicts future values. The linear regression technique shows a constant annual growth in ARPU. Figure 5.2 illustrates how the linear model predicts future ARPU values. This graph depicts the expected ARPU rise in the coming years, following a linear trend.

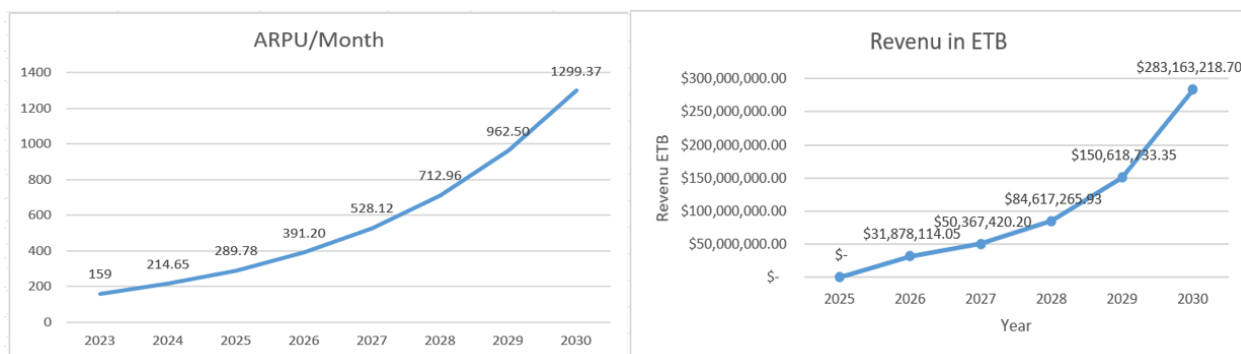


Figure 5.1: ARPU and Revenue Forecast

Revenue projections are mostly based on total service users and rates. Based on this concept, the study uses the previously forecasted user numbers and projected ARPU. The analysis integrates forecasts to estimate overall revenue for the following five years. This estimate considers expected variations in user numbers and ARPU values. The study uses

anticipated user counts and ARPU to estimate income over five years see Figure 5.2.

5.2 Techno-economic Evaluation

As discussed in Chapter 3, the cost of both capex and OPEX, as well as the revenue, are presented, which helps to analyze the CF, DCF, net CF, depreciation, and net income of the system, and the economic metrics NPV and IRR are summarized here in this section.

Table 5.1: CAPEX, OPEX and Revenue values in ETB.

Year	CAPEX	OPEX	TCO	Revenue
2025	(228,122,417.65)		(228,122,417.65)	
2026		(245,587.83)	(228,368,005.48)	32,130,432
2027		(270,146.61)	(228,392,564.27)	51,087,386.88
2028		(297,161.27)	(228,419,578.93)	86,337,683.83
2029		(326,877.40)	(228,449,295.05)	154,544,454.05
2030		(359,565.14)	(228,481,982.79)	292,089,018.16

5.2.1 Cash Flow Analysis

The cash flow statement details all cash inflows and outflows during the project's duration. A positive net cash inflow, where inflows exceed outflows, indicates that the project can cover all its expenses without issues. It's crucial to consider the time value of money in cash flow analysis, making discounted cash flows particularly important. Other metrics like NPV, IRR, and payback period also rely on the project's cash flows. In the projected cash flow statement for this project, the net cumulative cash inflow is negative for the first four years of operations. This is expected due to the high initial investment, which is fully deducted at once, pushing the net cumulative cash flow downward initially.

Table 5.2: Cash flow analysis values in ETB.

Year	Cash out Flow	Cash Inflow	Net cumulative cash inflow	Depresiosion	Discounted Cash flow	Net Income
1	(245,587.83)	31,884,844.17	(196,483,161.31)	(45,624,484)	28,986,221.97	(13,739,639.36)
2	(270,146.61)	50,817,240.27	(177,575,324.68)	(45,624,484)	41,997,719.23	5,192,756.74
3	(297,161.27)	86,040,522.56	(142,379,056.37)	(45,624,484)	64,643,518.07	40,416,039.02
4	(326,877.40)	154,217,576.65	(74,231,718.40)	(45,624,484)	105,332,679.91	108,593,093.12
5	(359,565.14)	291,729,453.02	63,247,470.22	(45,624,484)	193,978,759.47	246,104,969.49

However, it will gradually turn positive.

Another important parameter is the project's net income. Cash flow and income statements differ in how costs are allocated during a project's life cycle. Unlike cash flow statements, depreciation is used to disperse the initial investment over a five-year period. Income statements also include non-cash transactions such purchases, sales on account, and amortization. As a result, they do not accurately reflect the project's cash flow patterns. However, the project's net revenue is favorable. The first year of operation may result in a loss until revenue exceeds expenses. As the number of users grows, the project will generate a profit.

5.2.2 Investment Decisions Using NPV, IRR, and PBP

A positive NPV indicates that a project will generate enough cash flows to pay all initial costs and be profitable. An NPV of Birr 193.97 million for a project with initial outlays exceeding Birr 246.1 million over five years demonstrates strong financial viability.

The IRR is the rate at which the project's NPV equals zero. For our project, the IRR is 30%, which significantly exceeds of the initial specified discount factor (10%). This

Table 5.3: NPV, IRR and PBP values.

Parameters	Value
NPV	193,978,759.47
IRR	30%
PBP	4.48 (4 years and 5 month)

indicates that the project's expected return is much higher than its cost of capital, underscoring its financial viability. IRR and NPV are interrelated indicators. A higher NPV suggests that the IRR will be above the cost of capital, while a negative NPV indicates that the IRR is below the cost of capital.

Another key indicator of a project's viability is the payback period, which calculates the number of years needed to recoup the initial investment. While the IRR is useful, it should be evaluated alongside other benchmarks, such as industry standards. Given the substantial initial investment, a payback period of under 5 years is generally attractive.

5.3 Simulation Results and Performance Comparisons

5.3.1 Atoll planning tool for 5G NR networks

Atoll, developed by Forsk, is a comprehensive platform for designing and optimizing wireless networks. It supports many radio access technologies, such as 5G NR, LTE, NB-IoT, UMTS, GSM, and CDMA [33]. It also includes advanced technologies like MIMO, 3D Beamforming, and mm-Wave propagation. This platform provides a foundation for operators and vendors to design, optimize, and plan their networks[33]. As technology advances and user demands for better services grow, this tool becomes increasingly important in satisfying those needs.

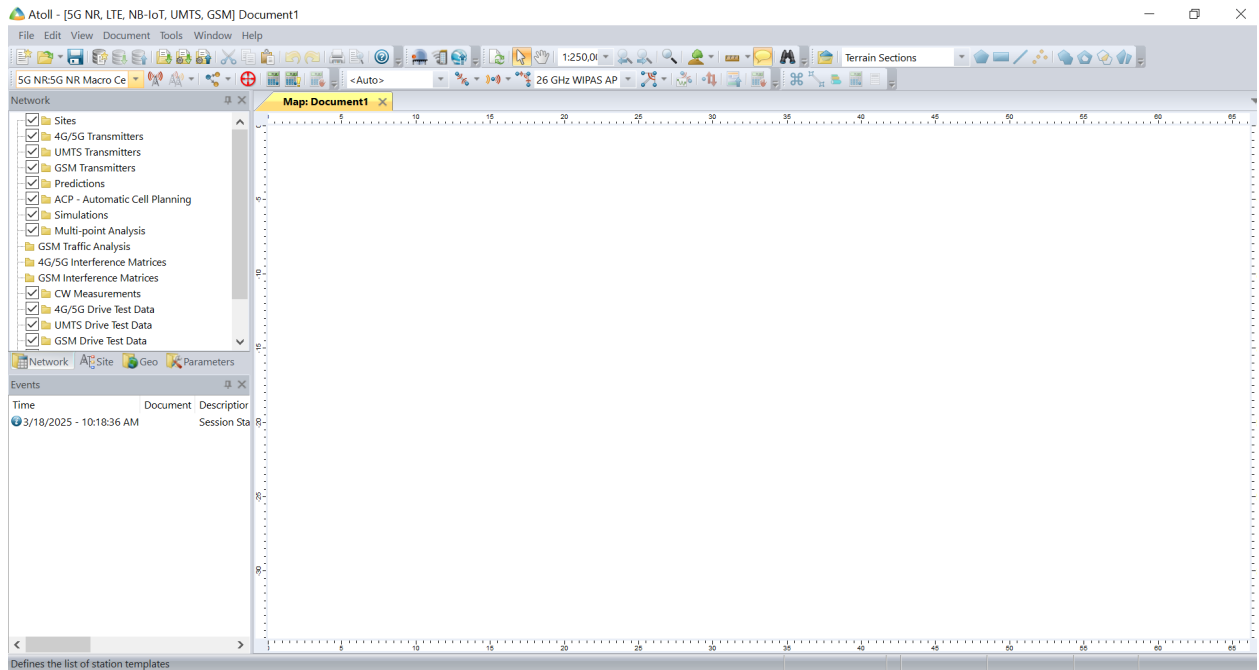


Figure 5.2: Atoll working environment.

General parameters for network configuration

Atoll enables modeling of network components such as base station, transmitter, and cell parameters.

- The term "site" refers to the geographical location of the base station and its transmitters.
- Transmitters create radio waves and use antennas to transmit and receive data.
- A cell is an RF channel established on a transmitter.

Atoll allows to specify the following cell parameters:

- **Carrier:-** The carrier of the cell in the frequency spectrum. Specified the carrier band width.

- **Max power (dBm):-** The cell's highest transmission power.
- **SSS EPRE (dBm):-** The SSS energy for each resource element. This value is used to determine the transmission power required for the secondary synchronization signal (SSS).
- **PSS EPRE offset / SSS (dB):-** The difference in energy of a PSS resource element against an SSS resource element. This value is used to determine the transmission power associated with the primary synchronization signal (PSS).
- **Layer:-** The cell belongs to the network layer. It might have a macro layer (for macro cells) or a small layer (for small/micro cells).
- **Cell type:-** This specifies whether the cell is set to primary PCell, secondary SCell (UL), or secondary SCell (DL).
- **Min SS-RSRP (dBm):-** The lowest SS-RSRP required for a user to connect to the cell. The SS-RSRP is compared to this threshold to determine whether or not a user is within the cell's coverage range.
- **SS/PBCH numerology:-** The cell uses the SS/PBCH numerology.
- **SS/PBCH periodicity:-** The SS/PBCH bursts are periodic.
- **SS/PBCH OFDM symbols:-** The OFDM signals that initiate SS/PBCH blocks, as well as the number of SS/PBCH blocks each SS/PBCH burst.
- **PDCCH overhead (OFDM symbols):-** The number of OFDM symbols per sub-frame allocated to the physical downlink control channel (PDCCH).

- **Traffic numerology:-** The cell's numerology for traffic channels (PDCCH, PDSCH, and PUSCH).
- **TDD DL OFDM symbols (%)**:- The proportion of downlink OFDM symbols to the total number of OFDM symbols per frame.
- **Radio equipment:-** cell's radio equipment.
- **Scheduler:-** The scheduler is used by the cell to choose bearers and allocate resources.
- **Diversity support (DL/UL)**:- The antenna diversity approach is supported by the cell in the downlink/Uplink.
- **Number of MU-MIMO users (DL/UL)**:- The average number of MU-MIMO users sharing resources on the downlink/uplink
- **Traffic load (DL/UL) (%)**:- The downlink/uplink traffic load percentage.
- **Max traffic load (DL/UL) (%)**:- The downlink/uplink traffic load not to be exceeded.
- **UL noise rise (dB)**:- The uplink noise rise in dB.
- **Fractional power control factor**:- This factor is used to compensate for path loss during fractional power regulation on the uplink. If this factor is set to 0.8, only 80% of the route loss will be used when estimating the received power.
- **Number of required PRACH RSI**:- The needed number of PRACH RSIs for this cell. The number of PRACH RSIs required for each cell is determined on the PRACH preamble format and cell size.

- **Max number of 4G/5G neighbors:-** The maximum number of 5G NR neighbors that the cell may have.
- **Max number of inter-technology neighbors:-** The maximum number of other technology neighbors that the cell may have.

Atoll offers pre configured station templates with basic specifications. For this study, one of these templates was used, with modifications made to the frequency band and carrier. The table below presents the final cell configuration utilized in this study.

Table 5.4: Parameters of 5G NR cell apply for this thesis.

Frequency band	n78 (3.5GHz)	n257 (28GHz)
Antenna Height	25	10
Carrier Bandwidth	100 MHz - NR-ARFCN 623333	200 MHz - NR-ARFCN 2059166
Max power (dBm)	49	36
Layer	Macro	Small Cell
Cell type	PCell	SCell DL, SCell UL
Min SS-RSRP (dBm)	-140	-140
SS/PBCH numerology	0 (15 kHz)	3 (120 kHz)
SS/PBCH periodicity	10 ms	10 ms
Radio equipment	5G NR	5G NR
Scheduler	Proportional Fair	Proportional Fair
Diversity support (DL/UL)	Transmit Diversity; SU-MIMO; MU-MIMO	Transmit Diversity; SU-MIMO; MU-MIMO
Max traffic load (DL/UL) (%)	100	100
Duplex Mode	TDD	TDD
Max number of 4G/5G neighbors	16	16
Max number of inter-technology neighbors	16	16

Traffic parameters

Atoll traffic parameters apply to all radio access technologies and establish user services, mobility, terminals, profiles, and environment based on user density [38]. Atoll users can access services such as telephony, internet, and broadband. 5G NR users primarily used broadband services, as future 5G networks will require large amounts of wide bandwidth data.

Table 5.5: 5G NR Broadband Service Characteristics.

Parameter	Uplink	Downlink
Highest/Lowest modulation	64QAM/BPSK	256QAM/BPSK
Highest/Lowest coding rate	0.95/0.3	0.95/0.3
Max/Min throughput demand	5,000 kbps/500 kbps	20,000 kbps/1000 kbps

The terminal utilized was a 5G smartphone with the following defined characteristics.

- Minimum power: -40 dBm
- Maximum power: 23 dBm
- Noise figure: 8 dB
- Frequency band: n78 and n257
- Carrier Aggregation Support: Yes
- Radio equipment: 5G NR
- MIMO Support: yes
- Antenna gain: 0 dB

- Tx antennas number: 4
- Rx antennas number: 4

MIMO features

Atoll supports a variety of MIMO configurations, including transmit and receive diversity, single-user MIMO (SU-MIMO), or spatial multiplexing, and multi-user MIMO (MU-MIMO), or collaborative MIMO [33].

During calculations, a user terminal with MIMO capabilities that is connected to a cell that supports SU-MIMO or MU-MIMO will benefit from the MIMO gain or not, depending on whether the PDSCH or PUSCH $C/(I+N)$ at the user's location is greater than or equal to the threshold defined in the 5G NR radio equipment.

Propagation models

Atoll offers various propagation models for calculating path loss based on specific conditions, frequencies, and radio technology. The 3GPP 38.901 standard for network planning employs two propagation models: Urban Macro (UMa) and Urban Micro (UMi) for this study.

Predictions and simulations

5G NR coverage estimates in Atoll enable for the analysis of effective signal levels, signal quality, and throughput, with each pixel of the map representing a non-interfering user with a certain service and terminal.

Table 5.6: 5G NR Prediction in Atoll[33].

KPI Parameters	Description
Coverage	Predicts the effective signal levels of various 5G NR signals for both downlink and uplink. The forecast comprises the SS-RSRP, PDSCH, and PUSCH signal levels.
Quality	Predicts interference levels. This prediction contains PDSCH and PUSCH at the C/(I+N) and SS-SIRN levels.
Service areas	Displays 5G NR radio bearers at the C/(I+N) level for each pixel in both the downlink and uplink.
Capacity	In 5G NR settings, it displays the maximum RLC allotted bandwidth throughput for both downlink and uplink.

5.3.2 Deployment area and Simulation Result

Geographical scope of study and data

The study is conducted in Bole, Addis Ababa, Ethiopia, in a sample area of 4 km².

The bounding rectangle's coordinates are shown below, and the coordinate system used is WGS 84/UTM zone 37 N.

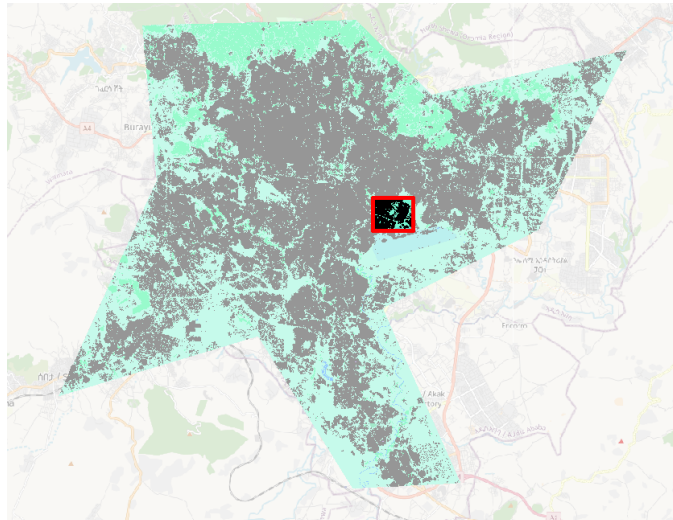


Figure 5.3: Selected area coordinates.

Atoll imports four types of geographic data to perform the various calculations (path

loss, coverage, signal level, etc.)

- Digital Terrain Model (DTM): DTM describes the elevation of the Earth at sea level. The propagation model automatically takes it into account during calculations.
- Clutter classes: A data file with a clutter class describes the area covered or the area used. The propagation model takes clutter classes into account in its calculations.
- Clutter heights: Clutter heights maps describe the height of the clutter above the DTM, with one height per pixel.
- Vector Layers: Atoll allows for the representation of polygons, like regions, lines, like roads or coastlines, and points

Simulation Result

Simulation offers a realistic and systematic method for analyzing complex systems. This study explores the notional planning of 5G networks through simulation, utilizing the Atoll software tool. The simulation encompasses link budget calculation, propagation modeling with terrain models, coverage prediction, and capacity estimation for 5G radio network planning.

A. 5G NR Coverage prediction by SS-RSRP

Synchronization Signal reference signal received power(SS-RSRP) is the most important metric for signal level and quality. The standard SS-RSRP 3GPP specification for coverage estimation, the SS-RSRP is evaluated according to simulation findings.

Table 5.7: SS-RSRP Value Category.

Range of SS-RSRP	Category
$-90 \leq \text{RSRP} \leq -70$ dBm	Excellent RF condition
$-110 \leq \text{RSRP} \leq -90$ dBm	Good RF condition
$-130 \leq \text{RSRP} \leq -100$ dBm	Bad RF condition

According to the simulation results,

- **Sub-band (3.5 GHz):-** The target area is covered on average by -87.38 dBm. This indicates a relatively strong signal, as values closer to 0 dBm represent stronger signals. An RSRP score of -87.38 dBm is regarded good and provides stable connectivity.
- **Mm-wave band (28 GHz):-** The target area is covered on average by -95.14 dBm. This is slightly weaker than the sub-band but still within a range that can offer decent connectivity. mm-wave frequencies often face more challenges with signal penetration and coverage, which can result in slightly lower RSRP values.
- **Carrier aggregation (3.5 GHz & 28 GHz):-** The target area is covered on average by -85.13 dBm. This is the strongest signal among the three configurations. Carrier aggregation combines several frequency bands to increase signal power.

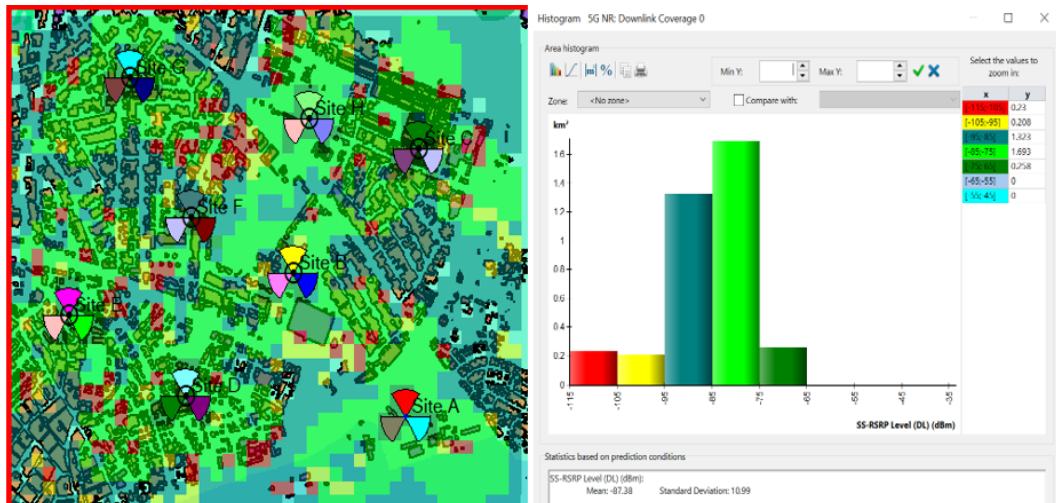


Figure 5.4: 5G sub-band(3.5GHz) Coverage prediction by SS-RSRP with ACP.

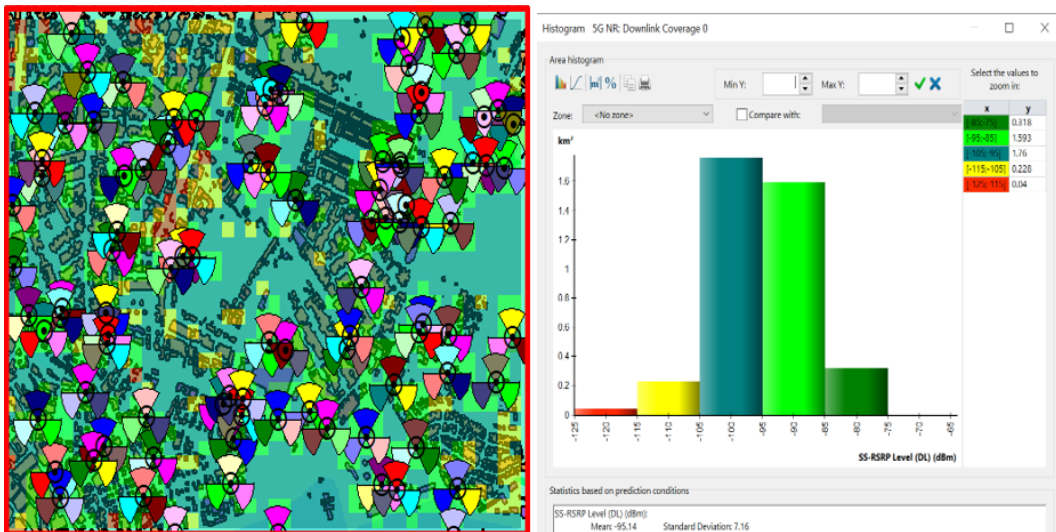


Figure 5.5: 5G mm wave-band(28GHz) Coverage prediction by SS-RSRP with ACP.

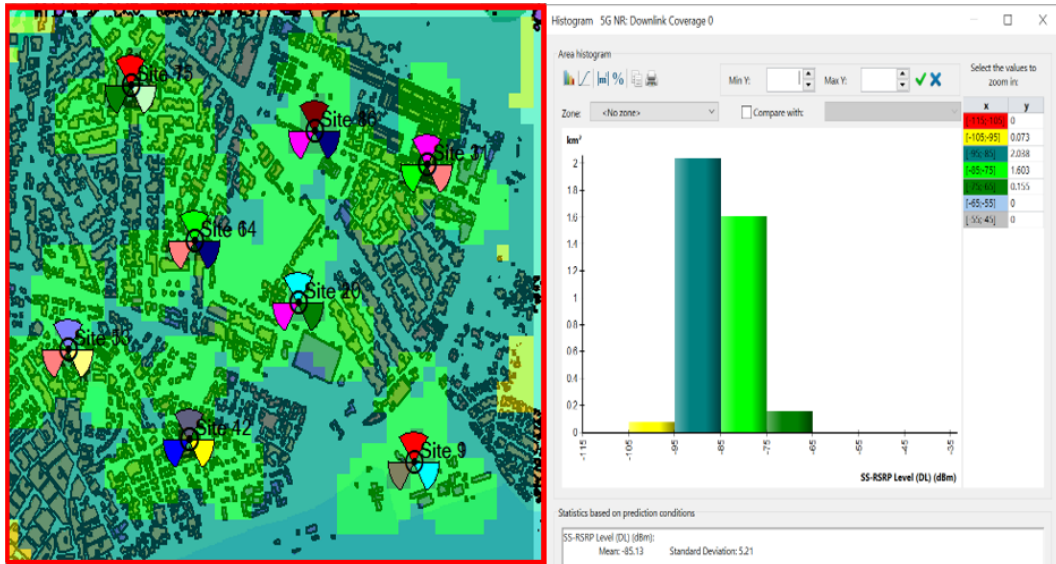


Figure 5.6: CA of 5G sub-band(3.5GHz) and mm wave-band(28GHz) Coverage prediction by SS-RSRP with ACP.

B. Quality predictions by $C/(I+N)$

The ratio of carrier signal power (C) to total interference (I) and noise (N) powers is known as $C/(I+N)$, and it is used to evaluate cellular network signal quality. This ratio is crucial for assessing the performance and reliability of the communication.

According to the simulation results,

- **Sub-band (3.5 GHz):-** An average quality of 7.61 dB suggests relatively good signal strength and lower interference in this band, making it suitable for reliable data transmission.
- **Mm-wave band (28 GHz):-** An average quality of 3.36 dB indicates higher interference and noise levels compared to the sub-band, which can affect the reliability and speed of data transmission.
- **Carrier aggregation (3.5 GHz & 28 GHz):-** An average quality of 2.99 dB shows

that combining these bands results in even higher interference and noise, potentially reducing the overall performance.

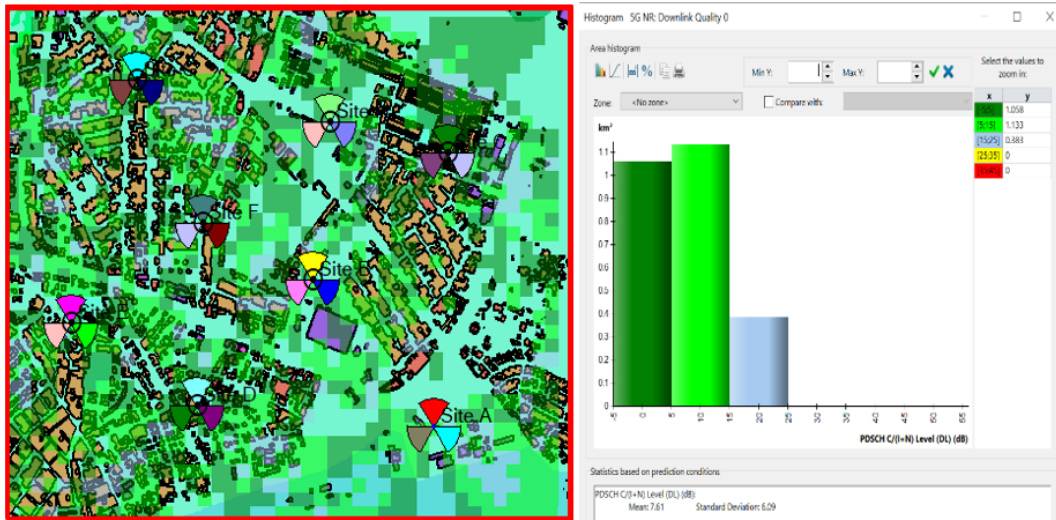


Figure 5.7: 5G sub-band(3.5GHz) Downlink Quality Prediction by PDSCH C/(I+N) Level(DL)(dB).

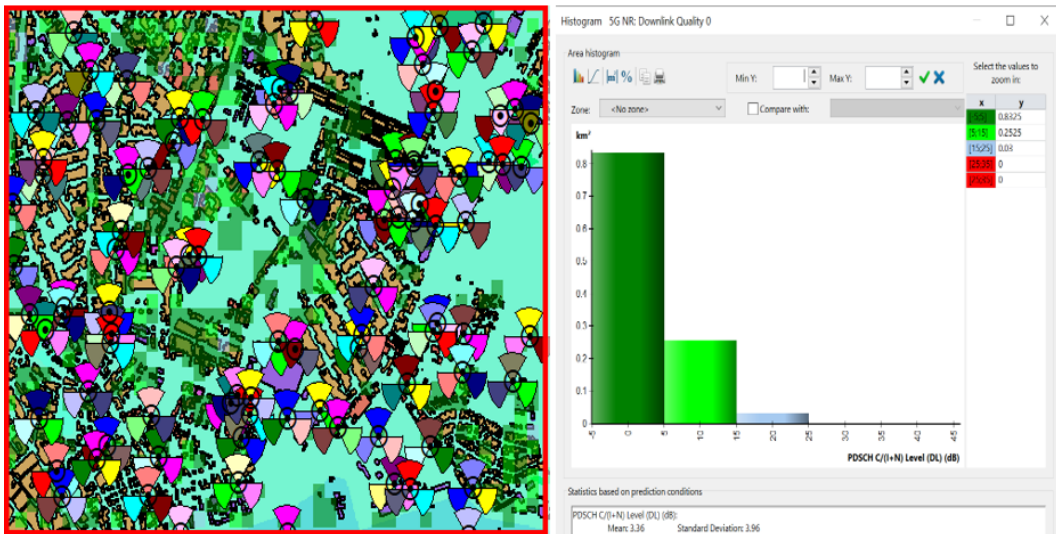


Figure 5.8: 5G mm wave-band(28GHz) Downlink Quality Prediction by PDSCH C/(I+N) Level(DL)(dB).

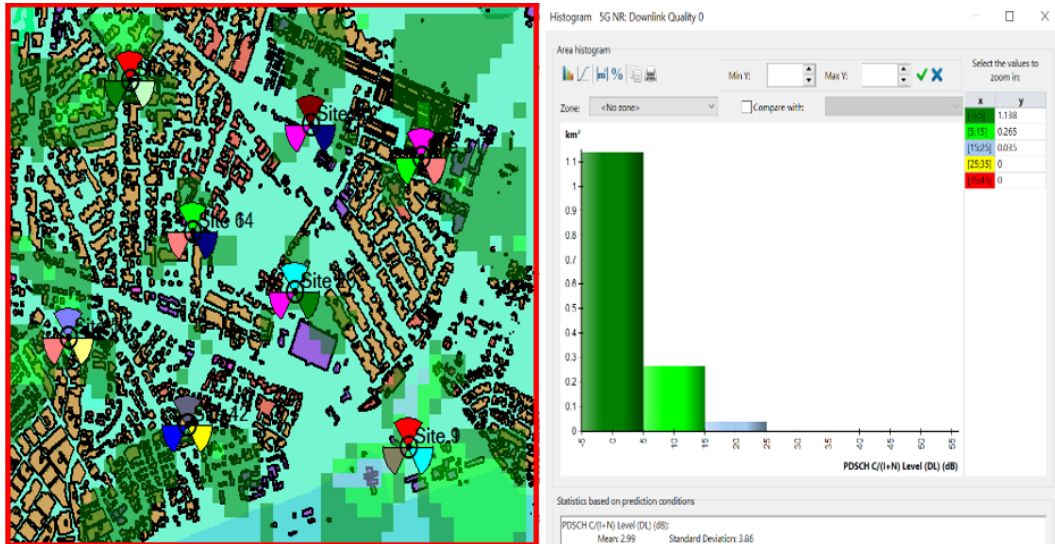


Figure 5.9: CA of 5G sub-band(3.5GHz) and mm wave-band(28GHz) Downlink Quality Prediction by PDSCH C/(I+N) Level(DL)(dB).

C. 5G NR Capacity Prediction by Throughput

The ATOLL network planning tool was utilized to simulate and estimate both downlink and uplink throughput, channel capacity, and overall cell performance. To align with network design standards, the cell edge coverage probability was set at 95%, ensuring reliable service at the network boundaries. Target throughput benchmarks were established at 10 Mbps (uplink) and 50 Mbps (downlink) for the 3.5 GHz band, and 25 Mbps (uplink) and 100 Mbps (downlink) for the 28 GHz band. In this context, throughput is the actual volume of data successfully delivered over the network within a given time frame, whereas data rate is the theoretical speed at which data can be carried. These metrics were derived from simulations designed to reflect realistic usage conditions across the different frequency bands.

The prediction results are shown in the figures below.

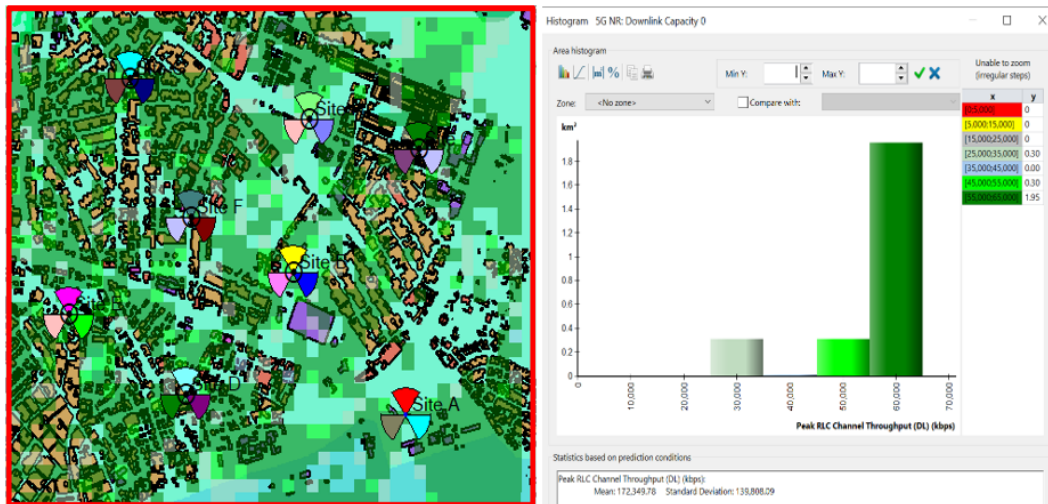


Figure 5.10: 5G sub-band(3.5GHz) Capacity prediction by Peak RLC Channel Throughput(DL).

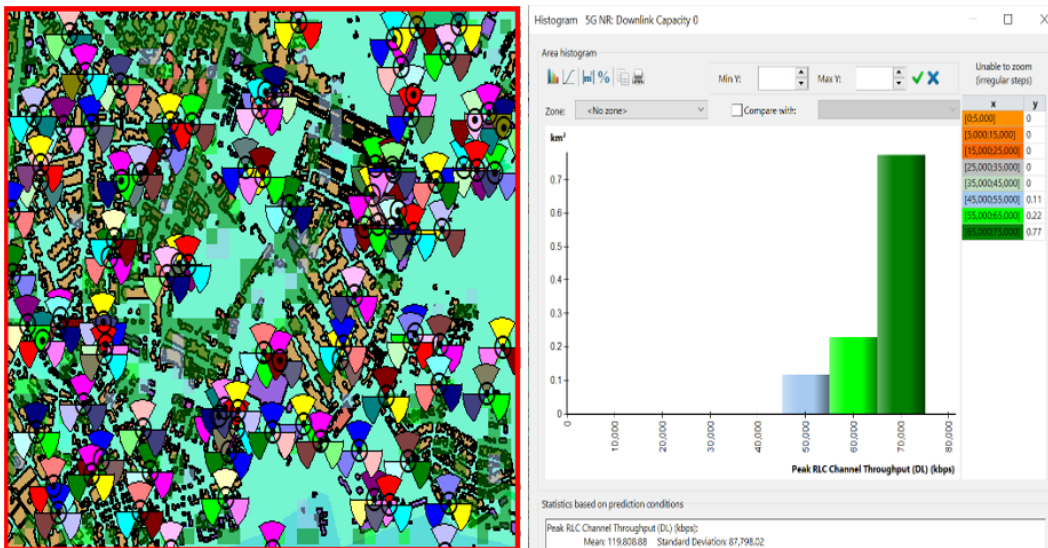


Figure 5.11: 5G mm wave-band(28GHz) Capacity prediction by Peak RLC Channel Throughput(DL).

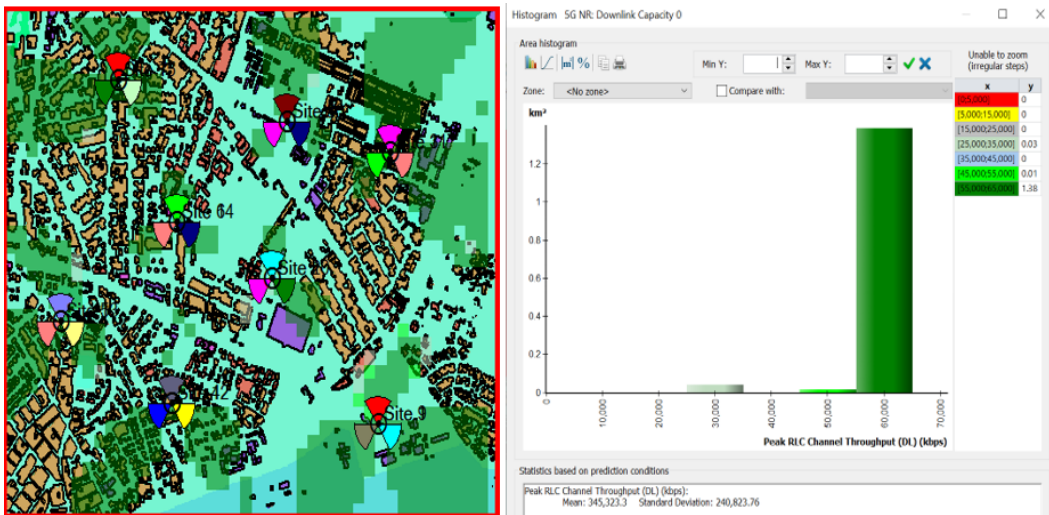


Figure 5.12: CA of 5G sub-band(3.5GHz) and mm wave-band(28GHz) Capacity prediction by Peak RLC Channel Throughput(DL).

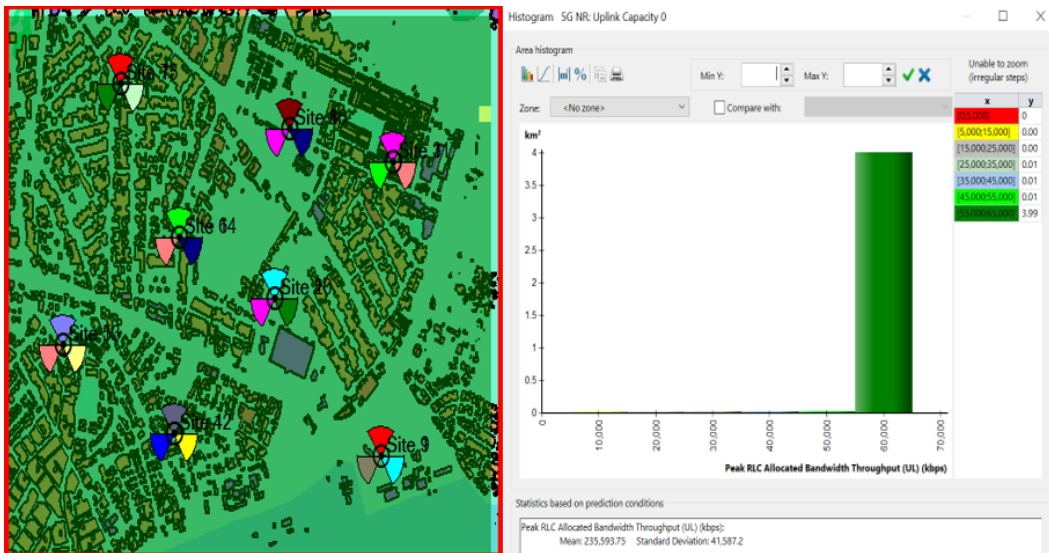


Figure 5.13: 5G sub-band(3.5GHz) Capacity prediction by Peak RLC Channel Throughput(UL)

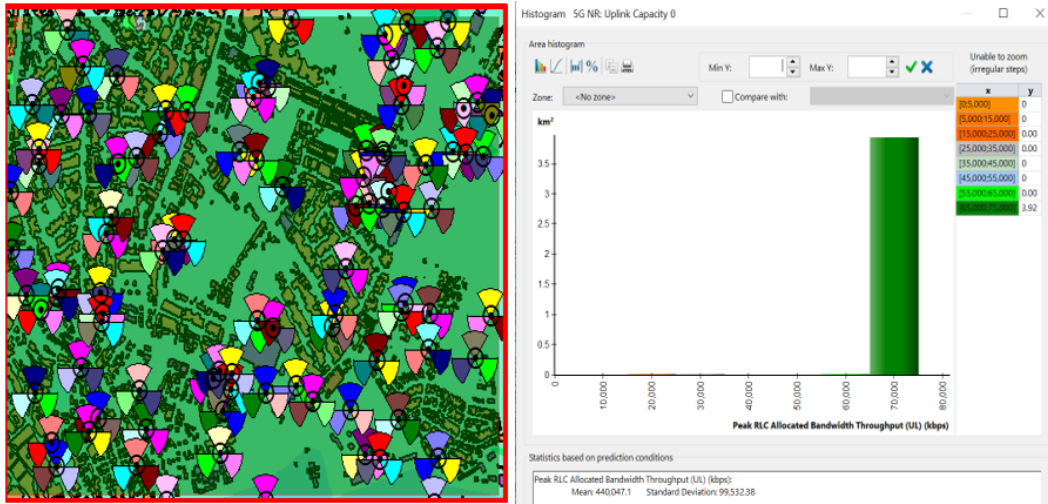


Figure 5.14: 5G mm wave-band(28GHz) Capacity prediction by Peak RLC Channel Throughput(UL).

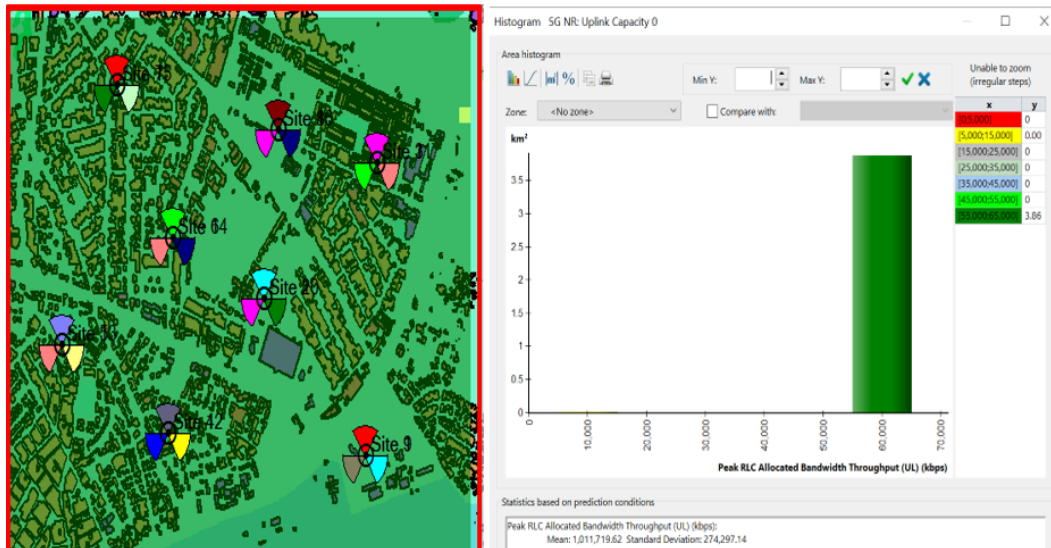


Figure 5.15: CA of 5G sub-band(3.5GHz) and mm wave-band(28GHz) Capacity prediction by Peak RLC Channel Throughput(UL).

5.3.3 Evaluation of Coverage and Capacity of Hybrid 5G Deployment

A simulation-based approach was employed to evaluate the performance of a hybrid 5G network deployment combining Sub 6GHz (3.5 GHz) and mmWave (28 GHz) frequency

bands. Using the ATOLL radio planning tool, the study assesses key performance indicators such as SS-RSRP (Reference Signal Received Power) and throughput to analyze both coverage and capacity. The simulation scenarios are designed to reflect realistic deployment conditions in the Bole area of Addis Ababa. The findings provide valuable insights into the effectiveness of hybrid 5G configurations in urban environments, highlighting the trade-offs and advantages of each frequency band and their combined use through carrier aggregation.

Coverage Evaluation

The coverage performance results are analyzed through radio planning, coverage evaluation, and capacity simulations, aiming to provide a comprehensive comparison of the coverage capabilities of each frequency band. By simulating the Sub 6GHz (3.5 GHz), mmWave (28 GHz), and their combined deployment through carrier aggregation, the study highlights the strengths and limitations of each configuration. Sub 6GHz demonstrates broader and more consistent coverage due to its superior propagation characteristics, while mmWave offers limited coverage but higher data rates in dense urban zones. The hybrid approach, combining both bands, shows improved signal strength and extended coverage, making it a promising solution for urban 5G deployment in areas like Bole, Addis Ababa.

Capacity Evaluation

The capacity performance of the hybrid 5G deployment was assessed through simulation-based throughput predictions for both downlink and uplink channels. Using the ATOLL planning tool, the study evaluated the data-handling capabilities of Sub 6GHz (3.5 GHz),

mmWave (28 GHz), and their combination via carrier aggregation. The results indicate that while the Sub 6GHz band provides moderate throughput with stable performance, the mmWave band delivers higher peak data rates but with limited coverage. Notably, the carrier aggregation configuration significantly outperforms the individual bands, achieving the highest downlink throughput of 345.3 Mbps. This improvement is attributed to the increased total bandwidth and optimized subcarrier spacing. These findings underscore the potential of hybrid deployment to fulfill the increasing need for fast data services in urban environments like Bole area.

Table 5.8: Simulation Results Values.

Parameters	3.5 GHz	28 GHz	CA 3.5 GHz & 28 GHz
Bandwidth	100MHz	200MHz	300MHz
Subcarrier Spacing	30	120	30&120
Mean SS-RSRP Value (dBm)	-87.38	-95.14	-85.13
Mean C/(I+N) (dB)	7.61	3.36	2.99
Data Rate DL (Mbps)	172.3	119.8	345.3

Chapter 6: **Conclusions and Future Work**

6.1 Conclusions

The rapid increase in demand for innovative data services for developing countries has driven the deployment of advanced mobile technologies like 5G network. However, these deployments are often vendor-driven and lack localized techno-economic assessments. As a result, resources are underutilized, and network performance and quality of service suffer once the investments become operational.

A techno-economic evaluation of 5G hybrid (sub-band 3.5GHz and mm-wave band for 28GHz) network deployment scenarios for the Bole area in Addis Ababa has been conducted in this thesis study, which also takes into account a techno-economic analytical modeling approach. NSA 5G deployment scenarios were formulated through planning method for this city. Consider the future market in the city while applying certain market forecasting assumptions. Additionally, 5G radio access network dimensioning was conducted for a 5-year study period, targeting a 94.5% market share. The feasibility of the proposed network in the given target area is NPV results are positive, with an NPV of 193,978,759.47 ETB for the study period, and the IRR is 30% which exceeds the defined discount rate. The calculated PBP is 4.48 years, which is less than five years. As per a result of the techno-economic analysis, the implementation of a 5G NR network in the target bole area is feasible. In addition to this, this thesis performs for sub band (3.5GHz), mm-wave band (28GHz) and carrier aggregation of sub band (3.5GHz) & mm-wave band (28GHz) pre-

dicting coverage and capacity in atoll software, with relation to signal level coverage and capacity prediction by Peak RLC Channel Throughput and which indicates that carrier aggregation of sub band and mm-wave are most effective for achieving high data rate and good coverage.

6.2 Future Work

The feasibility of 5G hybrid deployment is examined in this thesis for Bole area of Addis Ababa, Ethiopia, through a Techno-Economic Analysis. It focuses on utilizing Sub 6GHz and mm-Wave bands in the NSA deployment option. However, it does not address the cost implications of the SA deployment option but suggests extending the research to assess SA deployment and customer acceptance.

Future research could also analyze and optimize the 5G NR network for both NSA and SA deployment options using planning and optimization tools like WinProp and Atoll.

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