Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering
Communication Engineering Graduate Program

Techno-economic competitiveness alternative of 5G FWA in sub-urban areas: The Case of Bishoftu, Ethiopia

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Declaration

I, the undersigned, declare that this thesis is my original work, that it has not been submitted for a degree at this or any other university, and that all sources of materials utilized in the thesis have been properly credited.

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ABSTRACT

Telecommunication services generation popularity is so fast and plays a vital role in enabling Reliable Communication. Furthermore, these services have also been instrumental in accelerating digital transformations across various industries and sectors. It's amazing to see how technology has evolved over the years to make communication faster, easier, and more efficient than ever before. In today's fast-paced world, it's essential to have reliable and high-speed telecommunications services to stay connected and get things done efficiently. With the increase in remote work and online activities, the demand for high broadband speed and affordable telecom services has become even more critical. Service providers need to keep up with this demand and offer reliable and cost-effective solutions to their customers. Due to these trends, fixed wireless broadband access(FWA) is one of the right solution services for businesses that need high-speed internet connectivity at affordable prices. 5G Fixed Wireless Access (FWA) networks have the potential to provide ultra-high-speed broadband at an affordable price for suburban and rural areas, making them a potential competitor for other technologies like FTTH and copper. The main purpose of this thesis is to conduct a research investigation on the Techno-Economic Competitiveness of 5G FWA in sub-urban areas, with a specific focus on Bishoftu Town as an example.

Keywords— *5G, FWA, Sub-Urban, FTTH, TEA.*

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List of Abbreviations

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACTS	Advanced Communications Technology and Services
ACK	Acknowledgment
ARPU	Average Revenue per User
AS	Access Stratum
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BF	Bandwidth Factor
BS	Base Station
BTS	Base Transceiver Station
CA	Carrier Aggregation
CF	Cash Flow
CAPEX	Capital Expenditure
CBS	Coordinate Beam forming and Scheduling
CC	Component Carrier
CC&B	Customer Care & Billing
CDMA	Code Division Multiple Access
CCCH	Common Control Channel
CFI	Control Format Indicator
CIF	Carrier Indicator Field
CMC	Connection Mobility Control
CO	Central Office
CoMP	Coordinated Multi-Point
CPE	Customer Premises Equipment
CPR	Cost-Per-Response
CQI	Channel Quality Indicator
CRS	Cell-specific RS
dB	Decibel
DCI	DL Control Information
DL	Down Link

DL-SCH	DL Shared Channel
DCCH	Dedicated Control Channel
DCF	Discounted Cash Flow
DM-RS	Demodulation RS
DRA	Dynamic Resource Allocation
DSL	Digital Subscriber Line
DTCH	Dedicated Traffic Channel
DwPTS	DL Pilot Time Slot
DWDM	Dense WDM
EDGE	Enhanced Data Rate for GSM Evolution
eNodeB	enhanced NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETB	Ethiopian Birr
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FDP	Fiber Distribution Panel
FTTH	Fiber to Home
GB	Giga Byte
gNodeB	Next generation NodeB
GP	Guard Period
GPON	Gigabit Passive Optical Network
GPRS	General Packet Radio System
GSM	Global System for Mobile Communication
GTP	GPRS Tunneling Protocol
HARQ	Hybrid Automatic Repeat Request
HC	Handover Control
HSDPA	High Speed DL Packet Access
HSUPA	High Speed UL Packet Access
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
ICT	Information Communication Technology
IEEE	Institute of Electrical and Electronics Engineering
IMT	International Mobile Telecommunications
IoT	Internet of Things
IRR	Internal Rate of Return
JP	Joint Processing
KPI	Key Performance Indicator

LA	Link Adaptation
LOS	Line of Sight
LTE	Long Term Evolution
LTE-A	LTE Advanced
MBH	Mobile Backhaul
MBSFN	Multicast Broadcast Single Frequency Network
MCCH	Multicast Control Channel
MCS	Modulation and Coding Scheme
MEC	Mobile Edge Computing
MIMO	Multi-Input Multi-Output
MIFI	Mobile Wireless Fidelity
mmWave	Millimeter wave
MU-MIMO	Multi-User-MIMO
MW	Microwave
MME	Mobility Management Entity
NACK	Non-ACK
NAS	Non-AS
NLOS	Non-LOS
NMS	Network Management System
NPV	Net Present Value
OFDMA	Orthogonal Division Multiple Access
OLT	Optical Line Termination
ONU	Optical Distribution Unit
OPEX	Operational Expenditure
OSS	Operation Support Subsystem
ODN	Optical Distribution Network
ONT	Optical Network Terminal
OTT	Over the Top
PA	Power Allocation
PBP	Payback Period
PCCH	Paging Control Channel
PCFICH	Physical CFI Channel
PCH	Paging Channel
PCRF	Policy and Charging Rule Functions
PDCCH	Physical DL Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical DL shared Channel
P-GW	Packet Gateway
PON	Passive Optical Network
PMP	Point to Multipoint
PRACH	Physical RACH
PRB	Physical RB

PS	Packet Scheduling
P-SCH	Primary Synchronization Channel
PTP	Point to Point
PUCH	Physical UL Shared Channel
PUCCH	Physical UL Control Channel
QoS	Quality of Service
RAC	Radio Admission Control
RACH	Random Access Channel
RAN	Radio Access Network
RB	Resource Block
RBU	Remote Base Unit
RDS	Radio Dot System
RE	Resource Element
RLC	Radio Link Control
ROI	Return on Investment
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RRU	Remote Radio Unit
RS	Reference Signal
SC-FDMA	Single Carrier FDMA
SCTP	Stream Control Transmission Protocol
S-GW	Serving Gateway
SINR	Signal Interference and Noise Ratio
SMS	Short Message Service
SU-MIMO	Single User-MIMO
TCO	Total Cost of Ownership
TDMA	Time Division Multiple Access
TEA	Techno-economic Analysis
TERA	Techno-Economic Results from ACTS
TEP	Telecom Expansion Project
FWA	Fixed Wireless Access
TM	Transmission Mode
TTT	Time to Trigger
UCI	UL Control Information
UE	User Equipment
UL	Up Link
UL-SCH	UL Shared Channel
UMTS	Universal Mobile Terrestrial System
UpPTS	UL Pilot Time Slot
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
Wi-Fi	Wireless Fidelity

Chapter 1

Introduction

1.1 Background

Rapid advancements in 5G have seen the speeds increase exponentially, with latency going as low as a couple of milliseconds and the ability to connect millions of devices simultaneously [11]. Situated in the suburban locale of Bishoftu in Ethiopia, it experiences a fiasco of sorts with traditional wired infrastructure set against either obsolescence or steep cost considerations [1]. 5G FWA would somehow bridge the digital divide. The research looks into the techno-economic competitiveness of 5G FWA solutions vis-a-vis incumbent solutions, by studying their feasibility, cost-effectiveness and considering visual competitiveness with technologies like 4G, DSL and Fiber ODN. Through the case study of Bishoftu, this research provides some impetus for policy-makers and telecom operators on how to improve internet access and thereby empower socio-economic development in less-facilitated regions. [15]. The fast-growing

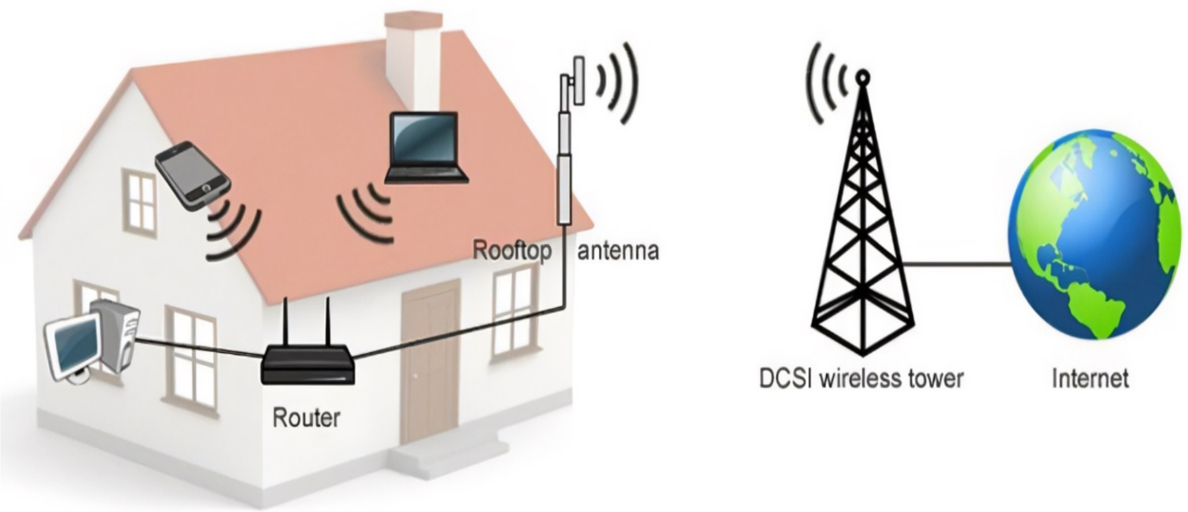

Figure 1.1: 5G-FWA Service. *[5]*

suburban town of Bishoftu, Oromia, experiences an increasing demand for dependable high-speed Internet. A beautiful town in Ethiopia, Bishoftu presents an enticing opportunity for the deployment of 5G FWA; with a growing population and newer business establishments demanding reliable Internet access, Bishoftu, through 5G FWA, can take a hesitant step into the digital realm [15] [1]. The 5G rollout is still in its early stages across the country, and Ethio Telecom has focused on launching 5G services in Addis Ababa and key regions. Based on coverage maps and development patterns, 5G services are gradually being extended to suburban regions like Bishoftu. The expansion of digital services such as online education, e-commerce, telemedicine, and remote work has accelerated the need for robust broadband infrastructure in suburban areas like Bishoftu. However, existing fixed broadband services (such as fiber-optic networks) are limited, particularly in suburban and semi-urban areas, due to high deployment costs and infrastructure challenges [55]. In this context, Fixed Wireless Access (FWA) enabled by the 5G network has emerged as a potential alternative to traditional fixed broadband solutions. 5G FWA promises high-speed, low-latency internet access without requiring extensive physical infrastructure (such as laying fiber), making it a potentially cost-effective solution for suburban and undeserved areas [14] [22].

The evolution of 5G Fixed Wireless Access (FWA) has been shaped by the need for high-speed internet connectivity in areas where traditional fixed-line broadband solutions are not feasible or cost-effective. FWA is a wireless broadband solution that uses radio waves to transmit data between a fixed location and a user's device. With the advent of 5G technology, FWA has gained significant attention as a potential alternative to fixed-line broadband solutions, particularly in suburban and rural areas [22], [59] [34]. The initial versions of FWA were based on 4G LTE technology, which provided a viable alternative to traditional broadband solutions in areas with poor network coverage. However, with the introduction of 5G technology, FWA has become even more attractive due to its higher data transfer rates and lower latency. 5G FWA promises to offer data transfer rates comparable to traditional fiber-optic broadband solutions, making it a viable option for areas that lack fixed-line connectivity. The evolution of 5G FWA has been driven by advancements in wireless technology, including the use of millimeter-wave frequencies and massive MIMO (Multiple-Input Multiple-Output) antenna systems. These technologies enable high-bandwidth data transfer rates and wider network coverage, making 5G FWA a viable option for broadband connectivity in suburban and rural areas. The rationale for mobile operators deploying 5G FWA extends beyond simply wanting to grow fixed broadband revenues. There is potential to grow revenues indirectly in pay TV and from bundling additional services (content add-ons or smart home, for example) with 5G FWA packages. 5G FWA can also be deployed as a defensive strategy to protect mobile revenues from the advances of fixed broadband providers. In the US, for example, cable MVNOs have shown increasing ambition in mobile, accumulating more than 4 million subscribers. To scale their fixed-mobile convergence offerings, all three major US mobile operators have 5G FWA plans, allowing them to extend their fixed broadband networks into markets where the cable providers are present[58].

Bellow Figure Indicates Overview of Wireline and 5G FWA Network.

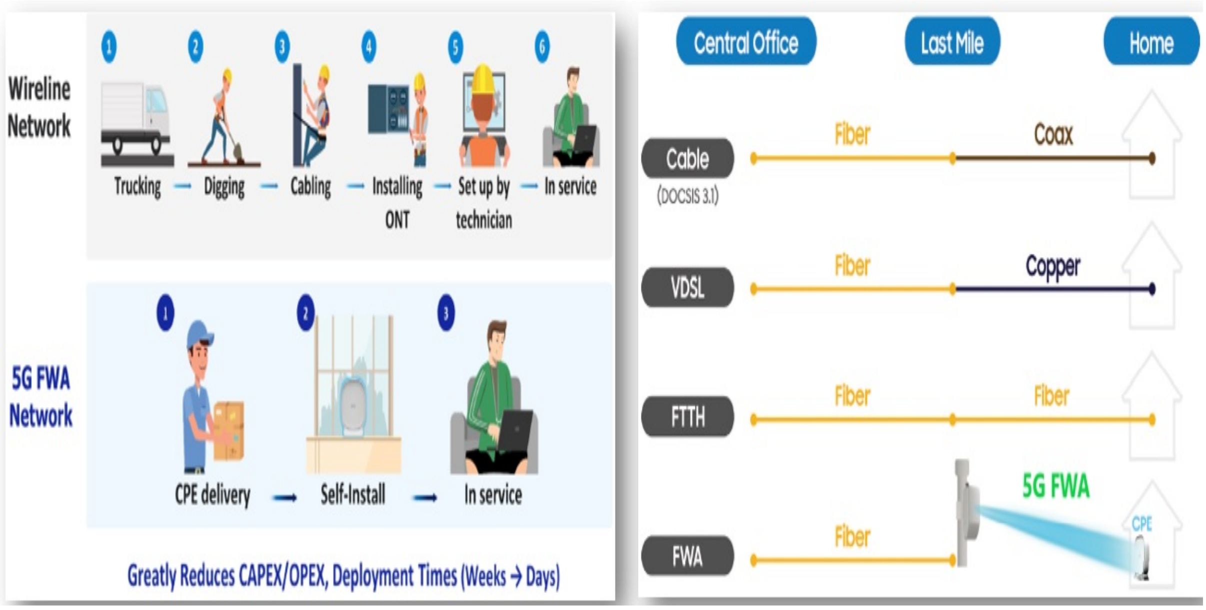

Figure 1.2: Overview of Wireline and 5G FWA Network [60][23]

For several years, many service providers have been using Fiber optic and copper cables to offer internet services to customers residing in areas with limited access to wired internet connections[16]. However, FWA has not been widely adopted by operators, except for a few countries such as Austria and Finland. Nonetheless, with more governments providing funding for broadband and more regulators considering wireless connections as a viable alternative to wired connections, many operators are now considering using FWA. The digital transformation we are experiencing today has brought about a significant change in communication networks. The introduction of 5G technology is a game-changer, as it not only promises faster internet speeds but also a complete rethinking of connectivity. As we stand at the threshold of this technological revolution, it is essential to understand its impact on suburban areas. Suburban areas, characterized by their proximity to urban centers yet distinct in their residential layout and infrastructure, often face unique challenges in accessing high-speed internet.

As we see in Figure 1.3 below, the market impact of FWA and its contribution to the market in global market size are very high.

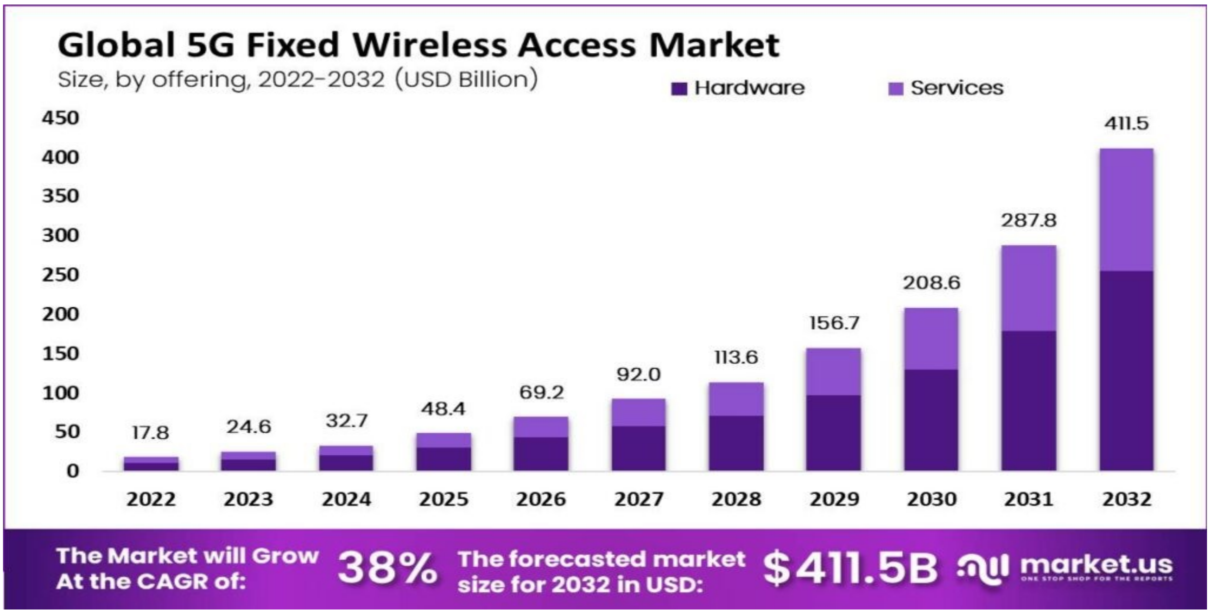

Figure 1.3: Global FWA Market Size Forecast Areas [18].

While urban centers typically benefit from robust fiber-optic networks, suburban regions frequently contend with limited broadband options due to factors like dispersed populations, geographical barriers, and infrastructure costs [56], [34]. Consequently, residents and businesses in these areas may experience subpar internet connectivity, hindering their ability to fully participate in the digital economy and enjoy modern amenities [2].

The thesis on the Techno-economic competitiveness of 5G in suburban areas starts with an introduction that highlights the challenges faced by industry stakeholders due to the rapid growth of internet services [1]. The introduction also discusses the evolution of wireless and fixed broadband technologies, along with the increasing demand for high-speed internet connectivity in suburban regions. It emphasizes the importance of choosing the right network architecture or technology based on factors such as geography, cost, coverage, and reliability[2]. The introduction further points out that no single broadband access technology will dominate the entire market due to varying factors. Finally, the document emphasizes the importance of techno-economic analysis in making cost-effective and flexible deployment decisions under different scenarios [56] [3].

1.2 Motivation

The driving force behind this research Thesis emerges from a profound acknowledgment of the transformative potential inherent in fifth-generation (5G) wireless technology within our nation. Additionally, it stems from a compelling necessity to confront the digital disparity prevalent in suburban regions such as Bishoftu, Ethiopia. These suburban areas, like Bishoftu, which have been earmarked for the implementation of smart city initiatives by the Ethiopian Government, routinely encounter obstacles in accessing reliable and high-speed broadband internet services [14]. These hurdles are primarily attributable to the absence of adequate infrastructure and the exorbitant costs associated with conventional wired solutions [59].

According to data gleaned from the 2022-07-01 Population Census [80] [81], Bishoftu boasted a population of 207,383 individuals inhabiting an area spanning 40.02 km^2, thereby yielding a population density of 5,182 individuals per square kilometer. Consequently, the introduction of such cutting-edge technology holds the promise of enhancing various facets of societal development, including economic prosperity, social inclusivity, and the overall quality of life within these regions.

1.3 Statement of the Problem

Suburban areas, such as Bishoftu in Ethiopia, where the Ethiopian government assigns its strategic alignment as a smart city, often face challenges in accessing reliable and high-speed broadband internet due to different reasons. Despite 5G technology advancing quickly in Ethiopia, the implementation of 5G Fixed Wireless Access (FWA) has not yet commenced. The rapid growth of digital services and the increasing demand for high-speed internet connectivity have made reliable broadband access essential for socioeconomic development. In Ethiopia, particularly in suburban areas like Bishoftu, access to high-speed internet remains limited and unreliable due to the underdeveloped fixed broadband infrastructure. Traditional fixed-line broadband solutions such as fiber optic networks require significant investment in infrastructure, which is often financially unsustainable in suburban and less densely populated areas [56] [26]. However, while 5G FWA is technologically promising, its techno-economic viability in suburban areas like Bishoftu remains unclear. Key challenges include the high initial deployment cost, potential interference from environmental factors, and competition with existing technologies, such as fiber optic ODN technologies[20].

This research seeks to address the question of whether 5G FWA can provide a competitive alternative in terms of both technology and economics for suburban areas like Bishoftu. The lack of a comprehensive techno-economic assessment of 5G FWA's potential in this specific context presents a gap in the literature and hinders decision-makers from formulating informed strategies for broadband infrastructure development. Consequently, this study aims to evaluate the economic feasibility, performance, and deployment challenges of 5G FWA in comparison to existing ODN broadband technologies, with a focus on suburban areas in Ethiopia.
We address the following key areas:

- Economic features, including Capital expenditure (CAPEX), operational expenditure (OPEX), and Total cost of ownership(TCO) for 5G FWA services compared to ODN networks.

- Technical performance, including coverage, data rates, and reliability compared to ODN in a suburban environment.

- Consumer demand and Economic implications for the city.

This research aims to fill the gap by conducting a detailed techno-economic analysis to evaluate the competitiveness of 5G FWA as a broadband solution in Bishoftu, Ethiopia. As we look at the figure the cost spent for Traditional ODN service from the international gateway to the subscriber.

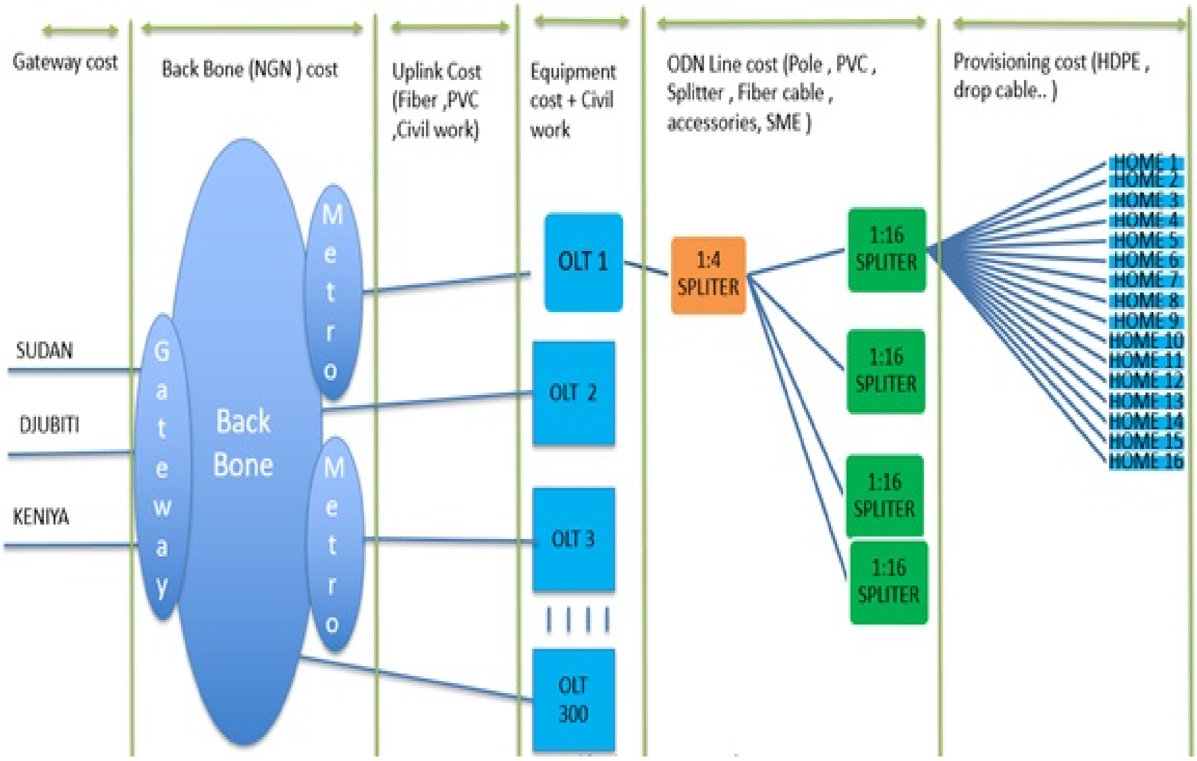

Figure 1.4: GPON-based ODN Service cost (Source: Ethiotelecom 300 OLT Business case)

As we show in Figure 1.4 above, the total cost starting from the Backbone gateway to the access users is so high because of the intermediate media expense. Ethio Telecom, Ethiopia's most prominent telecommunications operator, has undertaken a massive project, namely, the Optical Distribution Network (ODN) in 2020 [42][43]. The primary objective of this project is to establish a better connectivity infrastructure across the country [45]. The project requires significant investment costs to obtain land acquisition permissions, resolve right-of-way issues, and conduct installations and civil works. This includes laying optical fiber cables and installing splitters, distri-

bution boxes, and other accessories. However, the installation process has frustrated fixed network users due to longer waiting times and concerns about post-deployment maintenance issues. The primary problem addressed by this research proposal is the lack of comprehensive understanding regarding the techno-economic feasibility of 5G FWA deployment in suburban areas, particularly in the context of Bishoftu.
Is deploying 5G FWA financially and Technically feasible in suburban areas like Bishoftu?
The following are the key questions that the research to be addressed.

- How does the performance of 5G FWA (in terms of coverage, speed, and reliability) compare to alternative broadband technologies like Traditional ODN in the suburban context of Bishoftu?
- What are the capital and operational costs of deploying 5G FWA in Bishoftu, and how do these costs compare with alternative solutions?
- Can 5G FWA provide a cost-effective and competitive alternative to fixed broadband solutions in Bishoftu? What are the projected returns on investment (ROI), break-even points, and total cost of ownership (TCO) for 5G FWA deployment?

Addressing these critical question is essential to inform decision-makers, Telecom operators, and other stakeholders about the opportunities and challenges associated with 5G FWA deployment in suburban areas.

1.4 Research Objective

assess the feasibility and viability of utilizing 5G Fixed Wireless Access (FWA) as an alternative solution.

1.4.1 General Objective

This research aims to assess the techno-economic viability of 5G Fixed Wireless Access (FWA) as a viable option for broadband connectivity in suburban areas. The overall objective is to provide insightful recommendations that can help optimize the adoption and implementation of 5G FWA as a broadband solution in sub-urban areas in Ethiopia.

1.4.2 Specific Objective

The research proposal aims to provide stakeholders with actionable insights into the 5G FWA in suburban areas, enabling informed decision-making, and strategic investments aimed at bridging the digital divide and fostering inclusive development in communities like Bishoftu, Ethiopia. To achieve a comprehensive understanding of the techno-economic competitiveness of 5G Fixed Wireless Access (FWA) in suburban areas, with a specific focus on Bishoftu, Ethiopia, the research proposal outlines the following specific objective:

- To analyze the technical performance of 5G FWA compared to Traditional ODN technologies in a suburban setting.
- To estimate the CAPEX and OPEX for deploying 5G FWA infrastructure in Bishoftu.
- To evaluate the economic returns (ROI, payback period, and total cost of ownership) of 5G FWA deployment.
- explores the potential socio-economic benefits that 5G FWA can offer to Bishoftu residents, such as enhanced connectivity, improved services, and economic growth.

1.5 Literature Review

In Ethiopia, the broadband penetration study remains low, especially in suburban and rural areas [5]. According to reports by the Ethiopian Communications Authority (ECA) (2022), internet access in suburban areas like Bishoftu is hindered by the high cost of infrastructure, limited fiber deployments, and lack of competitive alternatives. The government's Digital Ethiopia 2025 Strategy emphasizes the importance of expanding broadband coverage to underserved areas, but achieving this through traditional fixed networks poses significant financial and logistical challenges.

Theme	**Key Findings from Literature**	**Gaps Identified**
5G Technology Overview	- 5G offers high speed, low latency, and massive connectivity. - Enables new applications like IoT, smart cities, and remote work.	Limited focus on 5G deployment in sub-urban and rural areas, especially in developing countries.
Fixed Wireless Access (FWA)	- FWA provides cost-effective broadband in areas with limited wired infrastructure. - 5G FWA can deliver fiber-like speeds without physical cables.	Few studies on the economic feasibility of 5G FWA in sub-urban areas.
Techno-Economic Analysis	- Techno-economic models help evaluate the feasibility of new technologies. - Factors include deployment costs, operational expenses, and revenue potential.	Lack of localized studies on the techno-economic competitiveness of 5G FWA in Ethiopia.
Sub-urban Connectivity	- Suburban areas face challenges like high deployment costs and low population density. - Existing solutions (e.g., 4G, DSL) are often insufficient for growing bandwidth demands.	Limited research on 5G FWA as a solution for sub-urban connectivity in Africa.
Case Studies on 5G FWA	- Successful 5G FWA deployments in urban areas (e.g., USA, Europe) show high user satisfaction. - Developing countries face unique challenges like limited spectrum and funding.	Few case studies on 5G FWA in sub-urban or rural contexts, particularly in developing countries.
Regulatory and Policy Frameworks	- Effective spectrum allocation and supportive policies are critical for 5G FWA deployment. - Regulatory barriers can delay or hinder 5G rollout.	Limited research on policy recommendations for 5G FWA adoption in sub-urban areas of developing nations.
Ethiopia's Telecom Landscape	- Ethio Telecom is expanding 4G and fiber networks but faces challenges in rural/sub-urban areas. - Limited competition and high infrastructure costs are key barriers.	No specific studies on 5G FWA deployment in Ethiopian sub-urban areas like Bishoftu.

Table 1.1: Literature Review on Techno-economic Competitiveness of 5G FWA in Sub-urban Areas

- A study by Negash et al. (2021) explored the challenges and opportunities for 5G deployment in Ethiopia, emphasizing the role of 5G FWA in bridging the digital divide. They concluded that 5G FWA could provide a cost-effective solution for suburban areas like Bishoftu, where the deployment of fiber networks is limited, and consumer demand for high-speed broadband is rising. However, the study also noted that policy support, spectrum allocation, and investment incentives are crucial for the successful rollout of 5G FWA in Ethiopia.

- According to Economic Viability of 5G FWA
  - Bouras et al. (2020) conducted a comprehensive cost-benefit analysis of 5G FWA in European suburban areas, highlighting that while the initial CAPEX may be higher due to the need for dense small cell deployments, the long-term operational costs are relatively low. They concluded that in areas where fiber deployment is difficult or expensive, 5G FWA can achieve a positive return on investment (ROI) within five years, provided there is adequate subscriber uptake.
  - Similarly, a study by Detecon (2021) analyzed the techno-economic aspects of deploying 5G FWA in emerging markets, such as Sub-Saharan Africa, where the infrastructure deficit is pronounced. Their findings show that 5G FWA can be deployed with a lower TCO than fiber in suburban regions, with significant cost savings on infrastructure such as trenches, poles, and cabling. They argue that the viability of 5G FWA is contingent upon the availability of affordable spectrum and subsidies or incentives from governments to reduce initial deployment costs. Moreover, 5G networks have the massive capacity to accommodate more users and devices, which is crucial in today's world where the number of internet-connected devices continues to increase. This means that more people can access the internet, and more devices can be connected to the network, without compromising on performance.

- According to 5G FWA in Suburban and Rural Areas, A study by Verma et al. (2022) [32] investigated the cost-effectiveness of FWA compared to fiber optic deployments in suburban Europe. Their findings revealed that 5G FWA provides a viable alternative in areas where the cost of laying fiber is prohibitively high. However, the study emphasizes that for FWA to be truly competitive, there must be sufficient consumer demand for high-speed services, and the network infrastructure must be optimized to handle peak traffic periods effectively. Similar studies by Rahman et al. (2021) show that the total cost of ownership (TCO) for 5G FWA is often lower than for fiber in regions with challenging terrain or sparse populations, making it a strong candidate for suburban regions.

1.6 Related Works

- ”Economic Analysis of 5G Fixed Wireless Access Deployment Strategies” by Chen et al. (2019): Chen et al [26]. Explore the economic implications of deploying 5G FWA in various scenarios, considering infrastructure costs, subscriber demand, and revenue models. Their analysis provides a comprehensive understanding of the cost-effectiveness and market potential of 5G FWA, which can inform the economic assessment component of the proposed research.
- ”5G Fixed Wireless Access: A Techno-Economic Study” by Gupta et al. (2021): Gupta et al[27]. conduct a techno-economic study on 5G FWA deployment, focusing on its technical capabilities, spectrum requirements, and cost considerations. Their research delves into the technical specifications of 5G FWA equipment and network architecture, as well as the associated investment and operational costs. Their findings can provide valuable insights into the technical feasibility and economic viability of 5G FWA in suburban environments.
- ”Broadband Deployment in Suburban and Rural Areas: A Comparative Analysis” by Johnson et al. (2018)[2]: This study compares broadband deployment strategies in suburban and rural areas, examining the challenges and opportunities associated with different technologies and infrastructure approaches. By analyzing case studies and empirical data, Johnson et al. identify key factors influencing broadband access and adoption in suburban environments[14], which can serve as a basis for understanding the context-specific challenges in Bishoftu.

1.7 Methodology

The methodology combines technical network planning, economic cost analysis, and consumer demand assessment to evaluate the feasibility and viability of deploying 5G FWA as a competitive alternative to traditional ODN.

- Literature Review: is the initial step, where existing literature, academic research, and industry reports related to the topic are reviewed to establish a theoretical framework and contextualize the research.
- Data Collection: involves gathering quantitative and qualitative data relevant to the techno-economic competitiveness of 5G FWA deployment in suburban areas, including infrastructure costs, market demand, regulatory frameworks, and stakeholder perspectives.
- Cost-benefit analysis: utilizes the collected data to assess the total cost of ownership (TCO) of deploying 5G FWA networks compared to traditional wired broadband solutions, analyzing economic viability, ROI, NPV, and other financial metrics.
- Technical Analysis: The first phase focuses on analyzing the technical feasibility of deploying 5G FWA in Bishoftu.
  1. Coverage and Capacity Planning: To assess the coverage area, data capacity, and infrastructure requirements for 5G FWA in suburban Bishoftu.
  2. Tools and Techniques: Radio propagation models (ATOLL), Frequency allocation analysis (sub-6 GHz and mmWave bands), and Network dimensioning (Number of base stations in Bishoftu).
- Economic Cost-Benefit Analysis: This phase evaluates the economic feasibility of deploying 5G FWA compared to alternative broadband technologies such as traditional ODN

  CAPEX and OPEX Estimation: To estimate the total capital expenditure (CAPEX) and operational expenditure (OPEX) for 5G FWA and ODN deployment.

- Documentation: involves documenting research methods, procedures, and findings to ensure adherence to standards and guidelines.

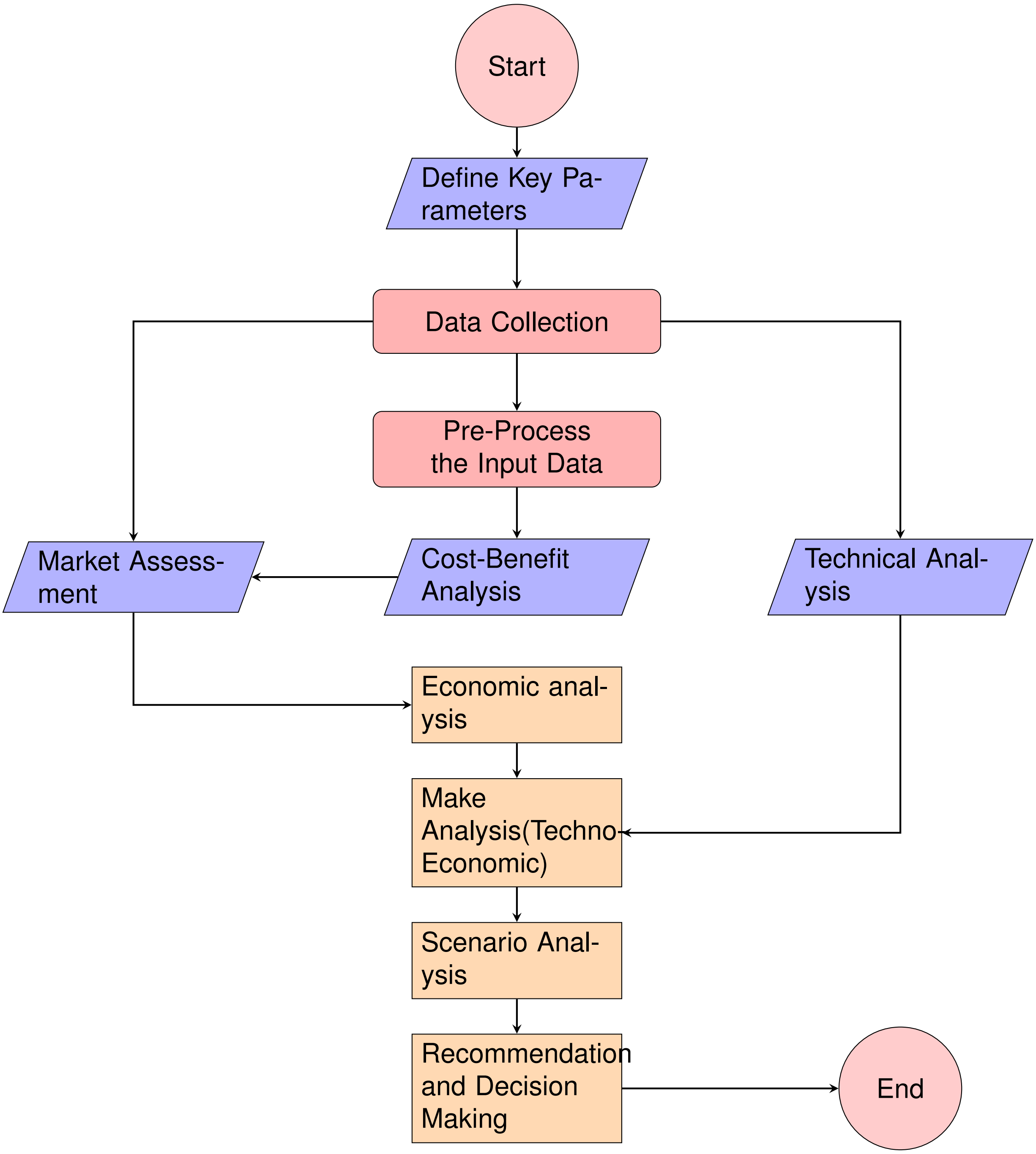

Figure 1.5: Work Plan and Methodology

1.8 Scope and Limitation

1.8.1 Scope

- The research focuses specifically on Bishoftu, a suburban area in Ethiopia, to analyze the techno-economic competitiveness of 5G Fixed Wireless Access (FWA) deployment within this context. The findings and recommendations are intended to apply to similar suburban areas facing similar challenges in broadband connectivity.
- The research investigates the deployment of 5G FWA technology compared with traditional optical wired called ODN technology, as a means of providing high-speed broadband internet access in suburban areas. It examines the technical capabilities, economic feasibility, and potential socio-economic impacts of 5G FWA deployment.
- The research assesses the economic viability and competitiveness of 5G FWA compared to traditional optical wired ODN broadband solutions in suburban environments. It includes cost-benefit analysis, return on investment (ROI), and scenario analysis to evaluate the total cost of ownership (TCO), financial performance, and market dynamics associated with 5G FWA deployment. The economic analysis will analyze the cost implications of deploying 5G FWA networks in suburban areas, taking into consideration capital expenditure (CAPEX), operational expenditure (OPEX), and return on investment (ROI).

1.8.2 Limitation

The scope of the research does not encompass the deployment process and economic expense for Base Transceiver Stations (BTS) and their connection back to the core site. Instead, the focus is only directed towards the access side of the network.
Other limitations like Time and Budget Constraints, Availability of Data, Infrastructure Limitations, and Technological Adoption are among them.

1.9 Expected Outcomes

- Assessment of the technical feasibility of deploying 5G FWA in suburban areas of Bishoftu
- Evaluation of the economic competitiveness of 5G FWA compared to alternative technologies (e.g., fiber-optic ODN FTTH)
- Identification of key factors influencing the adoption and success of 5G FWA in suburban environments
- Recommendations for telecom operators, academic knowledge, and stakeholders regarding the deployment and optimization of 5G FWA in suburban areas

1.10 Significance of the Study

- Significance Contribution to academic research on 5G FWA technology and its applicability in suburban contexts
- Practical implications for telecom operators, policymakers, and stakeholders in optimizing broadband connectivity in suburban areas
- Potential socio-economic benefits of improved broadband access in suburban regions

Chapter 2

5G FWA and ODN Overview

2.1 5G FWA

5G FW is a cutting-edge technology that brings high-speed internet connectivity to homes and businesses using wireless networks. Unlike traditional wired connections, 5G FWA utilizes cellular networks to deliver broadband services. It promises lightning-fast speeds, low latency, and flexibility[12].

- 5G FWA is presented as a promising alternative to traditional wired broadband solutions, offering high-speed internet connectivity with lower latency and the ability to bypass extensive cable infrastructure.
- The research aims to assess the economic viability of 5G FWA, comparing it to existing broadband solutions like Optical Distribution Networks (ODN), considering factors such as cost-effectiveness and return on investment.
- The study will conduct a thorough techno-economic analysis, including cost-benefit assessments and scenario analysis, to determine the feasibility and competitiveness of 5G FWA deployment in Bishoftu.
- The research is significant for Bishoftu's development as a smart city, potentially improving economic growth, social inclusion, and quality of life through enhanced broadband access.

2.1.1 5G FWA Techno-Economic Impact and Bishoftu conditions

The adoption of 5G FWA has significant implications for both technology and economics[24]. Here's how it could transform sub-urban areas.

5G FWA bridges the digital divide by providing high-speed internet access to underserved regions. Bishoftu, Ethiopia, stands to benefit from improved connectivity, enabling online education, telemedicine, and e-commerce.

Enhanced connectivity drives economic activities. Small businesses can expand their reach, and entrepreneurs can innovate using digital platforms. Bishoftu's local economy could thrive with 5G FWA.

The Suburban Imperative of 5G FWA refers to the growing need for 5G technology in suburban areas. As technology continues to advance, more and more people are relying on the Internet for work, education, and entertainment. With 5G FWA technology, people in suburban areas will be able to access faster internet speeds, which will allow them to do things like stream video content and work from home more easily. This is particularly important in suburban areas where there may not be as many options for high-speed internet. The implementation of 5G FWA technology in suburban areas will also be beneficial for businesses and local governments, as it will allow for more efficient communication and data transfer. Overall, the Suburban Imperative of 5G highlights the importance of ensuring that suburban areas have access to the same level of technology as urban areas to keep up with the changing technological landscape.

- **Digital Divide Mitigation**: In many suburban regions, access to high-speed internet is often limited due to inadequate broadband infrastructure, creating a digital divide that can hinder opportunities for education, healthcare, and economic participation. However, with the emergence of 5G FWA (Fixed Wireless Access), a lifeline is being provided to bridge this gap. By enabling wireless high-speed internet connectivity, 5G FWA is ensuring that all individuals in suburban areas have equal access to the resources and opportunities necessary to thrive in today's digital world.

- **Economic Growth and Innovation**: For suburban economies to flourish, they need to be well-connected. One of the key factors that drives innovation and growth in these areas is the adoption of 5G technology. This technology enables startups, telecommuters, and e-commerce ventures to thrive, while also facilitating the development of smart cities, autonomous transportation, and immersive AR/VR experiences. These cutting-edge technologies are often incubated in suburban labs and rely on robust 5G networks to function optimally. By embracing 5G technology, suburban areas can unlock a world of possibilities and take their economies to new heights.

- **Environmental Considerations**: When it comes to setting up a wireless infrastructure, traditional wired networks require extensive trenching which can harm the environment by disrupting the landscapes. However, with the advent of 5G Fixed Wireless Access (FWA), the physical footprint of the network has been significantly reduced. This aligns well with 5G's eco-friendly approach and makes it a more sustainable option for suburban areas. This thesis delves into the complex and interrelated competitive dynamics of 5G Fixed Wireless Access (FWA) in suburban areas, which encompass economic, technical, and social factors. Through a detailed analysis of the opportunities, challenges, and trade-offs involved, the objective is to provide valuable insights that can guide strategic decision-making for a connected future.

2.2 Significance of 5G FWA in Sub-Urban Areas

5G Fixed Wireless Access (FWA) in suburban areas is a game-changing technology that holds immense relevance and significance for several reasons.

- It offers lightning-fast internet speeds that are several times faster than traditional broadband connections, making it perfect for households that require large bandwidth for streaming, gaming, and other data-intensive applications.
- It is a more cost-effective and flexible solution than traditional wired connections, as it eliminates the need for laying down cables and other infrastructure.
- It is a greener alternative to wired connections, as it reduces the carbon footprint associated with digging up roads and laying down cables.

Finally, it is a highly scalable technology that can be easily upgraded to keep up with the ever-increasing demands of suburban households. All these factors make 5G FWA a highly attractive and viable option for suburban areas looking to upgrade their internet infrastructure.

2.2.1 5G FWA Revolution

Fixed Wireless Access (FWA) is a revolutionary wireless communication technology that is rapidly gaining momentum in the telecommunications industry. It is a type of broadband service that utilizes wireless connections to provide high-speed internet access to fixed locations, such as homes, offices, or businesses. Unlike mobile networks that cater to moving devices, FWA is designed to serve stationary endpoints. This makes it an ideal solution for areas where traditional wired communication infrastructure is limited and costly to deploy or feasible to implement. With the advent of 5G technology, FWA is becoming increasingly popular due to its unmatched speed, reliability, and low latency, making it a game-changer in the world of telecommunications. This makes it an ideal solution for suburban areas that are typically underserved by traditional broadband providers. Fixed Wireless Access (FWA) is an advanced technology that allows for the delivery of high-speed internet services without the need for physical cables such as fiber or copper. FWA makes use of radio signals to provide broadband connectivity to homes and businesses, offering an alternative to traditional wired connections. One of the key advantages of FWA technology is its ability to be deployed quickly and cost-effectively, making it a popular choice for telecommunications providers looking to expand their coverage areas. This is especially true in rural or remote areas where laying physical cables can be difficult, expensive, or simply impractical.

FWA technology also offers several other benefits for both providers and customers. Since it does not rely on physical cables, FWA can be set up in a matter of hours or days, as opposed to weeks or months for traditional wired connections. Additionally, FWA can offer faster speeds and lower latency than some wired connections, depending on the specific implementation and technology used. Overall, FWA technology has emerged as an attractive option for internet service providers looking to improve their coverage and reach more customers, particularly in areas where wired connections may not be feasible or cost-effective.

2.2.2 5G FWA Network Architecture

- Base Station (BS) or gNodeB: This is the primary node in the network responsible for transmitting and receiving wireless signals to and from user equipment (UE). In 5G FWA deployments, these base stations are strategically located to provide coverage to specific areas, such as suburban neighborhoods.
- Backhaul Connection: A high-capacity connection that links the base stations to the core network. This can include fiber optic cables, microwave links, or other wireless technologies. The backhaul connection ensures that data traffic from the base stations can be efficiently routed to the core network and beyond.
- User Equipment (UE): These are the devices used by subscribers to connect to the 5G FWA network. In residential or small business settings, UE might include fixed wireless routers or modems equipped with 5G connectivity. These devices communicate with the nearby base station to access the internet and other services.
- Core Network: The core network provides centralized management and control for the entire 5G FWA deployment. It includes elements such as the Mobile Edge Computing (MEC) platform, which can host applications and services closer to the edge of the network for lower latency and improved performance.
- Network Management System (NMS): This component is responsible for monitoring and managing the overall operation of the 5G FWA network. It provides network operators with tools for configuration, performance monitoring, fault detection, and troubleshooting

2.3 Optical Distribution Network (ODN)

An ODN (Optical Distribution Network) is the part of a fiber-optic network that connects the Optical Line Terminal (OLT) at the service provider's central office to the Optical Network Units (ONUs) or Optical Network Terminals (ONTs) at the customer premises [63][1] [30].

In short, an ODN: Distributes the optical signal from the OLT to multiple users. Uses passive components like fiber cables, optical splitters, connectors, and couplers to deliver data without the need for active power. Forms the middle layer between the OLT and the end-user equipment in a Passive Optical Network (PON). The ODN is a crucial part of the infrastructure for delivering high-speed internet in PON systems, such as GPON

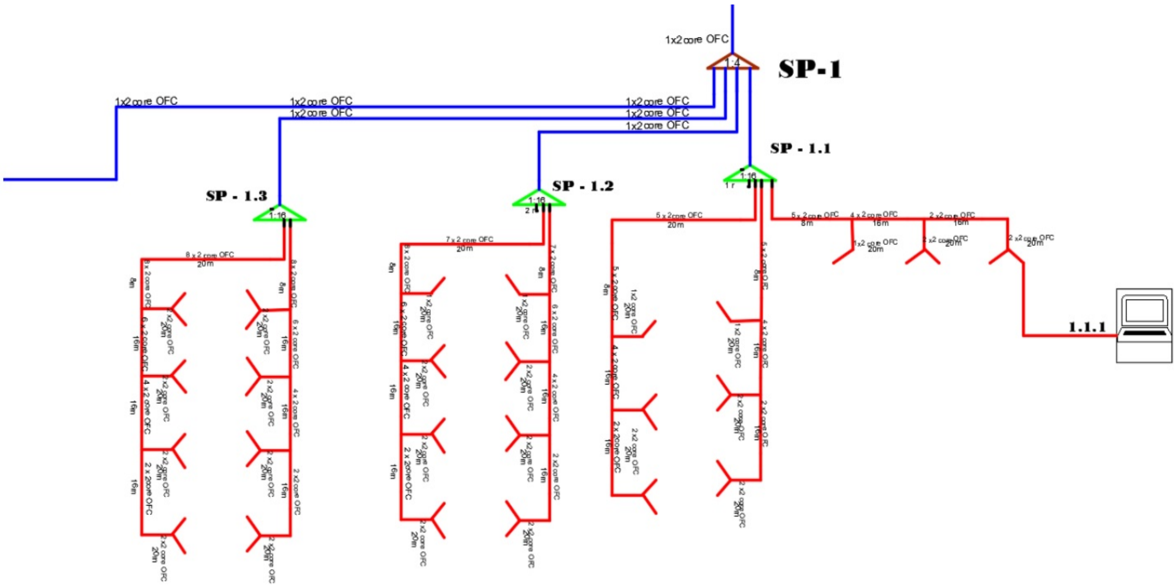

Figure 2.1: 1st and 2nd Splitter ODN Diagram (Source: Huawei Training manual)

2.3.1 Optical Line Terminal (OLT)

An OLT (Optical Line Terminal) is a device used in fiber-optic networks, specifically in Passive Optical Networks (PON) [25][32], to connect the central office of an Internet Service Provider (ISP) to customer premises, It acts as the central point of distribution in a GPON (Gigabit Passive Optical Network) or other PON systems [48].

OLT manages and controls the data traffic between the internet backbone and multiple users/subscribers [1]. Transmits data downstream to end-user devices (like ONTs or ONUs) over fiber optics. Receives data upstream from multiple end-users and aggregates it for the internet. The OLT is located at the service provider's site and typically serves a large number of users by splitting the optical signal into multiple lines that can reach many end-users through passive optical splitters.

Depending on the model, an OLT (Optical Line Terminal) GPON (Gigabit Passive Optical Network) card typically supports 8, 16, or 32 PON ports. Each PON port can serve multiple subscribers via Optical Network Units (ONUs) or Optical Network Terminals (ONTs).

For GPON, each PON port can typically handle up to 64 subscribers, though it can be higher, with split ratios of up to 1:128 in some scenarios. However, a split ratio of 1:32 or 1:64 is more commonly used to maintain quality of service.

For an OLT card with 8 PON ports and a split ratio of 1:64, the card could support up to 512 subscribers. For an OLT card with 16 PON ports and a split ratio of 1:64, it could support up to 1,024 subscribers. For an OLT card with 32 PON ports and a split ratio of 1:64, it could support up to 2,048 subscribers. The actual number of subscribers depends on the split ratio used, network design, and the bandwidth requirements of each subscriber. The number of GPON cards an OLT (Optical Line Terminal) can support depends on the specific model and manufacturer of the OLT. OLTs come in various sizes and configurations, typically classified into chassis-based or compact systems.

Compact OLTs: Smaller units might come with a fixed number of GPON ports integrated directly into the device. They may have between 4 to 8 GPON ports, which means they don't use swappable cards but have integrated ports [66]. Chassis-based OLTs: This are modular systems where you can insert GPON cards into slots, allowing more flexibility. Depending on the size of the chassis, a typical chassis-based OLT might have between 4 to 16 card slots. Larger, high-density OLTs can support up to 16 or 20 cards, depending on the chassis and manufacturer [71]. Each card in these OLTs typically supports between 8 to 32 PON ports. Therefore, the total number of subscribers the OLT can serve depends on both the number of cards it holds and the split ratio applied to each PON port [78]. GPON technology is fiber-based and can support 2.53 Gbps and 1.24 Gbps bandwidth per port for downlink and uplink respectively. Considering the 1:64 splitter, we will have 39.5 Mbps and 19.37 Mbps bandwidth for downlink and uplink respectively. This fiber-based technology can serve up to 20km, hence distance limitation is much better than copper.

2.4 User Equipment

UEs in the context of 5G FWA are the devices used by end-users to access the internet, such as routers or modems equipped with 5G connectivity. These devices communicate with nearby 5G base stations to receive and transmit data wirelessly, enabling high-speed internet access without the need for traditional wired connections. Customer premise equipment (CPE) is the telecommunications equipment that is installed at a customer's location, typically at their home or business. This equipment is used to connect the customer's premises to the public switched telephone network (PSTN) or other networks.

CPE can include a wide variety of equipment, such as telephone handsets, modems, routers, and other devices. In many cases, the CPE is provided by the customer's service provider, although the customer may also choose to purchase and install their own CPE. Customer premises equipment (CPE) for 5G Fixed Wireless Access (FWA) comes in various forms, each tailored to different user needs and deployment scenarios. Here are some common types:

- 5G Modems or Routers: These are devices similar to traditional modems or routers but equipped with 5G connectivity. They receive the 5G signal from the nearest base station and distribute it within the premises via Wi-Fi or Ethernet connections.

- Indoor 5G CPE: These devices are designed to be used indoors, typically in homes or offices. They may come in the form of compact boxes or sleek units with built-in antennas for receiving the 5G signal. Indoor CPEs usually offer Wi-Fi connectivity to distribute the internet connection to multiple devices within the premises.
- Outdoor 5G CPE: Outdoor CPEs are ruggedized units designed for outdoor installation, often mounted on rooftops or walls. They have larger antennas for better reception of the 5G signal and may offer higher performance compared to indoor CPEs. Outdoor CPEs are commonly used in rural or suburban areas where signal strength may be weaker.
- Integrated CPE with VoIP: Some CPE devices integrate Voice over Internet Protocol (VoIP) functionality, allowing users to make phone calls over the Internet. These CPEs combine 5G connectivity with voice services, providing a comprehensive communication solution for homes or small businesses.
- Enterprise-grade CPE: For larger businesses or organizations, there are enterprise-grade CPE solutions that offer advanced features such as support for multiple WAN connections, high-throughput capabilities, and advanced security features. These CPEs are designed to meet the demanding requirements of business-critical applications.
- Customized CPEs: In certain cases, CPEs may be customized to meet specific deployment needs or requirements of service providers. These customized CPEs may include additional features or functionalities tailored to the particular use case.

The type of CPE that is installed can have a significant impact on the quality and reliability of the customer's telecommunications network service. For example, a high-quality router can help to ensure that internet connections are fast and reliable, while a low-quality router may result in slow and unreliable connections. CPE can also be used to add features and functionality to a customer's telecom data service. For example, a customer may choose to install a VoIP adapter to their CPE to use VoIP services. In general, CPE is an important part of telecommunications service and infrastructure and can have a significant impact on the quality and reliability of service.

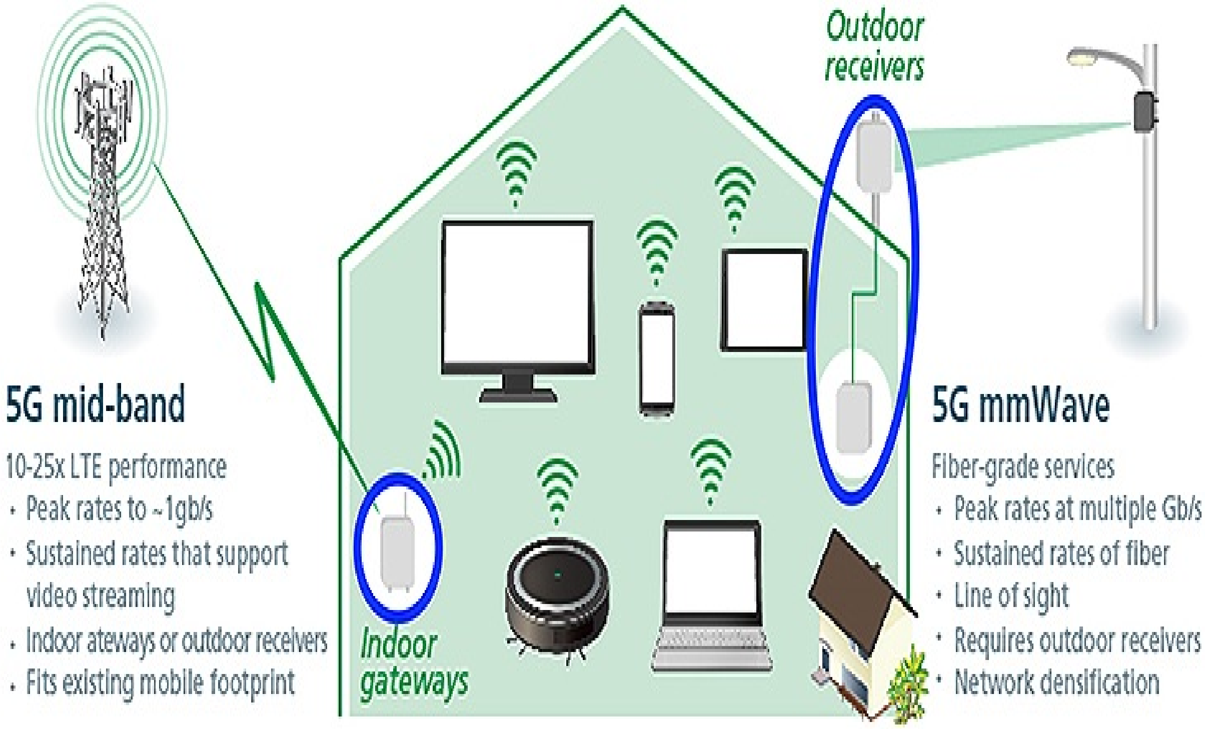

Figure 2.2: CPE image for 5G FWA [53]

Chapter 3

Techno-economic Analysis and Business Opportunities

3.1 Techno-economic analysis

In the context of telecommunications, the term ”techno-economics” was introduced during the European research program, Research into Advanced Communications for Europe (RACE) in 1985–1995 [6][59]. Later, the RACE 2087 Tool for Introduction Scenarios and Techno-economic studies for the Access Network (TITAN) project developed a methodology and a tool for the techno-economic evaluation of new narrowband and broadband services and access networks. Since the late 1990s, A TCO model for a 5G fixed wireless access (5G FWA) is now a commercial reality in developed and developing countries worldwide. While FWA solutions have been introduced around for more than two decades, the significant performance improvements enabled by 5G and the use of mmWave spectrum have resulted in speeds that are over 10 times faster than 4G. This research indicates make 5G FWA is a competitive solution compared to the predominant technologies in the fixed broadband market.

Here’s a breakdown of how such Techno-Economic analysis might be conducted:

3.1.1 Technical Analysis

- 5G Network Infrastructure: Assess the capabilities and costs associated with deploying 5G base stations, antennas, backhaul connections, and other network infrastructure components.
- Spectrum Allocation: Analyze the available spectrum bands for 5G FWA deployment and evaluate the costs and benefits of utilizing different frequency bands.
- Equipment Costs: Evaluate the costs of 5G user equipment (e.g., customer

premises equipment) and network equipment (e.g., base stations, routers, switches).

- Coverage and Capacity: Estimate the coverage area and capacity of 5G FWA networks based on factors such as cell density, propagation characteristics, and spectrum efficiency.

3.1.2 Economic Analysis

- Business Models: Evaluate different business models for offering 5G FWA services, such as subscription-based, pay-per-use, or bundled services.
- Revenue Streams: Estimate potential revenue streams from 5G FWA services, including subscription fees, advertising, value-added services, and wholesale agreements.
- Cost Structure: Identify the various costs associated with deploying and operating 5G FWA networks, including infrastructure costs, spectrum license fees, maintenance costs, and customer acquisition costs.
- Return on Investment (ROI): Calculate the expected ROI for deploying 5G FWA networks over a specified period, taking into account both capital expenditure (CapEx) and operational expenditure (OpEx).

3.1.3 Market Analysis

- Demand Forecasting: Estimate the demand for high-speed internet access in target markets and assess the willingness of customers to adopt 5G FWA services.
- Competitive Landscape: Analyze the competitive landscape for broadband services in the target market, including incumbent providers, cable operators, and other wireless ISPs.
- Regulatory Considerations: Consider regulatory factors that may impact the deployment and operation of 5G FWA networks, such as spectrum licensing, zoning

regulations, and net neutrality rules.

3.1.4 Risk Assessment

- Technical Risks: Identify potential technical challenges and risks associated with deploying 5G FWA networks, such as interference, latency, and equipment failures.
- Market Risks: Assess market risks, including competition from existing providers, changes in consumer preferences, and regulatory uncertainty.
- Financial Risks: Evaluate financial risks, such as fluctuations in equipment costs, interest rates, and exchange rates.

By conducting a comprehensive techno-economic analysis, stakeholders can make informed decisions regarding deploying 5G FWA networks, identifying opportunities for revenue generation, mitigating risks, and maximizing return on investment.

3.2 Techno-economic Result from ACTS (TERA) Framework

TERA is the most widely used and popular techno-economic tool in the telecom industry. TERA framework has two main starting points of techno-economic modeling, which are services and technical architectures. The main objective of TERA is to support consolidating, condensing and rationalizing the deployment guidelines for the introduction of advanced communication services and networks. Based on the forecasts and assumptions, as well as a few generic economic inputs such as the discount factor, period of study, and rest value of investments, the models calculate revenues, operational costs, and investment costs. It is also integrated with cumulative cash flow and decision-making criteria such as NPV, IRR, and PBP [6] [30]. TERA techno-economic approach model is modified and implemented based on the analysis objectives, system input, and output. It is simple to use and easily adapts to the various scenarios developed. The output of the tool is easy to interpret and traceable to the inputs because of the visibility of the in-use formulas [11].

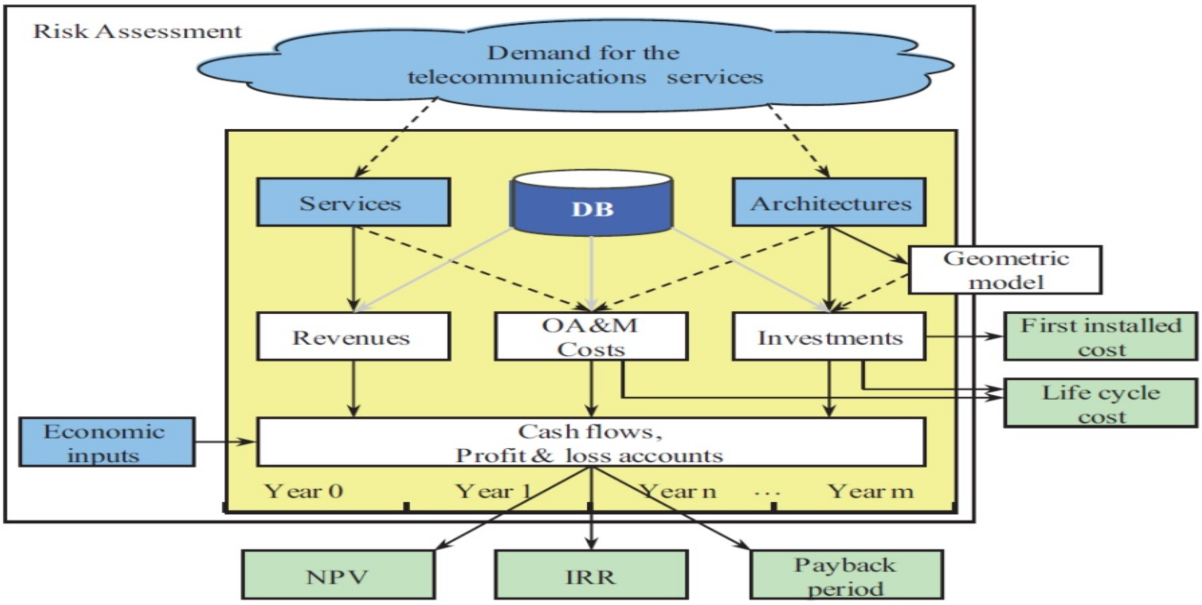

Figure 3.1: Framework for techno-economic modeling and analysis. *[56][59]*

A techno-economic analysis evaluates the technological viability and economic feasibility of deploying a service, like 5G Fixed Wireless Access (FWA), within a specific location, such as Bishoftu, Ethiopia. The analysis typically considers factors such as deployment costs, expected revenue, and overall competitiveness compared to alternative solutions[16].

To evaluate the economic feasibility and competitiveness of deploying 5G FWA in Bishoftu, a suburban town in Ethiopia, as a solution for providing high-speed broadband access to both residential and small-business users [22]. Network Infrastructure and Technology Considerations, Site Acquisition and Construction, Cost Estimation (Installation, material, and other costs), Revenue Estimation, Competitiveness Assessment, Break-Even Analysis, Sensitivity Analysis, Economic Technical Feasibility and Spectrum policy.

Chapter 4

Network Dimensioning

4.1 Geographical Landscape

Bishoftu is a growing town located approximately 40 kilometers southeast of Addis Ababa, with suburban characteristics. The area is experiencing population growth and urban expansion, which creates a demand for better internet connectivity. Bishoftu, also known as Debre Zeit, is a town located in central Ethiopia, about 47 kilometers southeast of Addis Ababa, the capital city. Here is a brief overview of its geographical Elevation: Around 1,900 meters (6,233 feet) above sea level

Topography: Bishoftu is situated within the Great Rift Valley, known for its flat plains interspersed with volcanic formations and crater lakes. The town is surrounded by five volcanic crater lakes: Lake Bishoftu, Lake Hora, Lake Bishoftu Guda, Lake Koriftu, and Lake Kilole, which are popular for tourism and recreation.

Climate: Bishoftu has a subtropical highland climate. The temperature is relatively mild due to its elevation, with average temperatures ranging from 15℃ to 28℃ (59℉ to 82℉).

4.1.1 Current Telecommunications Landscape:

Identify the current broadband The broadband infrastructure in Bishoftu, Ethiopia, is primarily supported by a combination of optical distribution networks (ODN) and mobile networks, which together provide internet services for both residential and business users. Here's an overview of the current infrastructure:

Optical Distribution Network (ODN)
Fiber-to-the-Home (FTTH): Ethio Telecom, the national telecom provider, has been

working on deploying fiber optic networks across major cities, including Bishoftu. FTTH is available in select areas of the city, offering high-speed internet services, especially to businesses, government institutions, and residential users. Capacity: FTTH provides speeds ranging from 50 Mbps to 300 Mbps depending on the service package. Coverage: The fiber network is mainly concentrated in commercial and densely populated areas of the town, with ongoing expansion efforts.

Main Provider: Ethio Telecom is the dominant provider of ODN infrastructure in Ethiopia. Mobile Broadband Networks: 3G/4G LTE Networks: Mobile broadband is the most widely used form of internet access in Bishoftu. 4G LTE network is available in Bishoftu, offering speeds of up to 150 Mbps in areas with good signal strength.
3G still available in more rural or less-developed parts of Bishoftu, with speeds between 2 Mbps to 10 Mbps.
Ethio Telecom is currently the main broadband provider in Bishoftu, offering both mobile broadband and fixed-line services (FTTH).
Recent reforms in the telecom sector have allowed new entrants, such as Safaricom Ethiopia, to begin operating in Ethiopia. However, Safaricom's network coverage is still expanding, and it may not yet have a significant presence in Bishoftu. Once operational, Safaricom is expected to offer 4G and 5G mobile services, as well as fixed wireless options.

4.1.2 Challenges and Gaps

Coverage and Penetration: While the fiber optic network and 4G LTE services exist, there are still gaps in coverage, particularly in suburban and rural parts of Bishoftu, where mobile internet is more common but can be slower and less reliable. The cost of broadband services, especially FTTH, remains relatively high for many reasons Like land acquisition, material cost, and Installation cost. As shown in the image below, the ODN Deployment in Bishoftu is facing significant challenges due to land acquisition and civil work, leading to slow service and high costs.

and also, ODN networks also have limited widespread adoption. Traditional solutions

Figure 4.1: Land Issue for ODN Deployment (Source: Ethiotelecom Audit division)

to address broadband gaps in suburban areas have been hampered by the significant investments required to deploy physical infrastructure such as fiber-optic cables. Additionally, the lengthy deployment timelines associated with laying cables can exacerbate connectivity disparities, leaving suburban communities underserved or unserved. as we see in Table 4.1 below, the adoption rate in this expected area (Bishoftu) is very low.

NE Detail	Total ODN Capacity	Current Customer Use
NOKIA.MSAN-211106-1-SER-DUKEM-2 svlan-3405	3008	210
Huawei.Mini-OLT-EIZ-BLADE.Dukem svlan-3353	704	72
NOKIA.MSAN-211106-1-SER-DUKEM-1 svlan-3412	448	31
ZTE.MSAN-04.Bishoftu svlan-2515	704	66
ZTE.MSAN-06.Bishoftu svlan-2516	128	11
ZTE.MSAN-21.Bishoftu	64	8

NE Detail	Total ODN Capacity	Current Customer Use
svlan-2518		
ZTE.MSAN-25.Bishoftu svlan-2517	192	91
ZTE.MSAN-29.Bishoftu svlan-2462	3072	561
NOKIA_OLT_Bishoftu_Keta_FX-4 svlan_3345	152	58

Table 4.1: Bishoftu ODN Customer Adoption Rate

Digital Divide: While urban centers like Bishoftu are seeing improved infrastructure, surrounding rural areas may still rely on slower mobile networks or have limited internet access.

Future Developments: With Ethiopia's ongoing telecom liberalization, new investments in broadband infrastructure are expected. This could improve both mobile network performance (e.g., 5G) and the fiber optic backbone in Bishoftu, enhancing internet speeds and availability.

The broadband infrastructure in Bishoftu is developing, with a combination of fiber optic and mobile networks playing a central role. The introduction of new players and the rollout of advanced technologies like 5G should further boost internet connectivity shortly.

4.2 Network Architecture

4.2.1 ODN Network Architecture

Ethio Telecom uses an ODN based on GPON (Gigabit Passive Optical Network) technology to distribute fiber connections to homes and businesses in Bishoftu.

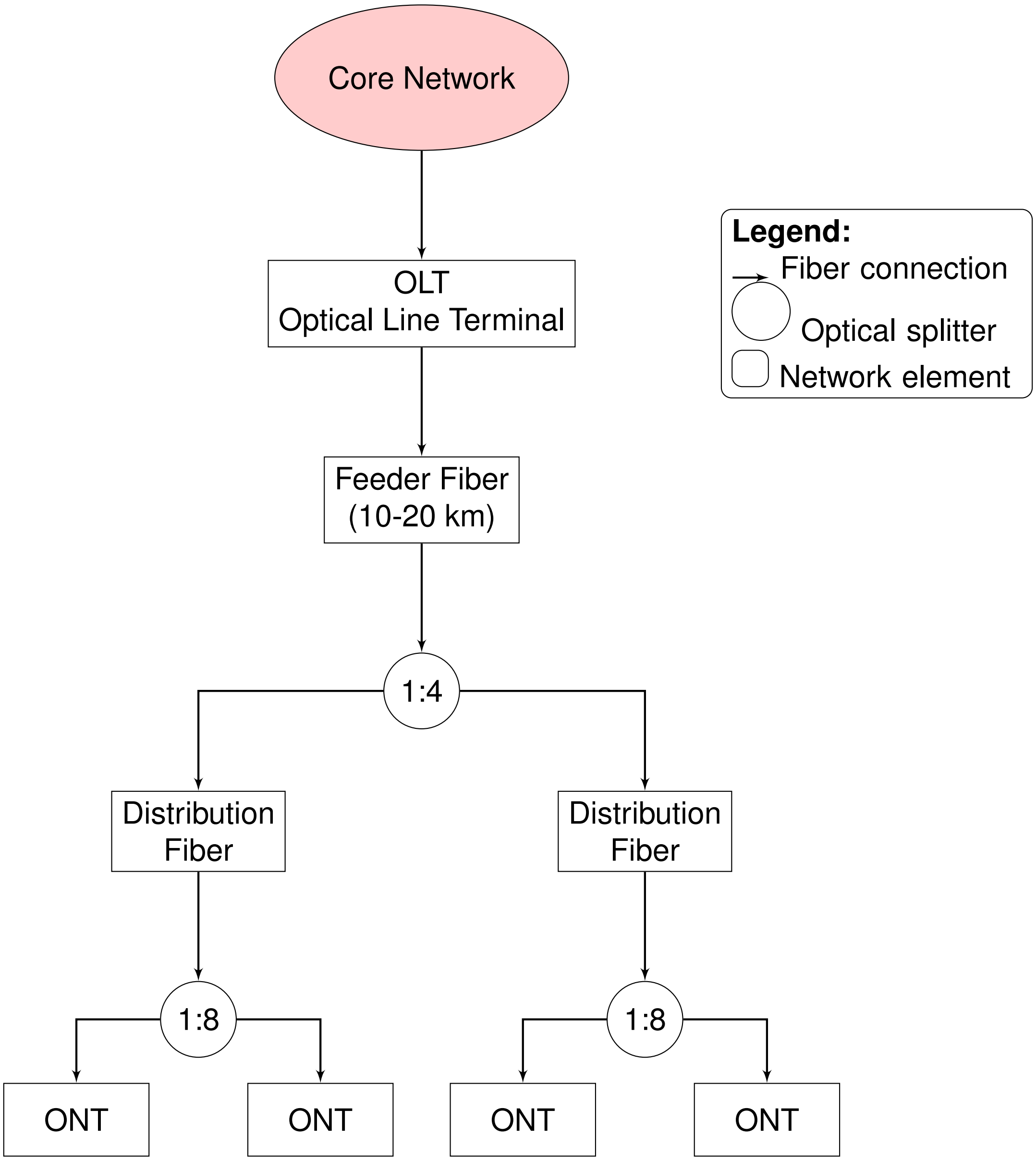

Figure 4.2: OLT/ODN Network Architecture (Point-to-Multipoint PON)

OLT is installed at the Ethio Telecom data center in Bishoftu and distributed in different mini exchanges and homes.

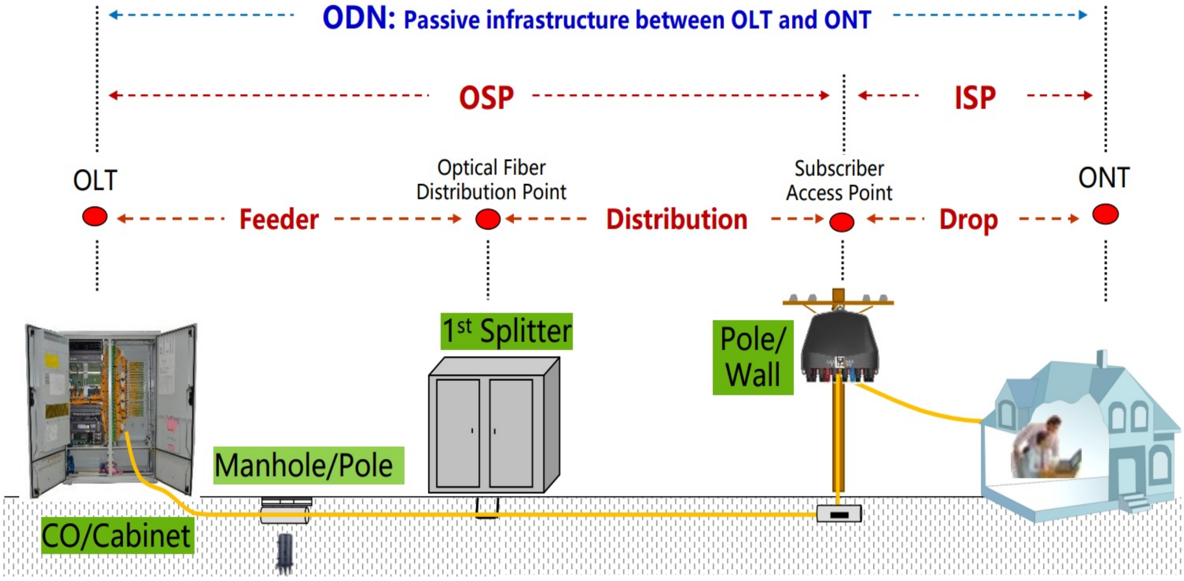

Figure 4.3: ODN Network Service

FWA Network Architecture

Ethio Telecom leverages its extensive national fiber backbone (18,000 km). gNBs (5G base stations): Located in urban hotspots and major regional cities such as Bahirdar, Dire Dawa, Adama, Bishoftu, etc. Fixed Wireless Access (FWA) replaces fiber-to-the-home (FTTH) in high-demand areas. CPE devices: Huawei/ZTE outdoor units provided to subscribers.

4.2.2 Customer Premises Equipment (CPE) and Its Deployment Method for FWA

Fixed Wireless Access (FWA) Customer Premises Equipment (CPE) is a device installed at a user's location (home or business) to receive and transmit wireless signals from a service provider's base station (tower or small cell). It enables high-speed internet connectivity without the need for traditional wired infrastructure (like fiber or copper cables). FWA CPE is a flexible and efficient solution for delivering high-speed internet

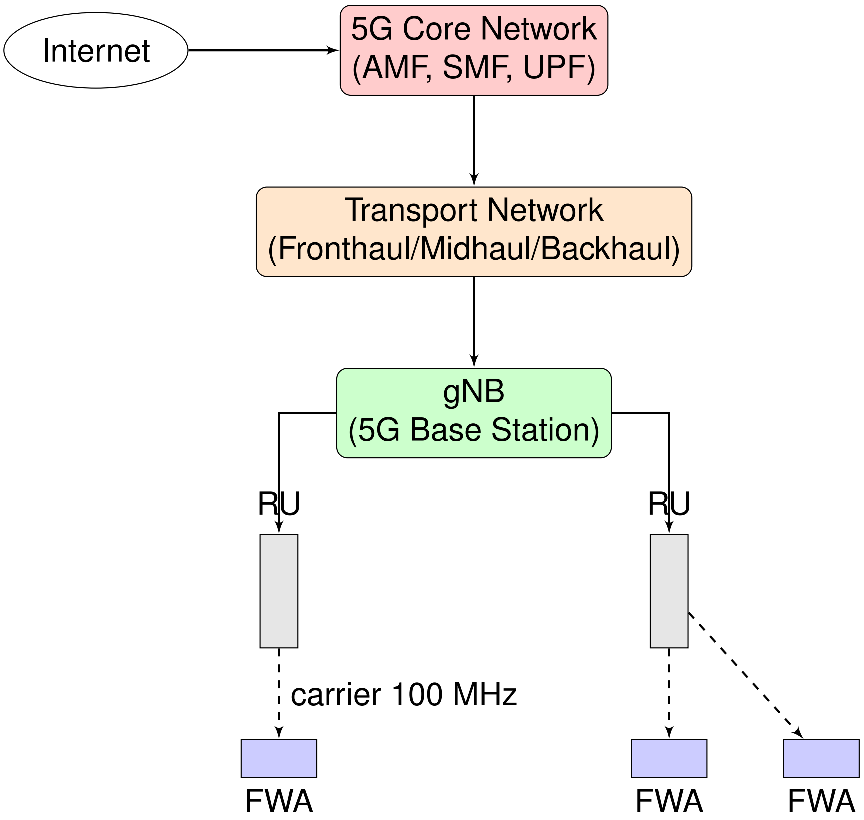

Figure 4.4: 5G Network Architecture for Fixed Wireless Access (FWA)

wirelessly. Proper deployment, including site survey and antenna alignment. ensures optimal performance, making it a key technology for bridging the digital divide.

CPE Installation

proper alignment for achieving optimal performance, highlighting the need to identify and account for potential obstacles such as trees and buildings that could cause interference. Proper alignment ensures efficient operation, whether in wireless communication, solar panel positioning, or optical systems, by minimizing signal loss, maximizing energy capture, or maintaining precision. Addressing these obstacles early in planning helps prevent performance degradation and ensures reliable functionality.

- Outdoor CPE Mounted on a roof, pole, or wall with clear LoS.
- Indoor CPE is placed near a window facing the tower.

Steps of CPE Configuration

1. Connect the CPE to power and pair it with the service provider's network.
2. Set up Wi-Fi/Ethernet for local device connectivity.
3. Testing and Optimization.
4. Verify signal strength, speed, and latency.
5. Adjust antenna direction if needed.

4.2.3 Economic Factors

Fixed Wireless Access (FWA) is a cost-effective alternative to wired broadband (like fiber or DSL) for suburban and semi-urban areas in Ethiopia, including towns like **Bishoftu (Debre Zeit)**. This report analyzes the **key economic factors** and their **implications** for FWA deployment in such regions.

Economic Factors Affecting FWA Deployment

A) Infrastructure Costs

Table 4.2: Infrastructure Cost Factors and Implications

Factor	**Implication**
Lower Capex than Fiber	FWA avoids costly trenching, poles, and fiber cabling.
Reduced Civil Works	No need for extensive digging or permits, speeding up deployment.
Reuse of Existing Towers	Mobile operators (e.g., Ethio Telecom) can leverage existing 4G/5G infrastructure.

Impact: Faster and cheaper rollout compared to fiber, making it viable for suburban expansion.

B) Affordability for End Users

Impact: Higher adoption rates among middle and lower-income residents in Bishoftu.

C) Market Demand & Revenue Potential

Table 4.3: Affordability Factors and Implications

Factor	**Implication**
Lower Subscription Costs	FWA plans are typically cheaper than fiber in early stages.
No Wiring Fees	Customers avoid installation charges common with fiber/DSL.
Prepaid & Flexible Plans	Pay-as-you-go options suit low-income households.

Table 4.4: Market Demand Factors and Implications

Factor	**Implication**
Growing Internet Demand	Increased need for home broadband due to remote work/education.
Limited Competition	Few wired ISPs in suburban areas mean FWA can dominate.
SME & Residential Use	Businesses (hotels, cafes) and homes drive demand.

Impact: Strong revenue potential for ISPs and mobile operators.

D) Regulatory & Licensing Costs

Table 4.5: Regulatory Factors and Implications

Factor	**Implication**
Spectrum Licensing Fees	Ethiopian Communications Authority (ECA) regulates wireless spectrum.
Taxes & Levies	Government policies may affect ISP profitability.
Local Permits	Easier to obtain than fiber right-of-way approvals.

Challenge: High spectrum costs could slow FWA expansion if not subsidized.

E) Operational Costs (Opex)

Challenge: Intermittent power in some areas may increase operational costs.

Economic Implications for Bishoftu (Debre Zeit)

Positive Implications

- **Faster Internet Penetration** – Quicker to deploy than fiber, bridging the digital divide.

Table 4.6: Operational Cost Factors and Implications

Factor	Implication
Power Requirements	CPE devices need stable electricity (solar/battery backup helps).
Maintenance & Support	Fewer physical repairs than fiber but requires RF optimization.
Backhaul Costs	If using microwave/fiber backhaul, costs vary by distance.

- **Boost to Local Economy** – Supports SMEs, e-commerce, and digital services.
- **Job Creation** – New roles in installation, maintenance, and customer support.
- **Scalability** – Can expand coverage incrementally based on demand.

Challenges & Risks

- **Electricity Reliability** – Power outages may require battery/solar solutions.
- **Spectrum Congestion** – High subscriber density could slow speeds if not managed.
- **Long-Term Competition** – If fiber expands later, FWA may become a secondary option.

Recommendations for FWA Success in Bishoftu

1. **Public-Private Partnerships (PPP)** – Government and ISPs can collaborate to reduce costs.
2. **Hybrid Solutions** – Use FWA for last-mile, but plan for future fiber upgrades.
3. **Localized Pricing Models** – Affordable packages for students and small businesses.
4. **Renewable Energy Integration** – Solar-powered CPE for areas with unstable electricity.

FWA is a **cost-efficient, scalable** solution for suburban Ethiopian towns like **Bishoftu**, offering faster internet access with lower upfront investment than fiber. However, **power stability, spectrum costs, and future competition** must be managed for long-term success.

4.3 Network Dimensioning

Network dimensioning is the initial phase of network planning, aimed at determining the required site density and configuration to meet coverage and capacity needs. This process involves calculating the cell range, sector throughput, and estimating the necessary network equipment. The outputs from this phase are used in the Techno-Economic Analysis (TEA) to estimate resource requirements and network costs. Two key results—coverage and capacity dimensioning—are obtained, with the larger value being selected as the final output per the dimensioning rule.

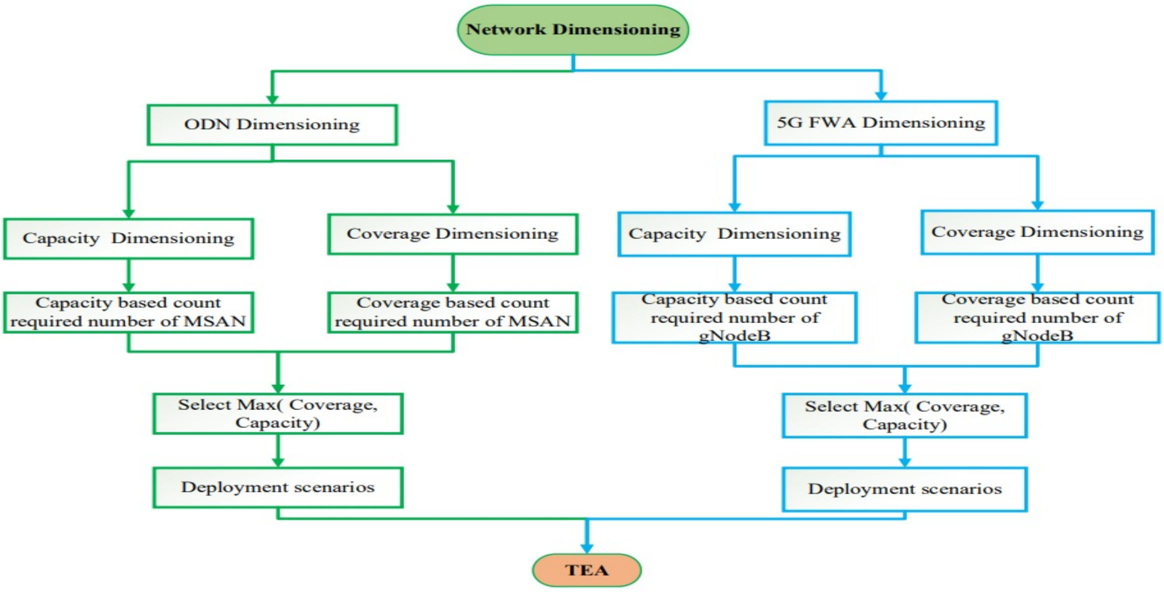

Figure 4.5: Ntk Dimentioning

4.3.1 5G FWA Coverage Dimensioning Approach

The coverage dimensioning process starts with Radio Link Budget (RLB) calculations to determine path loss for both Downlink (DL) and Uplink (UL). These calculations estimate the maximum allowable signal attenuation between the User Equipment (UE) and gNodeB antennas, as well as the required Signal-to-Interference-Noise Ratio (SINR) at the receiver, factoring in interference and shadowing effects.

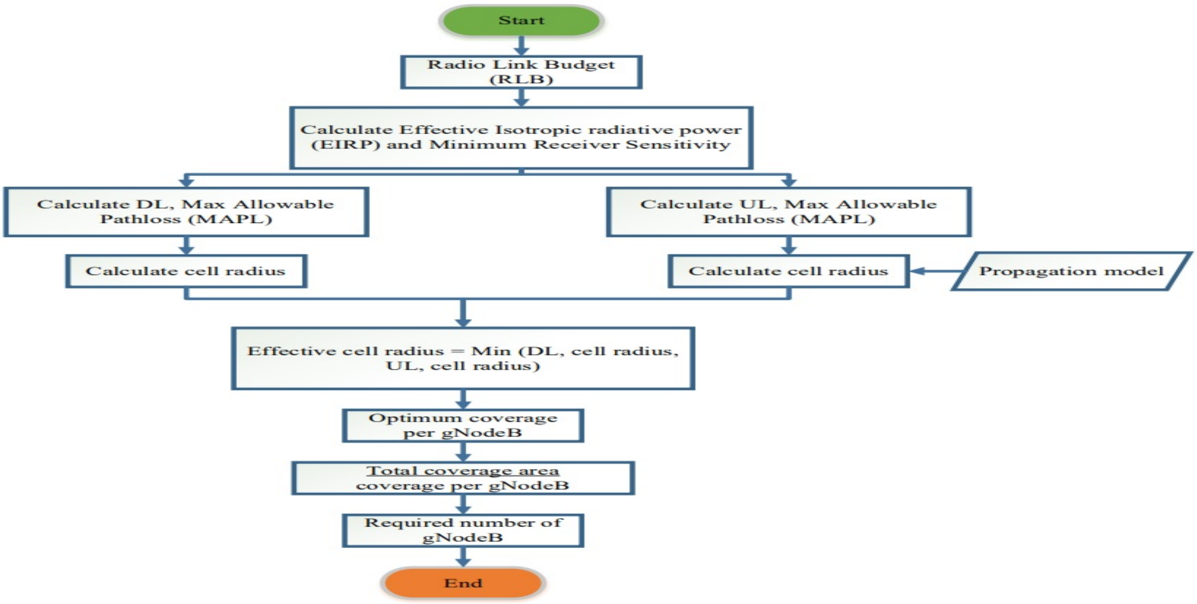

Figure 4.6: 5G FWA Coverage Dimensioning Flow Chart

The main goals of coverage dimensioning are:

- Define the coverage area for each gNodeB;
- Calculate the maximum allowable path loss;
- Estimate the resources needed for service in the deployment area;
- Ensure sufficient base stations to serve customers in the area.

Propagation Model

Propagation models are essential in network planning, especially for feasibility studies and initial deployment. A proper understanding of these models is critical for wireless communication dimensioning and planning. They are categorized into:

- Empirical models: Based on observations and measurements, mainly used to predict path loss.
- Deterministic models: Use electromagnetic wave propagation laws to calculate signal power at specific locations.
- Stochastic models: Less accurate but require minimal environmental data and processing power, using random variables to model the environment.

This thesis primarily uses an empirical propagation model. Among several models available for predicting path loss at 3.5 GHz—such as the Stanford University Interim (SUI) model, COST-231 Hata model, and Okumura-Hata model—the COST-231 Hata model was selected. It is suitable for all environments and aligns well with the target area's characteristics.

COST-231 Hata Propagation Model

Developed by the European Cooperation in Scientific and Technical Research (COST) action 231 group, this model estimates path loss using central frequency and the distance between the transmitter and receiver as input variables.

Key features: - Designed for carrier frequencies between 1500 and 2000 MHz but can be applied to higher frequencies by assuming antenna gain compensates for additional losses. - Simplified approach that does not require detailed geographical data, such as street width or building dimensions.

The path loss formula is:

$$PL(dB) = 46.3 + 33.9\log(f) - 13.82\log(h_{BS}) + [44.9 - 6.55\log(h_{BS})]\log(d) - a(h_{UE}) - C_o \tag{4.1}$$

Where: - PL: Path loss (dB) - f: Frequency (MHz) - h_{BS}: Base Station antenna height (m) - d: Distance between antennas (km) - h_{UE}: User Equipment (UE) antenna height (m) - C_o: 0 dB for suburban areas.

The model also includes formulas for the UE antenna height correction factor specific to urban, suburban, and rural areas. For suburban or rural areas, the user equipment (UE) antenna height correction factor is calculated using the formula:

$$a(h_{UE}) = 1.1\log(f) - 0.7h_{UE} - (1.5\log(f) - 0.8) \tag{4.2}$$

Where: - f is the frequency in MHz - h_{UE} is the UE antenna height in meters

Operating Frequency and Bandwidth

The key inputs for coverage dimensioning are the operating frequency band and bandwidth. Based on 3GPP Release 15 for 5G New Radio (5G NR), bands 77 and 78 (C-bands, 3300–4200 MHz and 4400–5000 MHz) are preferred due to their balance of coverage and capacity for cost-effective 5G deployment [45]. These bands utilize massive MIMO, Time Division Duplex (TDD), and at least 100 MHz bandwidth per network to enhance throughput. The spectrum is divided into three layers:

- Coverage and Capacity Layer (2–6 GHz): Balances coverage and capacity.
- Super Data Layer (more than 6 GHz): Supports high data rates for specific use cases, e.g., 24.25–29.5 GHz.
- Coverage Layer (less than 2 GHz): Ensures wide and deep indoor coverage, e.g., 700 MHz.

Parameter	Details
Frequency Bands	C-band (3300–4200 MHz and 4400–5000 MHz)
Bandwidth	Minimum 100 MHz per channel
Modes	Massive MIMO and Time Division Duplex (TDD)
Propagation Model	COST-231 Hata Model
Key Features	Optimized for Suburban Environments and Simplified path loss prediction

Table 4.7: Summary of Selected Frequency Bands, Bandwidth, Modes, and Propagation Models

Radio Link Budget Parameters Modeling

The radio link budget (RLB) in 5G operates similarly to previous mobile systems, estimating path loss based on key parameters, including gains and losses. It determines the Maximum Allowable Path Loss (MAPL) between the transmitter and receiver for both uplink (UL) and downlink (DL). By comparing the MAPL with the path loss from the selected propagation model, the cell radius can be calculated for different terrain types. The RLB considers several factors affecting cell coverage, including building penetration loss, feeder loss, antenna gain, and interference margins. These parameters collectively influence the calculation of all gains and losses essential for accurate coverage estimation. Key factors influencing cell coverage are:

- gNodeB Transmitter Power: The maximum power per branch, typically 46 dBm.
- gNodeB Antenna Gain: Related to antenna size and beam width. Low-gain antennas (15-17 dBi) suit urban areas, while high-gain antennas (18-20 dBi) extend coverage in rural areas.
- UE Transmitter Power: Typically 23 dBm, depending on the power class.
- Losses: Includes cable loss (1-6 dB for gNodeB) and body loss (2-3 dB when the UE is near the user's head).
- Effective Isotropic Radiated Power (EIRP): Indicates the power radiated in a desired direction, factoring in transmitter power, antenna gain, and losses.
- Cell Edge User Throughput: Minimum net throughput required at the cell edge, defined by the operator.
- Thermal Noise: Calculated as N=KBT K is Boltzmann's constant, T is 290 K, and B is the channel bandwidth (100 MHz for this study).

- Signal-to-Interference-Noise Ratio (SINR): Varies based on receiver design and vendor specifications.
- Receiver Sensitivity: Minimum signal strength required for decoding, expressed as Rs =NF+SINR+N.
- Slow/Shadow Fading Margin: Caused by natural obstructions or location changes, with a standard deviation of 5-12 dB based on clutter.
- Feeder Loss: Losses due to equipment between the antenna and receiver.
- Penetration Loss: Signal attenuation caused by building obstructions, varying by building type and clutter. These factors collectively determine cell coverage and performance.

a table 4.8 below showing the morphological penetration losses based on clutter type for the thesis

Clutter Type	Penetration Loss (dB)
Urban	20-30 dB
Suburban	10-20 dB
Rural	5-10 dB
Dense Urban	30-40 dB
Open Area (Low Clutter)	0-5 dB
Highway (Rural)	5-10 dB

Table 4.8: Morphological Penetration Losses Based on Clutter Type

The Maximum Allowable Path Loss (MAPL): determines the maximum distance a signal can travel before it becomes too weak for reliable communication. MAPL helps estimate the required number of gNodeB sites to cover the target area using suitable propagation models. The formula for MAPL is:

$$MAPL = EIRP - R_s - P_L - S_m - I_m + G_R X \tag{4.3}$$

Where: - $EIRP$ is the Effective Isotropic Radiated Power (dBm), - R_s is Receiver Sensitivity (dBm), - P_L is Penetration Loss (dB), - S_m is Shadow-Fading Margin (dB), - I_m is Interference Margin (dB), - G_{RX} is the Receiver Antenna Gain (dBi).

Parameter	**Downlink (DL)**	**Uplink (UL)**
Morphology	Sub Urban	Sub Urban
Data channel type	PDSCH	PUSCH
Duplex mode	TDD	TDD
System bandwidth (MHz)	100	100
Frequency band (MHz)	3500	3500
Cell edge rate (Mbps)	100	25
Max number of resource block (KHz)	273	273
MIMO Scheme	4x4	4x4
gNodeB Transmitter Power	46 dBm	N/A
gNodeB Antenna Gain	17.5 dBi	N/A
UE Maximum Total Transmitter Power	N/A	23 dBm
Cable Loss	3 dB	3 dB
Body Loss	2.5 dB	2.5 dB
Effective Isotropic Radiated Power (EIRP)	PTx + GTx - Total Tx Losses	PTx + GTx - Total Tx Losses
Cell Edge User Throughput	Required Target Throughput (Mbps)	Required Target Throughput (Mbps)
Thermal Noise	$N = KBT$	$N = KBT$
Noise Figure	7 dB	7 dB
Signal-to-Interference Noise Ratio (SINR)	Derived from system-level simulations	Derived from system-level simulations
Receiver Sensitivity	Rs = NF + SINR + N	Rs = NF + SINR + N
Slow/Shadow Fading Margin	8.5 dB	8.5 dB
Penetration Loss	15 dB	15 dB
Feeder Loss	3 dB	3 dB
Factor A and B	0.4	1.1

Table 4.9: 5G FWA Radio Link Budget DL/UL Parameters

Transmitter/Receiver(gNodeB/UE)	Link Budget Parameters
Tx output power (dBm)	A
Tx antenna gain (dBi)	B
TX cable and connector loss (dB)	C
Transmitter body loss (dB)	D
EIRP per subcarrier (dBm)	E=A+B-C-D
UE noise figure (dB)	F
Subcarrier spacing (kHz)	I
Subcarrier	J
PRB size (kHz)	G=I*J
Thermal noise (dB)	L=KBT
Receiver noise floor (dBm)	M=F+L
SINR (Linear)	N=Factor B*(2 power of (Data rate/Factor A)-1)
SINR (dB)	O=10*log N
Receiver sensitivity (dBm)	P=M+O
Control channel overhead (dB)	Q
Rx antenna gain (dB)	R
Body loss (dB)	S
Shadowing fading loss (dB)	T
Cell edge coverage probability	90-95 percent
Interference margin (dB)	V
Indoor penetration loss (dB)	W
MAPL (dB)	MAPL=E-P-Q+R-S-T-V-W

Table 4.10: 5G FWA Radio Link Budget Parameters [62].

Total Number of Users

The total number of 5G FWA users in Bishoftu, a suburban area of Ethiopia with a total population of 240,000 and an area of 27 square kilometers, you need to estimate the demand for 5G FWA services based on factors like population density, internet penetration, and market adoption rates. Here's a step-by-step guide to performing this calculation:

Determine Population Density Total Population: 240,000 (according to Worldometer report)
Area: 27 km2 (according to the current map report)
Population density:

$$\text{Population Density} = \frac{\text{Total Population}}{\text{Area}} = \frac{240,000}{27} = 8,889\,\text{people per km}^2 \tag{4.4}$$

Estimate Internet Penetration Rate The Internet Penetration Rate is the percentage of the population that uses the Internet. In Ethiopia, according to recent data, the internet penetration rate is approximately 30 percent (this can vary depending on the region and the source). Internet Users:

$$\text{Internet Users} = \text{Total Population} \times \text{Internet Penetration Rate} = 240,000 \times 0.3 = 72,000\,\text{users} \tag{4.5}$$

Estimate the 5G FWA Adoption Rate - Not all internet users will adopt 5G FWA immediately. The adoption rate depends on factors such as affordability, availability of 5G FWA services, and competition from other broadband technologies (e.g., fiber, 4G LTE). The initial adoption rate of 30 percent (this is a reasonable assumption for a suburban area with a growing demand for high-speed Internet). 5G FWA Users:

$$\text{5G FWA Users} = \text{Internet Users} \times \text{Adoption Rate} = 72,000 \times 0.30 = 21,600\,\text{users} \tag{4.6}$$

Refine the Estimate Based on Market Factors Affordability: If 5G FWA services are priced competitively, adoption rates could increase. For example, if the adoption rate increases to 40 percent, the number of 5G FWA users would be:

$$\text{5G FWA Users} = 72,000 \times 0.40 = 28,800 = \text{approximately}(29,000)\text{ users} \tag{4.7}$$

Final Estimate Based on the above calculations, the total number of 5G FWA users in Bishoftu can be estimated as follows: Low Estimate (30 percent Adoption Rate): 21,600 users High Estimate (40 percent Adoption Rate): 29,000 users According to Worldometer data, five percent of the total population in the city increases annually, so we consider +1,000 users a threshold. We have 30,000 total 5G FWA users. To calculate the 5G Fixed Wireless Access (FWA) coverage, we will use the provided path loss formula.

So, a total of 5G FWA users is 30,000

4.3.2 5G FWA Capacity Dimensioning Approach

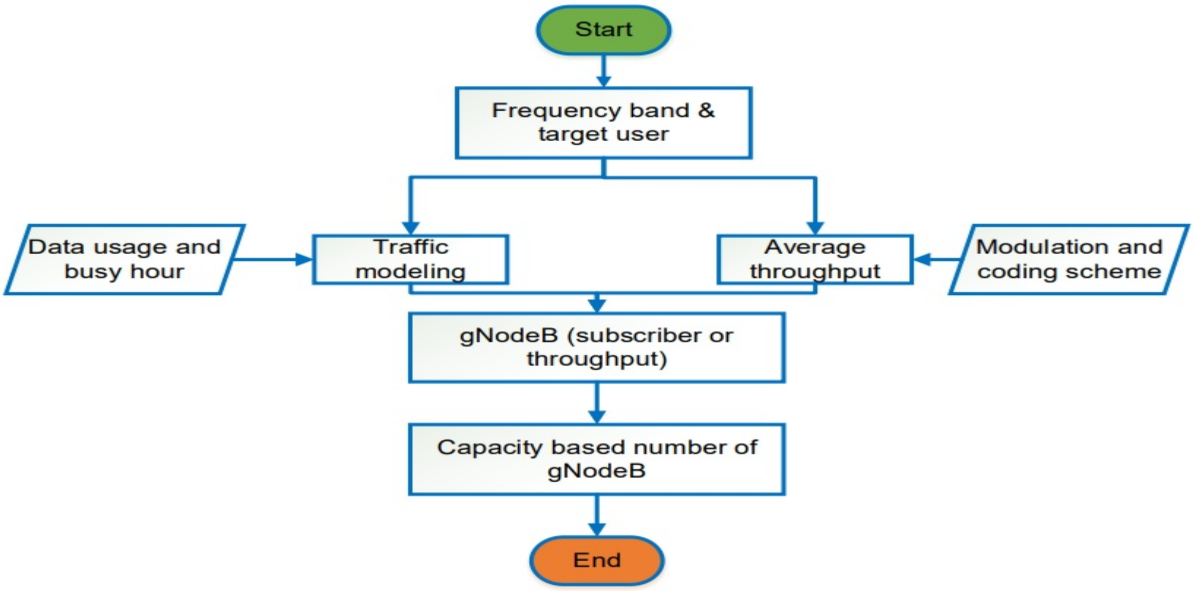

Figure 4.7: 5G FWA Capacity Dimensioning Flow Chart

Capacity dimensioning estimates the resources needed to handle specific traffic levels while maintaining the desired Quality of Service (QoS), throughput, or blocking probability. For 5G FWA, it depends on factors like the required data plan per user, modulation and coding schemes, available bandwidth, and SINR performance within the cell.

User Capacity per Base Station The total user capacity is 30,000 users. With 60 base stations, the user capacity per base station is:

$$\text{Users per Base Station} = \frac{30,000}{60} \approx 500\,\text{users} \tag{4.8}$$

Aggregate Throughput or Data Rate Modeling

Throughput refers to the maximum data rate a communication system can transmit. It serves as a quality indicator, representing the usual and non-redundant data transfer rate. A key goal of capacity planning is to estimate the number of sites needed to meet capacity requirements. Network operators determine these requirements based on projected traffic and the average cell throughput, which is essential for calculating the site count based on capacity.

The aggregate throughput for 5G New Radio (NR) is modeled according to the 3GPP TS 38.306 standard. The maximum data transfer rates for downlink (DL) and uplink (UL) are calculated using the following formula:

$$\text{5G NR Throughput} = 10^{-6} \sum_{j=1}^{J} \left(v_{\text{Layers}}(j) \cdot Q_m(j) \cdot f(j) \cdot R_{\text{max}} \cdot \frac{N_{\text{PRB}}^{\text{BW}(j),\mu} \cdot 12}{T_s^{\mu}} \cdot (1 - OH(j)) \right) \tag{4.9}$$

Where: - 10^{-6}: A constant factor to express throughput in Mbps. - j: The number of aggregated component carriers in a band or band combination, with a maximum value of 16. - $v_{\text{Layers}}(j)$: The maximum number of MIMO layers, up to 8 for DL and 4 for UL. - $Q_m(j)$: The modulation type, which can be QPSK (2), 16QAM (4), 64QAM (6), or 256QAM (8). - $f(j)$: A scaling factor for medium and high mobility, with possible values of 0.4, 0.75, 0.8, or 1. - R_{max}: The maximum coding rate as specified in 3GPP 38.212 and 38.214. For Low-Density Parity Check (LDPC), the maximum value is 948/1024. - $N_{\text{PRB}}^{\text{BW}(j),\mu}$: The maximum number of allocated Physical Resource Blocks (PRBs) within the given bandwidth and subcarrier spacing. For example, with 100 MHz bandwidth and 30 kHz subcarrier spacing, 273 PRBs are used. - T_s^{μ}: The average duration of an OFDM symbol in a frame. For normal cyclic prefix, $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}} = 3.577 \cdot 10^{-5}$. - $OH(j)$:

The control channel overhead. Typical values are: - For DL and UL in FR1: 0.14 and 0.08, respectively. - For DL and UL in FR2: 0.18 and 0.10, respectively.

This formula enables accurate modeling of 5G NR throughput, facilitating network planning and optimization to efficiently meet user demands.

Traffic Modeling

The primary purpose of traffic modeling is to represent the average subscriber behavior during the busiest time of day, referred to as the Busy Hour (BH). Network capacity is planned based on BH traffic since traffic usage varies throughout the day.

In this model, the BH is divided into three time periods within a 24-hour day.

- Morning BH: Between 10:00 and 11:00.
- Afternoon BH: Between 3:00 and 4:00.
- Evening BH: Between 8:00 and 9:00.

These three periods collectively account for three hours of BH traffic, which is assumed to represent 12.5 percent of the daily traffic. For this analysis, the total daily traffic is also assumed to be 12.5 percent of the monthly traffic.

The average total throughput per subscriber during the BH is calculated using the following formula:

$$\text{Average Throughput at BH (in Kbps)} = \frac{\text{Monthly Service Package} \times 8\,\text{bits/byte}}{\text{Number of Days} \times \text{Time in Seconds}} \times \text{BH Ratio} \tag{4.10}$$

Parameters: Monthly Service Package: Represents the total traffic allocated to a subscriber in a month (in Gigabytes). 8 bits/byte: Conversion factor to convert bytes to bits. Number of Days: The number of days in a month. Time in Seconds: Total seconds in a day. BH Ratio: The ratio of BH traffic to the total daily traffic, is assumed to be 12.5 percent.

This model provides a framework for estimating subscriber behavior and network demand during peak usage times, helping optimize network capacity planning.

Capacity-Based Site Counts

Once the traffic model and capacity requirements are estimated, the capacity-based site count can be calculated. This involves determining the maximum number of subscribers a single gNodeB (5G base station) can handle based on the available aggregate capacity and the average subscriber throughput during the Busy Hour (BH).

The maximum number of subscribers per gNodeB for downlink (DL) or uplink (UL) is determined using the following formula:

$$\text{Max. No. of Subscribers per gNodeB} = \frac{\text{Aggregate Capacity Throughput per Site}}{\text{Avg. Throughput per Subscriber at BH}} \tag{4.11}$$

Finally, the total number of gNodeBs required to accommodate all subscribers can be calculated as follows:

$$\text{Capacity-Based Site Count} = \frac{\text{Total Number of Subscribers}}{\text{Max. No. of Subscribers per gNodeB (DL, UL)}} \tag{4.12}$$

This approach ensures the network is planned efficiently to handle the required capacity while meeting subscriber demand during peak usage times.

4.3.3 ODN Coverage Dimensioning Approach

The coverage dimensioning process for an Optical Distribution Network (ODN) begins with a site survey of the target area. This survey evaluates environmental factors and determines if the location is suitable for fiber installation. Based on the findings, engineers select a planning method that aligns with the area's geographical topology, which could involve aerial, duct, underground, or hybrid installation methods.

The next step involves defining the territory of the MSAN (Multi-Service Access Node). Environmental factors such as main roads and rivers, along with technical constraints like link loss or power loss limits, play a critical role in setting the coverage boundaries.

Once the boundaries are determined, the topology preparation stage begins. During this phase, detailed cable plans are developed, including:

- Schematic plans
- Cable maps (showing cable routes)
- Distribution maps

These plans are created using planning tools like AutoCAD or Geographic Information System (GIS) software. In this thesis, the ODN network dimensioning is conducted using actual data from Ethio Telecom for the selected area. The methodology described here applies to both coverage-based and capacity-based dimensioning approaches, ensuring a clear and practical framework for network planning. Effective bandwidth planning ensures that current demand is met while allowing for future expansion. This process begins with data collection and identifying the customer type in the target area.

User forecasting is typically based on key factors, including Historical user growth trends, Regional population and population density, Quality of life indicators, and Market penetration factors. Additionally, the split ratio plays a critical role in determining both the optical power and the bandwidth. The split ratio directly affects the power budget required to support the physical reach of the network. The goal of user forecasting and bandwidth planning is to establish the minimum data rate needed per user and the physical reach of the network. These factors are essential for defining the capacity and coverage requirements of the network.

According to the ITU-T G.984 standard, which defines requirements for Gigabit-capable Passive Optical Networks (GPON), the following maximum fiber distances are specified: - Physical Distance: The differential fiber distance between the Optical Line Terminal (OLT) and the Optical Network Units (ONUs) can range between 10 km and 20 km. - Logical Distance: The maximum logical reach of the network can extend up to 60 km. This logical reach considers not only the physical cable length but also any delays introduced by the network equipment.

Within these distance limits, engineers can determine the number of Multi-Service Access Nodes (MSANs) needed for a specific target area. This is done by assessing factors such as:
Environmental Conditions: Includes terrain features (e.g., mountains, rivers), infrastructure challenges, and climate considerations that may impact fiber installation.
Prepared Topology: Refers to the network design, including the routes and connections of cables, distribution points, and MSAN placements.

These factors allow engineers to strategically position MSANs to optimize coverage, maintain signal quality, and ensure reliable service within the specified distance constraints.

Service Type	**Description**	**Bandwidth Required (Mbps)**
Data	Browsing the web, writing, and sending emails	5 Mbps
Voice	VOIP, video telephony, and voice conferencing	1 Mbps
Video (General)	Music on demand, multimedia content	2 Mbps
Online Gaming	Real-time gaming sessions	2 Mbps
SD Digital TV	Standard-definition digital TV	8 Mbps
HD Digital TV	High-definition digital TV	15 Mbps
Netflix (Full HD)	Streaming in full HD resolution	25 Mbps
Amazon Prime Video	Streaming in full HD resolution	25 Mbps
Additional TV Channels	Two HDTV channels	20 Mbps
Streaming Videos, Movies, Music	General streaming services	10 Mbps
Video Conferencing	Real-time video meetings	15 Mbps

Table 4.11: Service Types and Bandwidth Requirements

4.3.4 ODN Capacity Dimensioning Approach

The capacity of a Multi-Service Access Node (MSAN) in an Optical Distribution Network (ODN) depends on two key factors:

- The Type of GPON Card Used: GPON (Gigabit-capable Passive Optical Network) cards installed in the MSAN determine the data handling capabilities and overall performance of the network.
- The Splitting Ratio: This refers to how many end-users (or Optical Network Units, ONUs) can share a single optical fiber through passive splitters.

Fiber optic cables provide a very high data transmission capacity, making them ideal for modern communication networks. However, the practical capacity of a fiber optic network is influenced by its hardware components, such as the GPON card and splitters, rather than the cable itself.

Splitting Ratios in GPON: A single optical fiber core in a GPON network can be divided using splitters to connect multiple users. Common splitting ratios include:

- 1:32 – One fiber is shared among 32 users.
- 1:64 – One fiber is shared among 64 users.
- 1:128 – One fiber is shared among 128 users.
- 1:256 – One fiber is shared among 256 users.

Each splitting ratio has trade-offs: - Lower Ratios (e.g., 1:32) provide higher bandwidth per user but require more fibers or hardware at the MSAN. - Higher Ratios (e.g., 1:256) increase user density on a single fiber but reduce the bandwidth available per user and require more precise power and signal management.

In summary, ODN capacity dimensioning involves balancing the GPON card capabilities, splitting ratio, and user requirements to ensure optimal performance and scalability of the network.

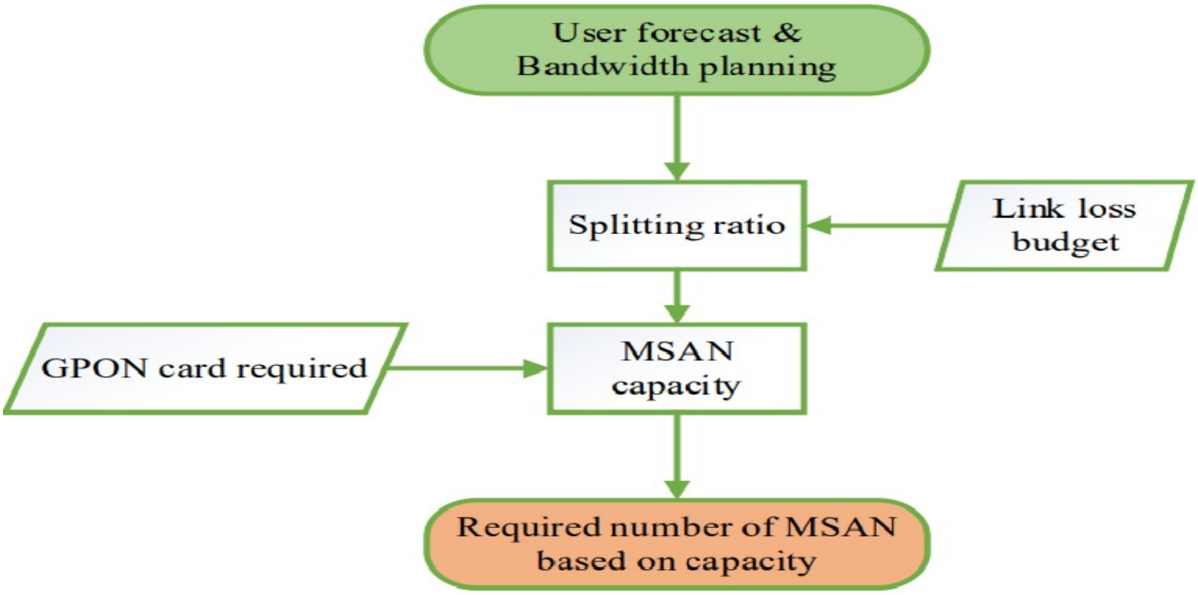

Figure 4.8: ODN capacity dimensioning process

Optical fiber communication is capable of transmitting clear and undistorted signals over long distances. However, its performance can be impacted by factors like installation loss and connector loss. To ensure optimal performance, the link loss budget is calculated based on the maximum allowable loss specified by the chosen standard before starting the capacity dimensioning process.

Link Loss Budget and Cost estimation of ODN Network

The link loss budget, also known as the power loss budget, represents the maximum loss that a transmitter or receiver can handle while maintaining proper operation. This loss can result from factors such as cable loss, splitter loss, splicing loss, and connector loss.

For link loss modeling, we will follow the ITU G.984.2 Class B+ standard, which sets the maximum allowable link loss between 13dB and 28 dB. To calculate the link loss budget, we sum all the losses in the fiber section and verify that the planned Optical Distribution Network (ODN) meets the required specifications.

The following formula calculates the total link loss:

$$T_{loss} = L_{cable} + L_{splitter} + L_{splice} + L_{connector} \tag{4.13}$$

No	Item	Description	Optical Power Attenuation (dB)
1	Fiber Optical Cable (G.652)	1310 nm optical cable (dB/km)	0.35
		1490 nm optical cable (dB/km)	0.25
2	Connecting Point	Fusion splicing point	0.1
		Adapter connector	0.2
		Mechanical splicing point	0.3
4	Splitter Unit	1:32 splitter	17
5		1:16 splitter	13.5
6		1:8 splitter	10.2
7		1:4 splitter	7.2
9	Redundancy	Redundancy loss	2

Table 4.12: Optical Power Attenuation Details

Where: - T_{loss} is the total loss - L_{cable} is the loss due to the type of cable used, including span loss and loop loss - $L_{splitter}$ is the loss caused by the splitter - L_{splice} is the loss due to splicing or jointing - $L_{connector}$ is the loss caused by the mechanical connector. After determining the link loss budget, the next step is to calculate the capacity of the MSAN, the capacity of the GPON card, and the required number of MSAN units. The calculations can be performed as follows:

1. MSAN Capacity:

$$\text{Capacity of MSAN} = \text{Splitter Ratio} \times \text{Number of Secondary Splitters} \tag{4.14}$$

2. Number of MSAN Units Based on Capacity:

$$\text{Number of MSAN Units} = \frac{\text{Total Number of Users}}{\text{Capacity of MSAN}} \tag{4.15}$$

3. Required Number of GPON Cards:

$$\text{Required Number of GPON Cards} = \frac{\text{Total Capacity of MSAN}}{\text{Capacity of GPON Card}} \tag{4.16}$$

4. Number of MSAN Units Based on Total Capacity:

$$\text{Number of MSAN Units} = \frac{\text{Total Number of Users}}{\text{Capacity of MSAN}} \tag{4.17}$$

These formulas allow for a precise calculation of the required infrastructure based on the user demand and the capacities of the MSAN and GPON cards.By strategically placing splitters and cabinets, maximize splitter ratios and minimize unnecessary fiber runs. the ODN coverage dimensioning involves careful planning of fiber paths, splitters, and distances, ensuring the network can support 30,000 homes with enough capacity for growth. By using a 1:32 splitter ratio and planning based on geographical constraints, operators can optimize both cost and coverage.

4.4 General Parameters

When performing a link budget calculation for a 5G Fixed Wireless Access (FWA) deployment in a suburban area, several general parameters need to be considered. These parameters include factors related to both the base station (gNodeB) and the user equipment (UE), as well as environmental conditions and regulatory constraints. Here are the general parameters typically involved:

- Transmit Power (gNodeB): The power level at which the gNodeB transmits signals to the user equipment (UE). The transmit power should be sufficient to provide adequate coverage and signal strength throughout the suburban area while complying with regulatory limits.
- Antenna Gain (gNodeB and UE): The directional gain provided by the antennas used at both the gNodeB and the UE. Antenna gain affects signal propagation and coverage area, with higher gain antennas providing increased signal strength and coverage distance.
- Receiver Sensitivity (UE): The minimum signal strength required by the UE to successfully receive and decode signals from the gNodeB. Receiver sensitivity determines the UE’s ability to maintain a reliable connection, especially in areas with weaker signal strength or higher interference levels.
- Path Loss Model: The path loss model used to estimate the attenuation of radio signals as they propagate from the gNodeB to the UE. Common path loss models

include the Okumura-Hata model, COST 231 Hata model, and the Free Space Path Loss (FSPL) model, which account for factors such as distance, frequency, antenna heights, and terrain characteristics.

- Frequency Band: The frequency band allocated for 5G FWA deployment, which may include sub-6 GHz bands (e.g., 3.5 GHz, 4.9 GHz) and mmWave bands (e.g., 24 GHz, 28 GHz). The choice of frequency band impacts signal propagation, coverage area, and penetration through obstacles.
- Channel Bandwidth: The bandwidth allocated for each 5G FWA channel, which determines the maximum data rate and spectral efficiency of the system. Larger channel bandwidths allow for higher data rates but may be subject to greater interference and regulatory constraints.
- Modulation and Coding Scheme (MCS): The modulation scheme and coding rate used to encode data transmitted over the wireless channel. Higher MCS values enable higher data rates but require higher signal-to-noise ratio (SNR) or signal-to-interference-plus-noise ratio (SINR) for reliable communication.
- Interference and Noise: Consideration of interference sources from neighboring cells or other wireless systems operating in the same frequency band, as well as background noise from environmental factors. Interference and noise impact signal quality and may require mitigation techniques such as frequency planning and interference avoidance.

By considering these general parameters in the link budget calculation, engineers can design and optimize 5G FWA deployments in suburban areas to achieve reliable connectivity, adequate coverage, and optimal performance for subscribers.

4.4.1 UE receiver characteristics

In a 5G Fixed Wireless Access (FWA) deployment in a suburban area, the characteristics of the User Equipment (UE) receivers play a critical role in ensuring reliable communication with the base station (gNodeB). The Okumura-Hata path loss model is commonly used to estimate the propagation loss for both Downlink (DL) and Uplink (UL) transmissions between the gNodeB and the UE. Let's explore how UE receiver characteristics are considered in the DL and UL budget analysis using the Okumura-Hata path loss model:

Downlink (DL) Budget Analysis:

- Receiver Sensitivity: The DL receiver sensitivity of the UE is a crucial parameter that determines the minimum signal strength required for the UE to successfully receive and decode DL signals from the gNodeB. The receiver sensitivity is budgeted based on the estimated DL path loss using the Okumura-Hata model and the gNodeB's DL transmit power.
- Noise Figure: The UE's noise figure characterizes the noise performance of its receiver. A lower noise figure indicates better sensitivity to weak signals in the presence of noise. The noise figure is considered in the DL budget analysis to ensure reliable DL signal reception, especially in suburban areas with varying levels of interference and noise.
- Antenna Gain: The UE's antenna gain is considered to improve DL signal reception and enhance the overall DL budget. Antenna parameters, such as orientation and placement, are optimized to maximize signal reception from the gNodeB while minimizing the impact of path loss and interference.
- Diversity Reception: Diversity reception techniques, such as spatial diversity or frequency diversity, may be employed in the UE's receiver to mitigate the effects of fading and multipath propagation in the wireless channel. Diversity reception enhances DL signal reliability and coverage in suburban environments with complex propagation conditions.

Uplink (UL) Budget Analysis:

- Transmitter Power: The UE's UL transmitter power is budgeted to ensure sufficient signal strength to reach the gNodeB while complying with regulatory power limits. The transmitter power is determined based on the estimated UL path loss using the Okumura-Hata model and the gNodeB's UL receiver sensitivity.

- Noise Figure: The UE's noise figure is considered in the UL budget analysis to ensure reliable UL signal reception at the gNodeB. A lower noise figure improves the UE's sensitivity to weak signals, enhancing UL communication quality and coverage in suburban areas with varying levels of noise and interference.
- Antenna Gain: The UE's antenna gain is optimized to improve UL signal transmission and minimize the impact of UL path loss. Antenna parameters, such as orientation and placement, are adjusted to maximize signal transmission to the gNodeB while mitigating the effects of path loss and interference.

By considering UE receiver characteristics in the DL and UL budget analysis using the Okumura-Hata path loss model, operators can optimize the performance and coverage of 5G FWA deployments in suburban areas, ensuring reliable connectivity and high-quality service for subscribers.

4.4.2 Range (Okumura-Hata path loss model)

In the context of a 5G Fixed Wireless Access (FWA) deployment in a suburban area, the Okumura-Hata path loss model is a commonly used method to estimate the propagation loss between the base station (gNodeB) and the user equipment (UE). The range calculated using this model is a crucial component of the ”D link budget” analysis. Let's explore how the Okumura-Hata path loss model is applied in this scenario:

- Path Loss Calculation: The Okumura-Hata model estimates the path loss between the gNodeB and the UE based on factors such as frequency, distance, antenna heights, and terrain characteristics. In a suburban environment, where buildings, trees, and other obstacles may affect signal propagation, the path loss calculation accounts for these factors to provide an accurate estimate of signal attenuation.

- Frequency Consideration: The Okumura-Hata model takes into account the operating frequency of the 5G FWA system, as higher frequencies tend to experience higher path loss due to increased susceptibility to attenuation from obstacles and foliage. For suburban deployments, which may involve frequencies in the mid-band or millimeter-wave spectrum, the model adjusts the path loss calculation accordingly to reflect the impact of frequency on signal propagation.
- Terrain and Obstacle Effects: The model incorporates terrain profiles and obstacle heights to account for the blocking and diffraction of radio waves in a suburban environment. Buildings, trees, and other structures between the gNodeB and the UE can cause additional path loss and signal degradation, which the Okumura-Hata model considers when estimating the range and path loss for the link budget analysis.
- Antenna Heights: The heights of the gNodeB and UE antennas above ground level are important parameters in the Okumura-Hata model, as they affect the line-of-sight (LOS) and non-line-of-sight (NLOS) propagation conditions. Higher antenna heights can improve signal propagation by reducing the impact of obstacles and increasing the likelihood of LOS conditions, thereby reducing path loss and extending the effective range of the FWA deployment.
- Coverage Prediction: By utilizing the Okumura-Hata model to estimate path loss, engineers can predict the coverage area of the 5G FWA network in the suburban environment. This information is essential for planning the placement of gNodeB sites and determining the spacing between them to ensure seamless coverage and sufficient signal strength for reliable connectivity to subscribers throughout the suburban area.

Overall, the Okumura-Hata path loss model plays a critical role in the ”D link budget” analysis for 5G FWA deployment in a suburban area, providing valuable insights into signal propagation characteristics and helping engineers optimize network design and coverage planning for optimal performance and user experience.

4.4.3 SINR

Calculating the required Signal-to-Interference-plus-Noise Ratio (SINR) for a 5G Fixed Wireless Access (FWA) deployment in a suburban area involves considering various factors such as the modulation and coding scheme (MCS), channel conditions, interference levels, and noise characteristics. Here's a general approach to determining the required SINR:

1. Determine Modulation and Coding Scheme (MCS)

2. Calculate Signal Power

3. Assess Interference Levels

4. Account for Noise

5. Determine Required SINR

6. Adjust SINR Requirement

7. Validate with Field Measurements

Overall, the calculation for the required SINR in a 5G FWA deployment in a suburban area involves a comprehensive analysis of signal, interference, and noise conditions to ensure reliable communication and meet performance targets. The specific SINR threshold will vary based on the system design, deployment scenario, and service requirements.

4.4.4 Sensitivity Analysis

Performing sensitivity analysis for my research called ”Techno-economic Competitiveness Alternative of 5G FWA in Suburban Areas: The Case of Bishoftu, Ethiopia” involves examining how changes in key variables or assumptions affect the outcomes or conclusions of my study. Here's how you could approach it:

1. Identify Key Variables 2. Define Ranges 3. Modeling 4. Analyze Results 5. Sensi-

tivity Charts/Graphs 6. Interpretation 7. Robustness Check

By conducting a sensitivity analysis, we can enhance the credibility and reliability of our research findings, providing valuable insights for decision-makers and stakeholders involved in the deployment of 5G FWA technology in sub-urban areas like Bishoftu, Ethiopia.

4.4.5 Payback Period

Calculating the payback period for your research on ”Techno-economic Competitiveness Alternative of 5G FWA in sub-urban areas: The Case of Bishoftu, Ethiopia” involves determining the time it takes for the initial investment in 5G FWA infrastructure to be recovered through the generated revenues or cost savings. Here’s how we can calculate it:

$$\text{Payback Period} = \text{Number of years before PCCF} + \frac{\text{Remaining investment to recover}}{\text{Net cash flow in the next period}} \tag{4.18}$$

which, PCCF = positive cumulative cash flow However, the calculation can become more complex if the cash flows vary significantly from year to year or if there are discount rates to consider. In such cases, a discounted cash flow (DCF) analysis or other more sophisticated methods may be used. Additionally, sensitivity analysis can help assess the impact of variations in key assumptions on the payback period.

Chapter 5

Results and Analysis

5.1 Implemented TEA Model

The excerpt describes implementing a modified TERA (Techno-Economic Results Assessment) model tailored to the specific objectives of a research study. Chapter three provided an overview of various techno-economic evaluation models and their applications. TEA models are typically restricted to project sponsors and are rarely commercially available. To address this, a modified TERA model was developed using MATLAB and MS Excel in this thesis, aligning with the study's objectives, system inputs, outputs, and techno-economic approach. The model is structured into three main components: technical, marketing, and economic parts, as illustrated in the Figure. This modular structure ensures a comprehensive analysis, combining technical feasibility, market dynamics, and economic sustainability.

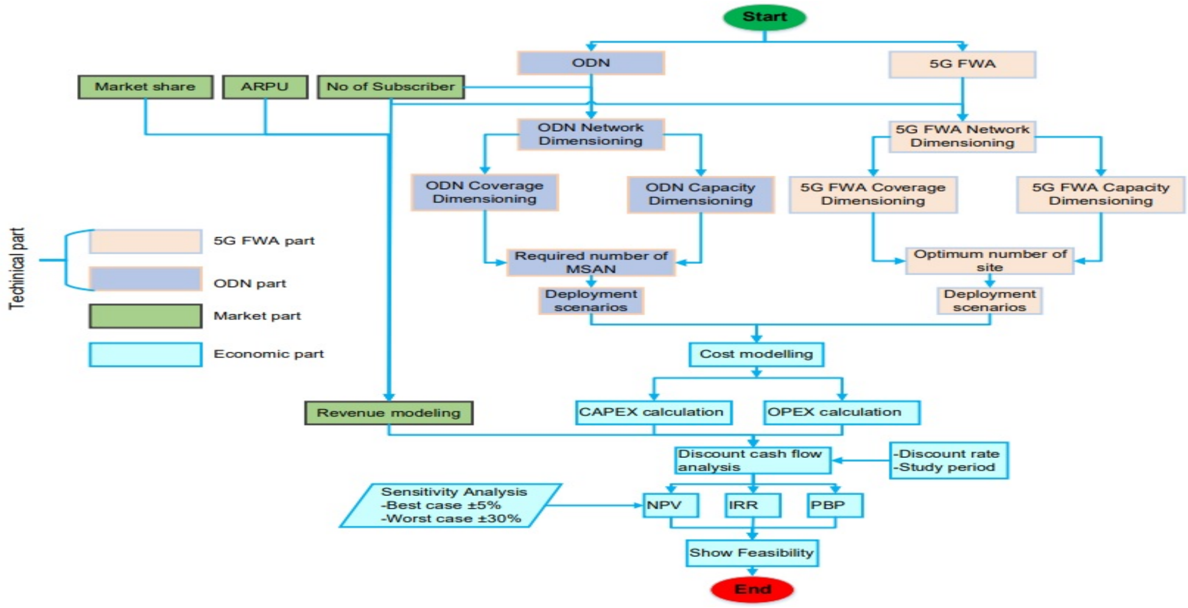

Figure 5.1: Modified and implemented techno-economic analysis model

5.1.1 Site Selection

Site selection plays a critical role in evaluating the deployment scenario, as both comparison technologies rely on actual geographical conditions [55]. For this study, data provided by Ethio Telecom served as the basis for selecting the area, with the decision informed by expert judgments and input from various stakeholders, including government strategies related to smart cities [43].

The Bishoftu area was ultimately chosen based on ODN (Optical Distribution Network) deployment data from several potential sites [62] [42]. This area is situated to the east of Addis Ababa, the capital city of Ethiopia, and falls under Ethio Telecom's South East Region (SER).

As illustrated in the figure, the Bishoftu area contains both fixed and wireless resources. On the wireless side, there are 64 existing macro base stations, including six sites equipped for typical 5G deployment. On the fixed network side, there are 34 fixed network elements, including nine MSAN (Multi-Service Access Node) units. These existing resources will be considered in the formulation of deployment scenarios, ensuring optimal use of available infrastructure.

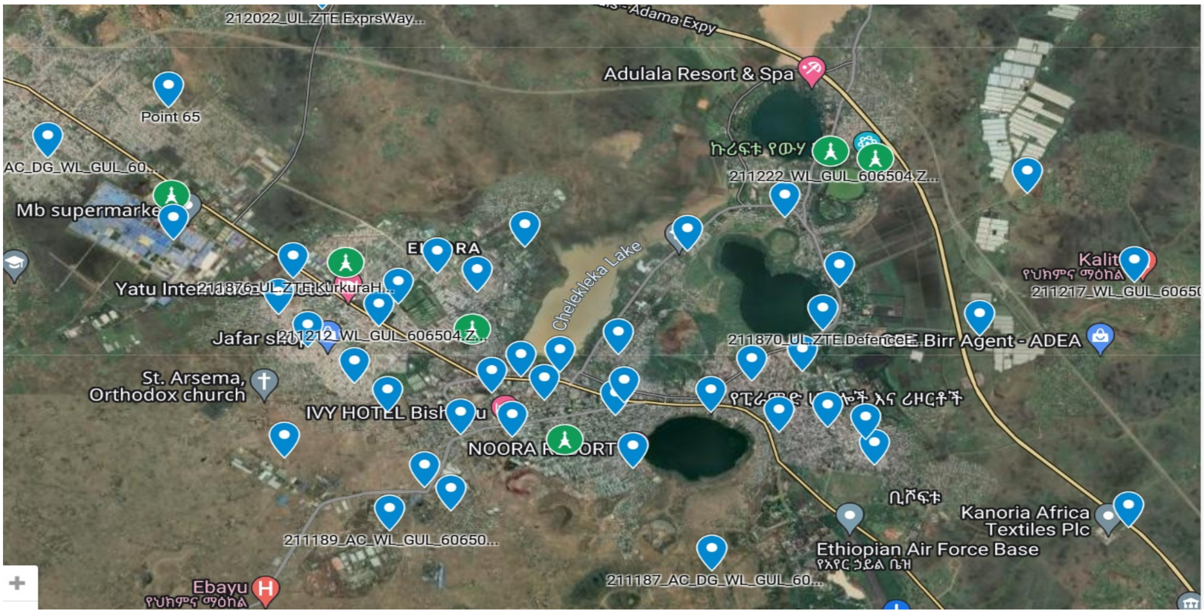

Figure 5.2: Bishoftu BTS

5.2 Deployment Scenario By Using TERA Model

Before selecting deployment scenarios, it's important to highlight that LTE can support fixed wireless access (FWA) services [4]. However, for the fastest fiber-like internet speeds and more effective comparative analysis, the study focuses on 5G FWA-based scenarios from the wireless domain. Additionally, there are various types of Fiber to the Home (FTTH) technologies that provide broadband services over optical fiber, including PON, GPON, GE-PON, XG-PON, and EPON. Among these, GPON-based Optical Distribution Networks (ODN) have been chosen for the scenario formulation due to their superior performance and compatibility with the selected area.

Following the site selection process, four deployment scenarios were developed in this study. Two of these scenarios are based on ODN, while the other two rely on 5G FWA. The specific requirements for each scenario are outlined below:

- Scenario 1 (Sc-1): 5G FWA with New Infrastructure This scenario involves deploying all 5G FWA-related assets using entirely new infrastructure.
- Scenario 2 (Sc-2): 5G FWA Using Existing Sites with Additional New Resources, there are 64 base stations (BS) currently operational. In this scenario, the operator reuses existing 2G, 3G, and 4G assets, such as antennas. Upgrades to the current sites are accounted for, and the addition of new resources for an additional site is carefully considered.
- Scenario 3 (Sc-3): ODN with New Infrastructure: This scenario focuses on deploying all ODN-related assets with a completely new infrastructure.
- Scenario 4 (Sc-4): ODN with Existing Infrastructure and New Additions In this scenario, existing backhaul, ducts, and other fixed network Resources are reused. However, if the current network is copper-based, the cost of upgrading to fiber is included as a new expense.

5.3 Technical Analysis

5.3.1 5G FWA Coverage Dimensioning & Budget Analysis

Coverage dimensioning is a critical process in the deployment of 5G Fixed Wireless Access (FWA) networks. Key parameters required to estimate the Maximum Allowable Path Loss (MAPL) include inputs from the Radio Link Budget (RLB), such as transmitter and receiver characteristics, the propagation model, geographical data, and the desired coverage probability [26].

A significant aspect of this study is the selection of the propagation model [55]. Moreover, the empirical propagation model aligns with the methodologies used by operators, as verified by the thesis's information sources [45]. This consistency ensures that the model is both realistic and applicable to the local context [61]. The table provided in the study summarizes the standard parameters and calculated values used for RLB estimation, offering a comprehensive overview of the coverage-related factors considered in this research.

Parameter	**Downlink (DL)**	**Uplink (UL)**
General Parameters		
Morphology	SubUrban	SubUrban
Cell edge coverage probability	90-95%	90-95%
Propagation model	Cost-231 Hata model	Cost-231 Hata model
User environment	Indoor, Outdoor	Indoor, Outdoor
Data channel type	PDSCH	PUSCH
MIMO Scheme	4x4	4x4
Duplex mode	TDD	TDD
Operation frequency	3500 MHz	3500 MHz
Operation bandwidth	100 MHz	100 MHz
gNodeB Transmitter Characteristics		
Data rate	100 Mbps	25 Mbps
gNodeB TX power	46 dBm	24 dBm

gNodeB antenna gain	11 dBi	0 dBi
Cable loss	2 dB	0 dB
EIRP	55 dBm	24 dBm
UE Receiver Characteristics		
UE noise figure	7.000 dB	2.000 dB
Temperature	290.000 K	290.000 K
Boltzmann constant	1.38×10^{-23} J/K	1.38×10^{-23} J/K
Max number of resource blocks	273.000	273.000
Subcarrier spacing	30.000 kHz	30.000 kHz
Subcarrier	12.000	12.000
PRB size	360.000 kHz	360.000 kHz
Thermal noise	-124.053 dB	-124.053 dB
Receiver noise floor	-117.053 dBm	-122.053 dBm
Factor A	0.400	0.400
Factor B	1.100	1.100
SINR (Linear)	5.123	0.596
SINR (Log)	7.095 dB	-2.244 dB
Receiver sensitivity	-109.958 dBm	-124.297 dBm
Control channel overhead	1.000 dB	1.000 dB
Rx antenna gain	0.000 dB	11.000 dBi
Body loss	3.000 dB	3.000 dB
Shadowing fading loss	7.000 dB	7.000 dB
Interference margin	3.000 dB	1.000 dB
Indoor penetration loss	15.000 dB	15.000 dB
Maximum allowed propagation loss	135.958 dB	131.297 dB
Cost-231 Hata Path Loss Model		
BS antenna height	30.000 m	30.000 m
MS antenna height	1.500 m	1.500 m
MS antenna gain function (small city)	0.069	0.069
Path loss exponent	35.225	35.225
Path loss constant (small city)	141.780 dB	141.780 dB

Cell radius range (small city)	0.518 km	0.383 km

Table 5.1: General Parameters for Downlink (DL) and Uplink (UL)

To calculate the Maximum Allowable Path Loss (MAPL) for both the Downlink (DL) and Uplink (UL), we use the following formula:

$$\begin{aligned}\text{MAPL} = {} & \text{EIRP} - \text{Receiver Sensitivity} + \text{Receiver Antenna Gain} - \text{Body Loss} \\ & - \text{Shadowing Fading Loss} - \text{Interference Margin} - \text{Indoor Penetration Loss} \\ & - \text{Control Channel Overhead}\end{aligned} \tag{5.1}$$

Using the provided parameters, we will calculate the MAPL for both the Downlink (DL) and Uplink (UL).

Calculation:

$$\begin{aligned}\text{MAPL}_{\text{DL}} = {} & \text{EIRP} - \text{Receiver Sensitivity} + \text{Receiver Antenna Gain} - \text{Body Loss} \\ & - \text{Shadowing Fading Loss} - \text{Interference Margin} - \text{Indoor Penetration Loss} \\ & - \text{Control Channel Overhead}\end{aligned} \tag{5.2}$$

$$\text{MAPL}_{\text{DL}} = 55 - (-109.958) + 0 - 3 - 7 - 3 - 15 - 1 \tag{5.3}$$

$$\text{MAPL}_{\text{DL}} = 55 + 109.958 - 3 - 7 - 3 - 15 - 1 \tag{5.4}$$

$$\text{MAPL}_{\text{DL}} = 164.958 - 29 = 135.958\,\text{dB} \tag{5.5}$$

Uplink (UL) Calculation Given Parameters: - EIRP: 24 dBm - Receiver Sensitivity: -124.297 dBm - Receiver Antenna Gain: 11 dB - Body Loss: 3 dB - Shadowing Fading Loss: 7 dB - Interference Margin: 1 dB - Indoor Penetration Loss: 15 dB - Control

Channel Overhead: 1 dB Calculation:

$$\begin{aligned}\text{MAPL}_{\text{UL}} = {} & \text{EIRP} - \text{Receiver Sensitivity} + \text{Receiver Antenna Gain} - \text{Body Loss} \\ & - \text{Shadowing Fading Loss} - \text{Interference Margin} - \text{Indoor Penetration Loss} \\ & - \text{Control Channel Overhead}\end{aligned} \tag{5.6}$$

$$\text{MAPL}_{\text{UL}} = 24 - (-124.297) + 11 - 3 - 7 - 1 - 15 - 1 \tag{5.7}$$

$$\text{MAPL}_{\text{UL}} = 24 + 124.297 + 11 - 3 - 7 - 1 - 15 - 1 \tag{5.8}$$

$$\text{MAPL}_{\text{UL}} = 159.297 - 28 = 131.297\,\text{dB} \tag{5.9}$$

Downlink (DL) MAPL: 135.958 dB
Uplink (UL) MAPL: 131.297 dB

Downlink (DL) Radio Link Budget of 5G FWA for Suburban Morphology

To calculate the number of gNodeBs for the downlink (DL) using the downlink MAPL of 135.958 dB, we need to determine the cell radius using the Cost-231 Hata propagation model and then calculate the coverage area of one gNodeB. Finally, we divide the total area (27 km²) by the coverage area of one gNodeB to find the number of gNodeBs required.

Calculate Cell Radius Using Cost-231 Hata Model

The Cost-231 Hata model for suburban areas is given by:

$$\begin{aligned}\text{Path Loss (PL)} = {} & 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_b) - a(h_m) \\ & + (44.9 - 6.55\log_{10}(h_b))\log_{10}(d) + C\end{aligned} \tag{5.10}$$

Where: - f: Frequency in MHz (3500 MHz) - h_b: Base station antenna height in meters (assume 30 m, typical for suburban areas) - h_m: Mobile station antenna height in meters (assume 1.5 m, typical for UE) - $a(h_m)$: Correction factor for mobile antenna height (for suburban areas, $a(h_m) = 0$) - d: Distance in km (cell radius) - C: Constant for suburban areas ($C = 0\,\text{dB}$) Simplify the Cost-231 Hata Model: For suburban areas, the formula simplifies to:

$$\begin{aligned}\text{PL} &= 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_b) \\ &\quad + \big(44.9 - 6.55\log_{10}(h_b)\big)\log_{10}(d)\end{aligned} \tag{5.11}$$

Substitute the known values: - $f = 3500\,\text{MHz}$ - $h_b = 30\,\text{m}$ - $h_m = 1.5\,\text{m}$

$$\begin{aligned}\text{PL} &= 46.3 + 33.9\log_{10}(3500) - 13.82\log_{10}(30) \\ &\quad + \big(44.9 - 6.55\log_{10}(30)\big)\log_{10}(d)\end{aligned} \tag{5.12}$$

Calculate the logarithmic terms: - $\log_{10}(3500) = 3.544$ - $\log_{10}(30) = 1.477$ Substitute these values:

$$\text{PL} = 46.3 + 33.9(3.544) - 13.82(1.477) + (44.9 - 6.55(1.477))\log_{10}(d) \tag{5.13}$$

$$\text{PL} = 46.3 + 120.1 - 20.4 + (44.9 - 9.68)\log_{10}(d) \tag{5.14}$$

$$\text{PL} = 146.0 + 35.22\log_{10}(d) \tag{5.15}$$

Solve for Cell Radius (d): The MAPL is the maximum allowable path loss. For the Downlink (DL), MAPL = 135.958 dB. Set PL = MAPL:

$$135.958 = 146.0 + 35.22\log_{10}(d) \tag{5.16}$$

$$35.22\log_{10}(d) = 135.958 - 146.0 \tag{5.17}$$

$$35.22\log_{10}(d) = -10.042 \tag{5.18}$$

$$\log_{10}(d) = \frac{-10.042}{35.22} = -0.285 \tag{5.19}$$

$$d = 10^{-0.285} = 0.518\,\text{km} \tag{5.20}$$

So, the cell radius is approximately 0.518 km. Calculate the Coverage Area of One gNodeB The coverage area of a single gNodeB is given by the formula for the area of a circle:

$$\text{Coverage Area} = \pi r^2 \tag{5.21}$$

Where r is the cell radius in km.

$$\text{Coverage Area} = \pi(0.518)^2 = 0.843\,\text{km}^2 \tag{5.22}$$

Calculate the Number of gNodeBs The total area to be covered is 27 km², and the coverage area of one gNodeB is 0.843 km². The number of gNodeBs required is:

$$\text{Number of gNodeBs} = \frac{\text{Total Area}}{\text{Coverage Area of One gNodeB}} \tag{5.23}$$

$$\text{Number of gNodeBs} = \frac{27}{0.843} = 32.02 \tag{5.24}$$

Since we cannot have a fraction of a gNodeB, we round up to the next whole number:

$$\text{Number of gNodeBs} = 33 \tag{5.25}$$

The number of gNodeBs required for the suburban area of Bishoftu is 33. Summary of Results: Downlink (DL) MAPL: 135.958 dB Cell Radius: 0.518 km Coverage Area of One gNodeB: 0.843 km² Total Area: 27 km² Number of gNodeBs: 33

Uplink (UL) Radio Link Budget for 5G FWA of Suburban Morphology

In the uplink scenario, the user equipment (UE) transmits to the base station. The key differences in the uplink compared to the downlink are the transmitter power (which is much lower in the UE), antenna gains, and possible increased interference due to the lower signal strength from mobile devices.

To calculate the number of gNodeBs for the uplink (UL) using the uplink MAPL of 131.297 dB, we need to determine the cell radius using the Cost-231 Hata propagation model and then calculate the coverage area of one gNodeB. Finally, we divide the total area (27 km²) by the coverage area of one gNodeB to find the number of gNodeBs required.

Calculate Cell Radius Using Cost-231 Hata Model

The Cost-231 Hata model for suburban areas is given by:

$$\text{Path Loss (PL)} = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_b) - a(h_m) + \big(44.9 - 6.55\log_{10}(h_b)\big)\log_{10}(d) + C \tag{5.26}$$

Where: - f: Frequency in MHz (3500 MHz) - h_b: Base station antenna height in meters (assume 30 m, typical for suburban areas) - h_m: Mobile station antenna height in meters (assume 1.5 m, typical for UE) - $a(h_m)$: Correction factor for mobile antenna height (for suburban areas, $a(h_m) = 0$) - d: Distance in km (cell radius) - C: Constant for suburban areas ($C = 0\,\text{dB}$)

Simplify the Cost-231 Hata Model: For suburban areas, the formula simplifies to:

$$\text{PL} = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_b) + (44.9 - 6.55\log_{10}(h_b))\log_{10}(d) \tag{5.27}$$

Substitute the known values: - $f = 3500\,\text{MHz}$ - $h_b = 30\,\text{m}$ - $h_m = 1.5\,\text{m}$

$$\text{PL} = 46.3 + 33.9\log_{10}(3500) - 13.82\log_{10}(30) + (44.9 - 6.55\log_{10}(30))\log_{10}(d) \tag{5.28}$$

Calculate the logarithmic terms: - $\log_{10}(3500) = 3.544$ - $\log_{10}(30) = 1.477$ Substitute these values:

$$\text{PL} = 46.3 + 33.9(3.544) - 13.82(1.477) + (44.9 - 6.55(1.477))\log_{10}(d) \tag{5.29}$$

$$\text{PL} = 46.3 + 120.1 - 20.4 + (44.9 - 9.68)\log_{10}(d) \tag{5.30}$$

$$\text{PL} = 146.0 + 35.22\log_{10}(d) \tag{5.31}$$

Solve for Cell Radius (d): The MAPL is the maximum allowable path loss. For the Uplink (UL), MAPL = 131.297 dB. Set PL $=$ MAPL:

$$131.297 = 146.0 + 35.22\log_{10}(d) \tag{5.32}$$

$$35.22\log_{10}(d) = 131.297 - 146.0 \tag{5.33}$$

$$35.22\log_{10}(d) = -14.703 \tag{5.34}$$

$$\log_{10}(d) = \frac{-14.703}{35.22} = -0.417 \tag{5.35}$$

$$d = 10^{-0.417} = 0.383\,\text{km} \tag{5.36}$$

So, the cell radius is approximately 0.383 km. Calculate the Coverage Area of One gNodeB The coverage area of a single gNodeB is given by the formula for the area of a circle:

$$\text{Coverage Area} = \pi r^2 \tag{5.37}$$

Where r is the cell radius in km.

$$\text{Coverage Area} = \pi(0.383)^2 = 0.461\,\text{km}^2 \tag{5.38}$$

Calculate Number of gNodeBs The total area to be covered is 27 km², and the coverage area of one gNodeB is 0.461 km². The number of gNodeBs required is:

$$\text{Number of gNodeBs} = \frac{\text{Total Area}}{\text{Coverage Area of One gNodeB}} \tag{5.39}$$

$$\text{Number of gNodeBs} = \frac{27}{0.461} = 58.57 \tag{5.40}$$

Since we cannot have a fraction of a gNodeB, we round up to the next whole number:

$$\text{Number of gNodeBs} = 59 \tag{5.41}$$

Final Answer: The number of gNodeBs required for the suburban area of Bishoftu is 59. Summary of Results: Uplink (UL) MAPL: 131.297 dB

Cell Radius: 0.383 km

Coverage Area of One gNodeB: 0.461 km²

Total Area: 27 km²

Number of gNodeBs: 59

Parameters	**DL**	**UL**
MAPL (dB)	135.958	131.297
Cell radius range (Km)	0.518	0.383
Number of gNodeB	33	59

Table 5.2: Coverage Dimensioning for DL and UL

After comparing both options, we selected the higher number of gNodeBs, which is 59, for the 5G Fixed Wireless Access (FWA) coverage.

5.3.2 5G FWA Capacity Dimensioning

In addition to the fundamental parameters and mathematical approach described in Subsection 4.2.4, the input parameters used for the capacity dimensioning are explained as follows: The article outlines the monthly data plan offerings, user categories, and traffic modeling for wireless broadband services, comparing current LTE/LTE-A services provided by Ethio Telecom with global trends in 5G usage. Users are categorized into three groups based on their monthly data plans:
Gold: 100 GB monthly data.
Silver: 50 GB monthly data.
Bronze: 25 GB monthly data.
Based on local and global trends, it is assumed that:
1. 5G users will consume twice as much data as LTE-A WTTH users.
2. New user categories for 5G are defined with corresponding monthly data volumes:
Entry-Level Users: 50 GB.
Basic Users: 100 GB.
Professional Users: 200 GB.
Users are not expected to use 100% of their data plans due to practical and behavioral considerations. usage distribution is:
70% for professional users.
20% for basic users.
10% for entry-level users.
This framework provides a basis for estimating traffic demands and designing a network that aligns with user trends and service requirements for 5 G. To calculate the throughput (in Mbps) based on the provided data, we need to compute the total traffic per user category and derive the throughput considering monthly data usage and

service distribution.

5.3.3 Calculation of Total Average Throughput at Busy Hour (BH)

Calculate Average Throughput for Each User Category

- **Professional User:**

$$\text{Av. Throughput} = \frac{200 \times 10^9 \times 8}{30 \times 3600 \times 0.125} = 18.519\,\text{Mbps} \tag{5.42}$$

- **Basic User:**

$$\text{Av. Throughput} = \frac{100 \times 10^9 \times 8}{30 \times 3600 \times 0.125} = 9.259\,\text{Mbps} \tag{5.43}$$

- **Entry User:**

$$\text{Av. Throughput} = \frac{50 \times 10^9 \times 8}{30 \times 3600 \times 0.125} = 4.630\,\text{Mbps} \tag{5.44}$$

Multiply by Usage Ratio

- **Professional User:**

$$18.519\,\text{Mbps} \times 70\% = 12.963\,\text{Mbps} \tag{5.45}$$

- **Basic User:**

$$9.259\,\text{Mbps} \times 20\% = 1.852\,\text{Mbps} \tag{5.46}$$

- **Entry User:**

$$4.630\,\text{Mbps} \times 10\% = 0.463\,\text{Mbps} \tag{5.47}$$

Calculate Total Average Throughput at BH

$$\text{Total Average Throughput at BH} = 12.963 + 1.852 + 0.463 = 15.278\,\text{Mbps} \quad (5.48)$$

User Category	Av. Throughput (Mbps)	Usage Ratio (%)	Contribution (Mbps)
Professional	18.519	70	12.963
Basic	9.259	20	1.852
Entry	4.630	10	0.463
Total Average Throughput at BH			15.278

Table 5.3: Calculation of Total Average Throughput at BH

These values represent the average Busy Hour throughput per user category based on the given input.

Aggregate Throughput

The aggregate throughput was calculated using the 3GPP TS 38.306 5G NR standard and the main parameters used to calculate aggregate throughput are summarized in Table below To calculate the maximum number of users per gNodeB and the total

Parameter	Downlink (DL)	Uplink (UL)
Frequency	3.5 GHz	3.5 GHz
Bandwidth (MHz)	100 MHz	100 MHz
Overhead (OH)	0.14	0.08
Max. Code Rate (Rmax)	948/1024	948/1024
Number of Carriers (J)	8	6
Number of Layers (V)	8	4
Scaling Factor/Signaled Per Band (f)	1	1
Max. Number of Resource Blocks	500	500
Sub-carrier Per Resource Block	12	12
Sub-carrier Spacing	30 KHz	30 KHz
Average OFDM Symbol Duration (Ts)	-	-
Numerology ()	1	1
Bits Per Symbol From Modulation Scheme	8	8

Table 5.4: Aggregate Throughput Parameters for 5G FWA Deployment in Suburban Areas (Source: 3GPP TS 38.306 & burden_federal_nodate)

number of capacity-based site counts for 30,000 total users with 30 Mbps DL and 20 Mbps UL user demand, we will use the provided inputs and follow these steps:

Calculate Max. Number of Resource Blocks (RBs) The number of RBs is determined by the bandwidth and subcarrier spacing (SCS). From the provided inputs: Bandwidth: 100 MHz Subcarrier Spacing (SCS): 30 kHz For 30 kHz SCS, the number of RBs per MHz is approximately 5 RBs/MHz. Therefore:

$$\text{Number of RBs} = 100 \times 5 = 500\,\text{RBs} \tag{5.49}$$

Calculate the Maximum Number of Users per gNodeB The maximum number of users per gNodeB is determined by the number of RBs and the resource allocation per user. Assuming 1 RB per user per scheduling interval, the maximum number of users per gNodeB is:

$$\text{Max. Users per gNodeB} = 500 \tag{5.50}$$

Calculate the Total Number of Capacity-Based Site Counts To calculate the total number of capacity-based site counts, we need to consider: 1. The total number of users (30,000). 2. The maximum number of users per gNodeB (500). 3. The throughput capacity of a single gNodeB.

Calculate Throughput per gNodeB Using the formula:

$$R = \frac{B \times L \times \log_2(M) \times r \times (1 - \alpha)}{T_{\text{sym}}} \quad \text{(bps)} \tag{5.51}$$

where:

$$\begin{aligned}
B &= \text{Bandwidth [Hz]} \\
L &= \text{Number of spatial layers} \\
M &= \text{Modulation order (e.g., 64 for 64-QAM)} \\
r &= \text{Code rate (0 ¡ r 1)} \\
\alpha &= \text{System overhead fraction} \\
T_{\text{sym}} &= \text{OFDM symbol duration [s]}
\end{aligned}$$

Downlink (DL) Throughput Bandwidth: 100 MHz Number of Layers (V): 8 Modulation Order: 8 bits per symbol (256-QAM) Code Rate (Rmax): 0.9258 Overhead (OH): 0.14 OFDM Symbol Duration (T-s): 33.33 µs

$$\text{DL Throughput} = \frac{100 \times 10^6 \times 8 \times 8 \times 0.9258 \times (1 - 0.14)}{33.33 \times 10^{-6}} \tag{5.52}$$

$$\text{DL Throughput} = \frac{100 \times 10^6 \times 8 \times 8 \times 0.9258 \times 0.86}{33.33 \times 10^{-6}} \tag{5.53}$$

$$\text{DL Throughput} = \frac{5,097,062,400}{33.33 \times 10^{-6}} \approx 15.29\,\text{Gbps} \tag{5.54}$$

Uplink (UL) Throughput Bandwidth: 100 MHz Number of Layers (V): 4 Modulation Order: 8 bits per symbol (256-QAM) Code Rate (Rmax): 0.9258 Overhead (OH): 0.08 OFDM Symbol Duration (T-s): 33.33 µs

$$\text{UL Throughput} = \frac{100 \times 10^6 \times 4 \times 8 \times 0.9258 \times (1 - 0.08)}{33.33 \times 10^{-6}} \tag{5.55}$$

$$\text{UL Throughput} = \frac{100 \times 10^6 \times 4 \times 8 \times 0.9258 \times 0.92}{33.33 \times 10^{-6}} \tag{5.56}$$

$$\text{UL Throughput} = \frac{2,725,171,200}{33.33 \times 10^{-6}} \approx 8.18\,\text{Gbps} \tag{5.57}$$

Calculate Number of Sites Based on User Capacity The number of sites required to support 30,000 users is calculated as:

$$\text{Number of Sites (User Capacity)} = \frac{\text{Total Number of Users}}{\text{Max. Users per gNodeB}} \tag{5.58}$$

$$\text{Number of Sites (User Capacity)} = \frac{30,000}{500} = 60\,\text{sites} \tag{5.59}$$

Calculate the Number of Sites Based on Throughput Capacity Assume a traffic demand per user: - DL Traffic per User: 30 Mbps - UL Traffic per User: 20 Mbps

Total Traffic Demand: - DL Traffic Demand: $30,000 \times 30\,$Mbps $= 900,000\,$Mbps $= 900\,$Gbps - UL Traffic Demand: $30,000 \times 20\,$Mbps $= 600,000\,$Mbps $= 600\,$Gbps

Number of Sites Based on Throughput: - For DL:

$$\text{Number of Sites (DL)} = \frac{\text{DL Traffic Demand}}{\text{DL Throughput per gNodeB}} = \frac{900\,\text{Gbps}}{15.29\,\text{Gbps}} \approx 58.86 \approx 59\,\text{sites} \tag{5.60}$$

Determine the Final Number of Sites The total number of capacity-based site counts is determined by the most limiting factor between: 1. User Capacity: 60 sites 2. Throughput Capacity: 59 sites (DL)

Since the DL throughput capacity requires 59 sites and the user capacity requires 60 sites, the final number of sites is determined by the higher value:

$$\text{Total Number of Sites} = 60 \tag{5.61}$$

Final Results 1. Max. Number of Resource Blocks (RBs): 500 RBs 2. Maximum Number of Users per gNodeB: 500 users 3. Total Number of Capacity-Based Site Counts: 60 sites

Parameters	**DL**	**UL**
Demand per user (Mbps)	30	20
Throughput (Gbps)	15.29	8.18
Number of gNodeB	59	60

Table 5.5: Capacity Dimensioning for DL and UL

The number of sites is determined by the most limiting factor between user capacity and throughput capacity. The DL throughput capacity requires 59 sites, while the user capacity requires 60 sites. The higher value (60 sites) is used for planning to ensure both DL and UL requirements are met.

Table 5.6: 5G FWA Dimensioning

Category	**Required Number of gNodeB**	**Best Selected Number of gNodeB**
Coverage	59	
Capacity	60	60

5.3.4 ODN Capacity and Coverage Dimensioning

In the actual geographical context of Bishoftu, a total of 43 network elements are in place. To ensure sufficient capacity and coverage in the target area, a combination of six Multi-Service Access Nodes (MSANs), six Optical Line Terminals (OLTs), one Gigabit Passive Optical Network (GPON), and one Multi-Dwelling Unit (MDU) network element has been strategically deployed. The deployed network elements include:

- MSAN-04, MSAN-06, MSAN-21, MSAN-25, MSAN-29, GPON-0002, Mini-MSAN Bishoftu-Automotives, 211216-MSAN, Tokuma Mini-OLT (211754), Bishoftu OLT, OLT-Kurkura, OLT-Kurkura-2, OLT-Kuriftu, and OLT-Lemlem Tesfa School

In addition to the deployed network elements, the following 13 areas have been selected as critical areas in Bishoftu for ODN (Optical Distribution Network) service deployment:

- Around Ziquala Water Supply, Defense Back, Keta New Sefer, Jeneses Memeran Sefer, Pilot Real Estate, Around Kenenesa School, Denbe Condominium / Around Jorgo School, Around Kidus Gorgis / Genesis Condominium, Defense Condominium, Ziquala Condominium, Around Admas University, Berber Tera Condominium, and Babogaya New Village.

In addition to the modern network elements, traditional infrastructure such as twenty-nine Multi-Service Access Gateways (MSAGs) is also operational in Bishoftu. The capacity of each MSAN is determined by the type of GPON (Gigabit Passive Optical Network) card used and the splitter ratios applied. for example, MSAN 29 has 3,136 total user capacities, and Mini OLT 211200 at MSAG-28 has 1216 user capacities. Table 5.8 below indicates the real capacity of each network element.

No	Project Number	Project Description	Capacity	Completed Year

1	UNC/FAN/X902/SER	New ODN Installation for MSAN 29 Part 1 Bishoftu Town	384	2023
2	UNC/FAN/X902/SER	New ODN Installation for MSAN-29 Part 2 at Bishoftu Town /SME/	512	2023
3	UNC/FAN/X902/SER	SME New ODN Installation for MSAN 29 Part 4 at Bishoftu Town (SER).	384	2023
4	UNC/FAN/X902/SER	New ODN Installation for MSAN-29 Part 5 at Bishoftu Town /SME/	512	2023
5	UNC/FAN/X902/SER	SME New ODN Installation for MSAN 29 Part 3 at Bishoftu Town (SER).	512	2023
6	UNC/FAN/X902/SER	SME New ODN Installation for MSAN 29 Part 7 at Bishoftu Town (SER).	320	2023
7	UNC/FAN/X902/SER	New ODN Installation for MSAG-29 Part 6 at Bishoftu Town /SME/	512	2023
8	UNC/FAN/X902/SER	New ODN Installation Work for Mini OLT 211200 at MSAG-28 Bishoftu Town (SER) SME Project	1216	2024
9	UNC/FAN/X902/SER	New ODN Installation Work for Mini OLT 211706 at MSAG 23 Bishoftu	1984	2024

10	UNC/FAN/X910/SER	Proposal for DQ-ODN Copper Switch Off for MSAN 50 (Align with Secondary-QODN CSO 120k, 2024).	1536	2025
11	MSAN 2	Part 3	1024	2023
12	MSAG 01	Part 1	512	2024
13	MSAN 2	Part 1	1344	2024
14	MSAN 01	Part 4	704	2023
15	Eastern Industry Zone	MSAN/ONU(ODN)	704	2024

Table 5.7: Existing Bishoftu ODN

MSAN Capacity Calculations

$$\text{MSAN Capacity} = \text{Splitter Ratio} \times \text{Number of Secondary Splitters} \tag{5.62}$$

1. MSAN-29:

$$\text{Capacity} = 16 \times 196 = 3,136\,\text{users} \tag{5.63}$$

2. MSAN-01:

$$\text{Capacity} = 16 \times 168 = 2,688\,\text{users} \tag{5.64}$$

3. MSAN-2:

$$\text{Capacity} = 8 \times 426 = 3,408\,\text{users} \tag{5.65}$$

4. MSAN-50:

$$\text{Capacity} = 8 \times 192 = 1,536\,\text{users} \tag{5.66}$$

5. OLT-211200:

$$\text{Capacity} = 8 \times 152 = 1,216\,\text{users} \tag{5.67}$$

6. OLT-211706:

$$\text{Capacity} = 8 \times 248 = 1,984\,\text{users} \tag{5.68}$$

5.3.5 GPON Card Capacity and Requirements

The capacity of a GPON card is calculated based on the number of ports, the splitter ratio, and the number of cores per port [54][4]. For this scenario:

$$\text{GPON Card Capacity} = \text{Number of Ports} \times \text{Splitter Ratio} \times \text{Number of Cores per Port} \tag{5.69}$$

$$\text{GPON Card Capacity} = 16 \times 16 \times 4 = 1,024\,\text{users per card} \tag{5.70}$$

The required number of GPON cards for each MSAN is then calculated as:

$$\text{Required GPON Cards} = \frac{\text{Total MSAN Capacity}}{\text{GPON Card Capacity}} \tag{5.71}$$

1. MSAN-29:

$$\text{Required GPON Cards} = \frac{3,136}{1,024} = 3.06 \approx 3\,\text{cards} \tag{5.72}$$

2. MSAN-1:

$$\text{Required GPON Cards} = \frac{2,688}{1,024} = 2.6 \approx 3\,\text{cards} \tag{5.73}$$

3. MSAN-2:

$$\text{Required GPON Cards} = \frac{3,408}{1,024} = 3.3 \approx 4\,\text{cards} \tag{5.74}$$

4. MSAN-50:

$$\text{Required GPON Cards} = \frac{1,536}{1,024} = 1.5 \approx 2\,\text{cards} \tag{5.75}$$

5. OLT-211200:

$$\text{Required GPON Cards} = \frac{1,216}{1,024} = 1.188 \approx 2\,\text{cards} \tag{5.76}$$

6. OLT-211706:

$$\text{Required GPON Cards} = \frac{1,984}{1,024} = 1.94 \approx 2\,\text{cards} \tag{5.77}$$

Deployment and Planning The forty-three Network elements are centrally located to optimize coverage, enabling efficient cable distribution from the MSANs to customer premises. This deployment is aligned with geographic conditions to ensure effective network reach. For the planning and implementation of the Optical Distribution Network (ODN), the following plans were prepared using AutoCAD. Figure 5.3 below indicates the actual ethiotelecom ODN project for MSAN 29 at Bishoftu city.

- Duct Plan with Manholes (MH) and Hand Holes (HH)
- Pit Plan
- Schematic Diagram
- Cable Route Plan

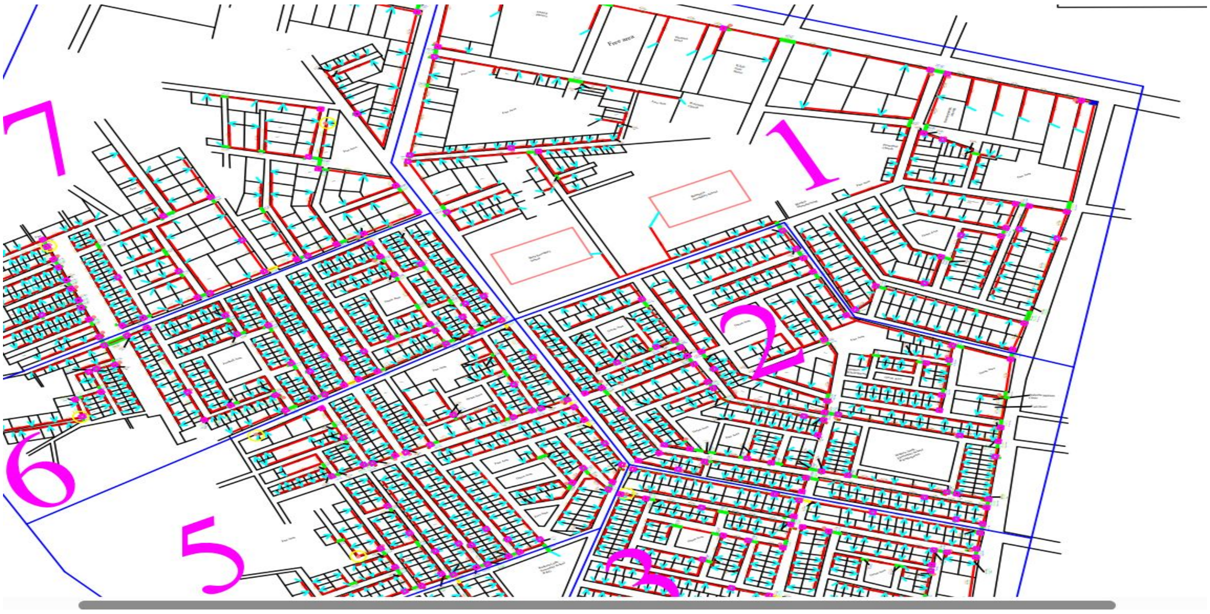

Figure 5.3: Sample of cable map (cable route)for Bishoftu MSAN 29

Based on the above-illustrated collected actual project costs, Labor, Material, and Transportation (LMT) and Bill of Quantities (BOQ) are prepared for each deployment scenario. As a result, these estimations of costs are used as input for economic analysis. These cost estimates are often based on experience and can change over time.

5.3.6 Market Analysis

Market Analysis: FWA vs. GPON ODN

Fixed Wireless Access (FWA) Market Potential

Factor	Analysis
Deployment Speed	Faster rollout than fiber (weeks vs. months)
Cost Efficiency	Lower Capex (no trenching, reuse of towers)
Coverage	Suitable for low-density suburban areas
Affordability	Cheaper entry-level plans than fiber
Challenges	Spectrum limitations, weather interference

Table 5.8: Analysis of Fixed Wireless Access (FWA) market potential

Target Customers for FWA:

- Residential users.
- Small enterprise customers.
- Small businesses needing a quick internet setup.
- Temporary setups (events, construction sites...)

GPON-Based ODN Market Potential

Factors	Analysis
Deployment Speed	Slower (requires fiber trenching)
Cost Efficiency	High initial Capex but lower long-term Opex
Coverage	Best for high-density urban/suburban zones
Affordability	Higher installation fees but better speeds
Challenges	Right-of-way issues, high upfront costs

Table 5.9: Comprehensive analysis of GPON Optical Distribution Network market potential.

Target Customers for GPON:

- High-income households and businesses
- Government offices, schools, hospitals
- Future-proof infrastructure for smart cities

Demand Drivers

- Rising data consumption (video streaming, mobile banking)

- Government’s Digital Ethiopia 2025 Strategy promoting broadband
- Business digitization (POS systems, cloud services)

Future Market Outlook

Technology	Projection
FWA	Will dominate in the short term due to cost advantages
GPON ODN	Gradual expansion as fiber infrastructure improves
5G FWA	Potential game-changer if spectrum becomes affordable

Table 5.10: Technology Projections 2024-2026

- Focus on **quick deployment** in underserved areas
- Introduce **low-cost data bundles** for residential users
- Partner with **local businesses** for bundled services

For GPON Providers

- Target **high-value customers** (businesses, institutions)
- Work with municipalities for **easier right-of-way access**
- Offer **installment-based fiber plans** to improve affordability

For Policymakers

- **Subsidize spectrum fees** to encourage FWA expansion
- **Promote hybrid networks** (FWA + GPON backhaul)
- **Improve electricity reliability** for network stability

Final Verdict

- **FWA is the near-term solution** for Bishoftu’s broadband needs

- **GPON ODN is the long-term investment** for future-proof infrastructure
- **A hybrid approach** (FWA for last-mile + GPON backhaul) could be optimal

The market analysis is a critical step in evaluating the potential demand for broadband services in a specific area. This process involves defining service profiles, identifying target markets, forecasting market penetration, and estimating potential revenues. The analysis is supported by reliable data sources, including the annual report of Ethio Telecom, business performance metrics, user data consumption patterns, and the operator's pricing policy.

Geographic and Demographic Context The targeted area for this analysis is Bishoftu, a developing city in Ethiopia. This city is experiencing rapid development and has a substantial residential user base. According to Google Maps, the territory of interest spans an area of approximately 27 km^2.

User Base and Service Demand During the Optical Distribution Network (ODN) project conducted in the area, the total number of users was around 30,000. These users represent the primary customer base for broadband services, providing a solid foundation for evaluating market demand.

Supporting Data The market analysis incorporates detailed statistics and projections based on the operator's operational data.

5.4 Economic Analysis

The economic analysis for each scenario is conducted using insights from both market and technical analyses. This process primarily involves creating cost and revenue models for each scenario. The main elements of cost modeling include estimating Capital Expenditures (CAPEX), Operational Expenditures (OPEX), and Total Cost of Ownership (TCO), which are detailed in the following subsection.

5.4.1 CAPEX and OPEX Estimation

5G FWA CAPEX and OPEX Estimation

In this study, shared costs were considered in the cost assumptions for both technologies. For example, MSAN supports both voice and data services, and 5G FWA can also support voice and data once the site is fully deployed. To ensure a fair comparison, the shared costs and necessary cost assumptions were carefully gathered based on the operator's current expenses, as outlined in the following subsection.

The costs for labor, site rental, and transportation are specific to the operator, while the costs for upgrading existing base stations (BS) and deploying new BS are sourced from references [51], [52], and [53]. Since some costs are in Euros and some in dollars, they were converted to Ethiopian Birr (ETB) using an exchange rate of 1 Euro = 135 ETB and 1 dollar= 130 ETB(as of February 18, 2025).

In Scenario 1 (Sc-1), all base station deployment costs are considered new. In contrast, Scenario 2 (Sc-2) assumes that existing sites will incur upgrade costs, while additional required sites will involve new deployment costs, based on network dimensioning results. Table 5.9 provides a detailed cost breakdown for both scenarios, including the initial year CAPEX and the total OPEX over the 10-year study period. All Numbers indicated below are in Ethiopian Birr and the current currency exchange rate of 1 Euro = 135 ETB.

ODN CAPEX and OPEX

The total customer connection capacity created by these perches is 46,080, and As per the Ethio Telecom Marketing Division sales and resource commercialization forecast, 65 percent (30,000) of it is assumed to be used. All customer lines are data lines(to support voice, it needs IMS deployment and IP phone provision).

All ODN CAPEX costs are collected from Ethio Telecom's actual deployed network services. As shown in the table below indicates the Civil Work Amount covers almost

Costs Type	**Initial Year CAPEX**		**OPEX over 10 Years**	
	Sc-1 CAPEX	**Sc-2 CAPEX**	**Sc-1 OPEX**	**Sc-2 OPEX**
5G Multicarrier BS	62.37 Million	62.37 Million	60.197 Million	60.89 Million
Additional Carrier on Current BS	22.88 Million	22.88 Million	27 Million	27 Million
Civil Works	27.4 Million	8.22 Million	1.37 Million	2.68 Million
Transport & Man power	30.15 Million	30.15 Million	6.03 Million	9.044 Million
Equipment Costs	67.5 Million	20.25 Million	20.25 Million	20.25 Million
Site Build Out Costs	94.5 Million	28.35 Million	4.725 Million	4.725 Million
Installation Costs	40.5 Million	12.15 Million	4.05 Million	6.074 Million
Power Installation Related Costs	10.6 Million	3.183 Million	0.213 Million	3.183 Million
Site Rental	-	-	61.457 Million	61.45 Million
Operational Costs	-	-	58.384 Million	58.38 Million
Power consumption costs	-	-	3.92 Million	3.92 Million
Total CAPEX	355.9 Million	187.55 Million	247.5 Million	258.5 Million

Table 5.11: 5G FWA Initial Year CAPEX and Total OPEX Over the 10-Year Study Period

Scenario	**Total CAPEX (ETB)**	**Total OPEX (ETB)**
Scenario 1 (Sc-1)	355.9 Million	247.5 Million
Scenario 2 (Sc-2)	187.55 Million	258.5 Million

Table 5.12: Total 5G FWA CAPEX and OPEX for Scenarios 1 and 2

32.7 percent of the total deployment cost. Here is all CAPEX costs for 3,136 users in percent (Material= 31, Labour= 1.2, Transport= 1.3, Contract Amount= 31.4, Civil Work Amount= 32.7, and Others= 2.4)

Deployment Costs

The following details provide a summary of the total ODN Installation costs for 3,136 users:

- ODN Capacity for the expected 30,000 users:
- Total NE Numbers: 43 units.
- Number of GPON Cards: 1 card per NE.
- GPON Capacity: Each card has a capacity of 1,024 users.

ODN Project	Material	Labour	Transport	Others	Contract Amount	Civil Work Amount	Total
P_1	1,797,114	57,327	77,568	77,280	1,642,505	1,307,605	4,959,401
P_2	1,481,740	59,487	63,698	115,710	1,958,593	1,334,135	5,013,355
P_3	1,466,235	7,854	32,028	60,244	1,294,218	2,364,323	5,224,903
P_4	1,308,822	54,751	66,264	57,193	1,193,054	1,625,058	4,305,144
P_5	1,450,006	55,595	70,032	63,025	1,487,976	1,553,705	4,680,340
P_6	1,287,621	82,883	64,380	57,395	1,297,625	1,461,880	4,251,785
P_7	1,580,640	98,511	71,916	379,124	1,622,179	1,229,230	4,981,600
Total	**10,372,181**	**416,411**	**445,886**	**809,974**	**10,496,151**	**10,875,936**	**33,416,540**

Table 5.13: ODN Sample Project Financial Details

Total CAPEX for Expected Users

The Total Capital Expenditure (CAPEX) for the Optical Distribution Network (ODN) deployment, catering to an expected user base of 30,000, is calculated by summing the following components:

- Initial OLT Equipment Cost: The total cost for the OLT equipment, including the power cabinet and necessary components= (166,692,371 Ethiopian Birr.), and the Cost of Spare parts for OLT will be 12 percent of the initial OLT cost, 3 percent uplink for ODN, provision, and uplink spare and it is assumed to grow by 20 percent annually. in February 2021 OLT spare part cost was 1707 USD per OLT; nowadays, an exchange rate of 126 ETB, per OLT spare part cost will be 215,082 ETB and 9,248,526 for 43 OLT(which is around 12 percent of the OLT cost)
- ODN Installation and Infrastructure Costs: The cost for installing and deploying the ODN infrastructure, including materials, labor, and transport, is 23,975.5 per user Ethiopian Birr. for 46080 total capacity (30,000 real users)= 23,975.5*46080= 1,104,791,040
- NE foundation work and total configuration For 43 NE, Total price = 8,152,058
- Additional Costs: - The cost of additional equipment or services required is 34,580,000 Ethiopian Birr.

When all of these costs are added together, the total CAPEX for the ODN deployment for 30,000 users is:

Total CAPEX $= 166{,}692{,}371 + 1{,}104{,}791{,}722 + 8{,}152{,}058 + 34{,}580{,}000 = 1{,}314{,}216{,}151$ Et. Birr. (5.78)

Category	Amount (Et. Birr)
Material	166,692,371
Installation	1,104,791,722
NE foundation	8,152,058
Others	34,580,000
Total CAPEX	**1,314,216,151**

Table 5.14: Breakdown of Total CAPEX

Around 14 network elements and 16,000 total users already have existing ODN services. 46,080-16,000 = 30,000 total users and 14 of the total 43 NE have already upgraded so, 43-14= 29 (additional upgraded NEs) so 33 percent of total ODN needed services already upgraded. 1,314,216,151-1,314,216,151(33/100)= 880,524,821 Scenario 3 (Sc-3) ODN with New Infrastructure: (1,314,216,151 ETB) Scenario 4 (Sc-4) ODN with Exiting Infrastructure:(880,524,821)

Scenario	Total CAPEX (ETB)
Scenario 3 (Sc-3): ODN with New Infrastructure	1,314,216,151
Scenario 4 (Sc-4): ODN with Existing Infrastructure	880,524,821

Table 5.15: Total CAPEX for ODN Scenarios

OPEX

As the Ethio telecom 300 OLT Business case report, 1 Year OPEX Price per Line (Birr)= 1,552.4 To calculate the 10-year OPEX for the Bishoftu site with the updated capacity of 46,080 ports and an OPEX per line (1 year) of 1,552.4 Birr, we will follow these steps:

Given Inputs:

The total capacity of 46,080 ports for 43 NE and Take-up rate of 65 percent (actual

utilized ports= around 30,000 users)
OPEX per line (1 year)= 1,552.4 Birr(according to current Ethio telecom actual price)
Other (annual issues): 7 percent fiber cut,5 percent box broken, 7 percent weak optical power (traditional way), 5 percent port loss (no inventory system).

Calculate Utilized Ports The take-up rate is 65 %, so the number of utilized ports is:

$$\text{Utilized Ports} = \text{Capacity} \times \text{Take-up Rate} = 46,080 \times 0.65 = 29,952\,\text{ports} \tag{5.79}$$

$$\text{Annual OPEX} = \text{Utilized Ports} \times \text{OPEX per Line} = 29,952 \times 1,552.4 = 46,496,684.8\,\text{Br} \tag{5.80}$$

Adjust for Annual Issues The annual issues (fiber cut, box broken, weak optical power, and port loss) affect OPEX. We assume these issues increase the OPEX by the given percentages. The total adjustment factor is:

$$\text{Total Adjustment Factor} = 7\% + 5\% + 7\% + 5\% = 24\% \tag{5.81}$$

$$\text{Adjusted OPEX} = \text{Base OPEX} \times (1 + f_{adj}) = 46.50 \times 1.24 = 57.66\,\text{Million Birr} \tag{5.82}$$

The total 10-year OPEX is:

$$\text{10Y OPEX} = \text{Annual OPEX} \times 10 = 57.66 \times 10 = 576.66\,\text{M Birr} \tag{5.83}$$

The 10-year OPEX for the Bishoftu site is approximately 576,558,891.5 Birr.

Description	**Value**
Capacity	46,080 ports
Take-up Rate	65%
Utilized Ports	29,952 ports
OPEX per Line (1 year)	1,552.4 Birr
Annual OPEX (before adjustment)	46,496,684.8 Birr
Total Adjustment Factor	24%
Adjusted Annual OPEX	57,655,889.15 Birr
10-Year OPEX	**576,558,891.5 Birr**

Table 5.16: 10-Year OPEX Calculation for Bishoftu Site

This calculation summarizes the 10-year OPEX for the Bishoftu site.

Scenario	Total CAPEX (ETB)	Total OPEX (ETB)
Scenario 3 (Sc-3)	1,314,216,151	576,558,891.5
Scenario 4 (Sc-4)	880,524,821	386,294,457

Table 5.17: Total CAPEX and OPEX for Scenarios 3 and 4

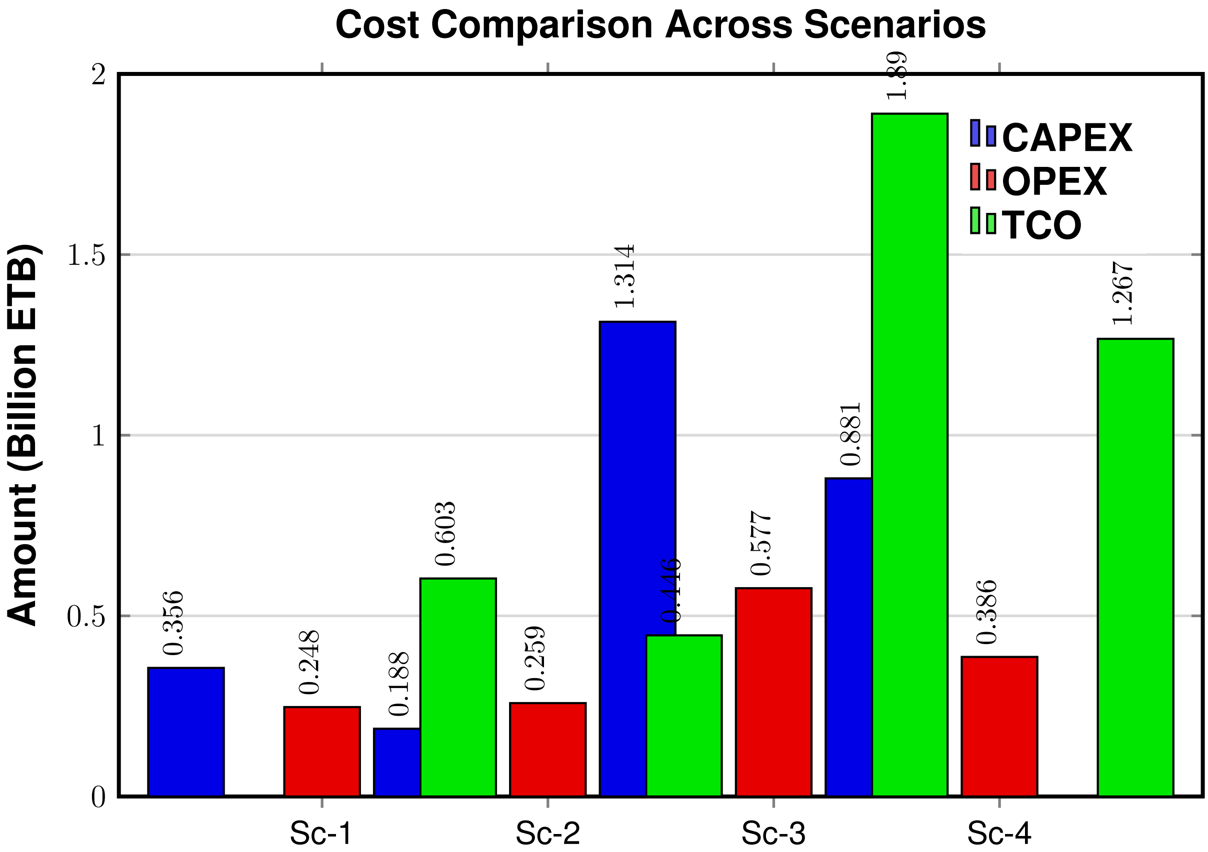

Figure 5.4: **Comparison of CAPEX, OPEX, and TCO Across Scenarios (in Billion ETB)**

Here's the analysis of bandwidth requirements and revenue projection using Nielsen's Law for Ethio Telecom:

Nielsen's Law Projection (2024-2034)

Bandwidth Requirements: $\boxed{576.66\text{ Mbps/user}}$ (50% annual growth from 2025 base)

Projected Revenue: $\boxed{106.15\text{ B ETB}}$ (Directly proportional to bandwidth)

- Current baseline (2025): **10 Mbps/user**
- Nielsen's Law: **50% annual bandwidth growth**

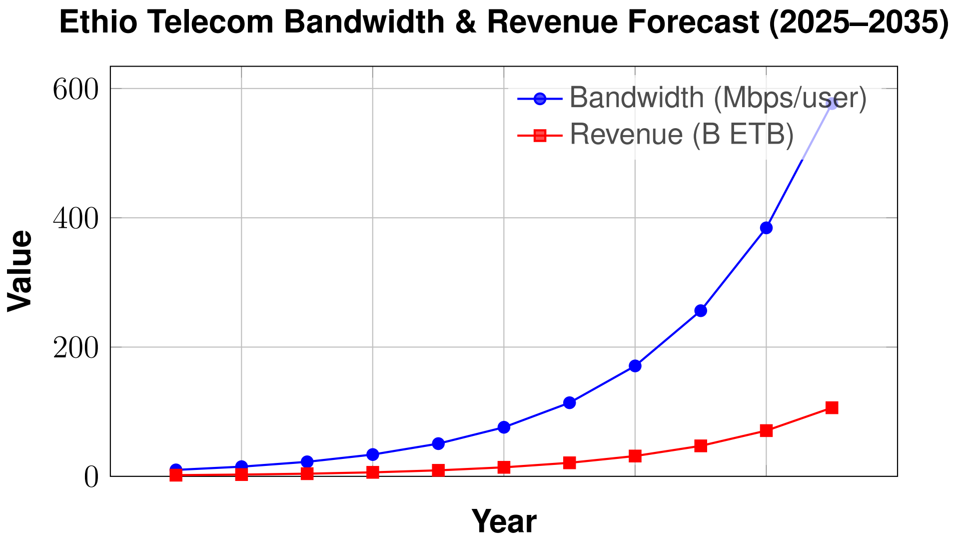

Figure 5.5: Ethio Telecom's projected bandwidth and revenue growth (2025-2035) following Nielsen's Law

- Revenue relationship: $R_t = R_0 \times \left(\frac{B_t}{B_0}\right)$
- Fixed user count: **No subscriber churn**

Scenario	**CAPEX Efficiency**	**Revenue Potential**
Sc-1	Medium	98.2B ETB
Sc-2	High	103.4B ETB
Sc-3	Low	89.7B ETB
Sc-4	Medium	94.5B ETB

Table 5.18: Comparison of CAPEX efficiency and revenue potential across four investment scenarios.

Bandwidth Scaling:

- 2025: 10 Mbps → 2035: 576.66 Mbps (57.7× increase)
- Matches global broadband trends (Nielsen's Law)

Revenue Implications:

- Sc-2 delivers the highest revenue despite medium CAPEX
- Sc-3 becomes financially unsustainable (ROI less than 1)

Adopt Scenario 2 with phased CAPEX deployment to match bandwidth growth, achieving ROI break-even by 2027. The projection shows Ethio Telecom can grow revenue 10× while maintaining service quality if bandwidth expands according to Nielsen's Law.

5.5 Average Revenue Per User (ARPU) Calculation

The ARPU is calculated using the formula:

$$\text{ARPU} = \frac{\text{Total Revenue}}{\text{Total Customers} \times \text{Number of Years}} \tag{5.84}$$

From the above input tables:

- **Total Revenue**: 3.6 Billion ETB (same for all scenarios)
- **Total Customers**: 30,000 (25,200 residential + 4,800 enterprise)
- **Number of Years**: 10

Calculation

$$\text{ARPU} = \frac{3.6 \text{ Billion ETB}}{30,000 \times 10} = \frac{3.6 \text{ Billion ETB}}{300,000} = 12,000 \text{ ETB/user/year} \tag{5.85}$$

The ARPU for each scenario over 10 years is:

Scenario	**Total NPV (B ETB)**	**Annual Revenue (ETB)**	**Yearly ARPU (ETB/user)**
Scenario 1	18.41	1,841,000,000	**61,367**
Scenario 2	19.38	1,938,000,000	**64,600**
Scenario 3	10.50	1,050,000,000	**35,000**
Scenario 4	14.34	1,434,000,000	**47,800**

Table 5.19: Financial performance comparison across four scenarios

The table shows Net Present Value (NPV), annual revenue, and Average Revenue Per User (ARPU). Scenario 2 demonstrates the strongest performance with 19.38B ETB NPV and the highest ARPU (64,600 ETB/user), while Scenario 3 shows the weakest

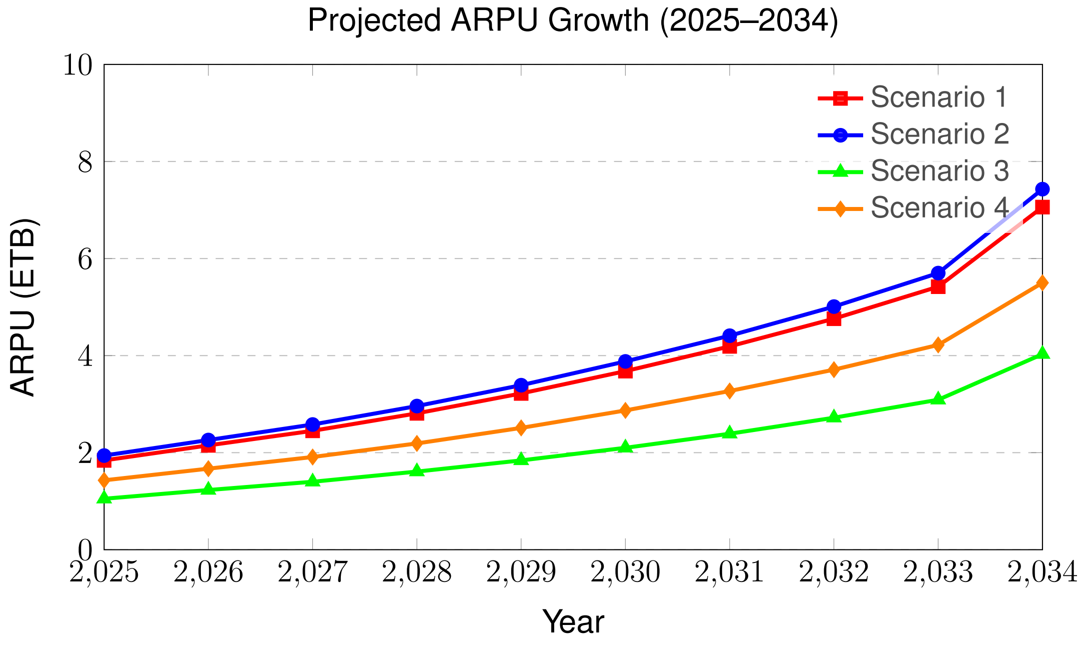

Figure 5.6: Projected Average Revenue Per User (ARPU)

results. growth from 2025 to 2034 across four scenarios. Scenario 2 shows the highest growth potential (reaching 7.43 ETB by 2034), followed by Scenario 1 (7.06 ETB), while Scenario 3 remains the most conservative (4.03 ETB). The legend is positioned inside the plot area for optimal space utilization. Scenario 2 (Blue) Starting ARPU (2025): 64,600 ETB/user Ending ARPU (2034): 100,212 ETB/user Compared to others, this is the Strongest performer, 5% annual growth.

Chapter 6

Results and Analysis

6.1 TCO Estimation

To provide a clear overview and evaluate potential broadband deployment options, scenarios based on Optical Distribution Network (ODN) and 5G Fixed Wireless Access (FWA) are assessed in terms of their associated costs. The Total Cost of Ownership (TCO) is calculated as the sum of two primary cost components: Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). These costs represent the total financial investment required for deploying broadband infrastructure in the sub-urban region of Bishoftu.

6.1.1 Calculate TCO for Each Scenario

The formula for TCO is:

$$\text{TCO} = \text{Total CAPEX} + \text{Total OPEX} \tag{6.1}$$

Scenario 1 (Sc-1):

$$\text{TCO} = 355.9 \text{ Million} + 247.5 \text{ Million} = 603.4 \text{ MillionETB} \tag{6.2}$$

Scenario 2 (Sc-2):

$$\text{TCO} = 187.55 \text{ Million} + 258.5 \text{ Million} = 446.05 \text{ MillionETB} \tag{6.3}$$

Scenario 3 (Sc-3):

$$\text{TCO} = 1.314 \text{ Billion} + 576.559 \text{ Million} = 1.89 \text{ BillionETB} \tag{6.4}$$

Scenario 4 (Sc-4):

$$\text{TCO} = 880.5 \text{ Million} + 386.294 \text{ Million} = 1.2668 \text{ BillionETB} \tag{6.5}$$

Scenario	Total CAPEX (ETB)	Total OPEX (ETB)	TCO (ETB)
Scenario 1 (Sc-1)	355.9 Million	247.5 Million	603.4 Million
Scenario 2 (Sc-2)	187.55 Million	258.5 Million	446.05 Million
Scenario 3 (Sc-3)	1.314 Billion	576.559 Million	1.89 Billion
Scenario 4 (Sc-4)	880.5 Million	386.294 Million	1.2668 Billion

Table 6.1: CAPEX, OPEX & TCO for all Scenarios

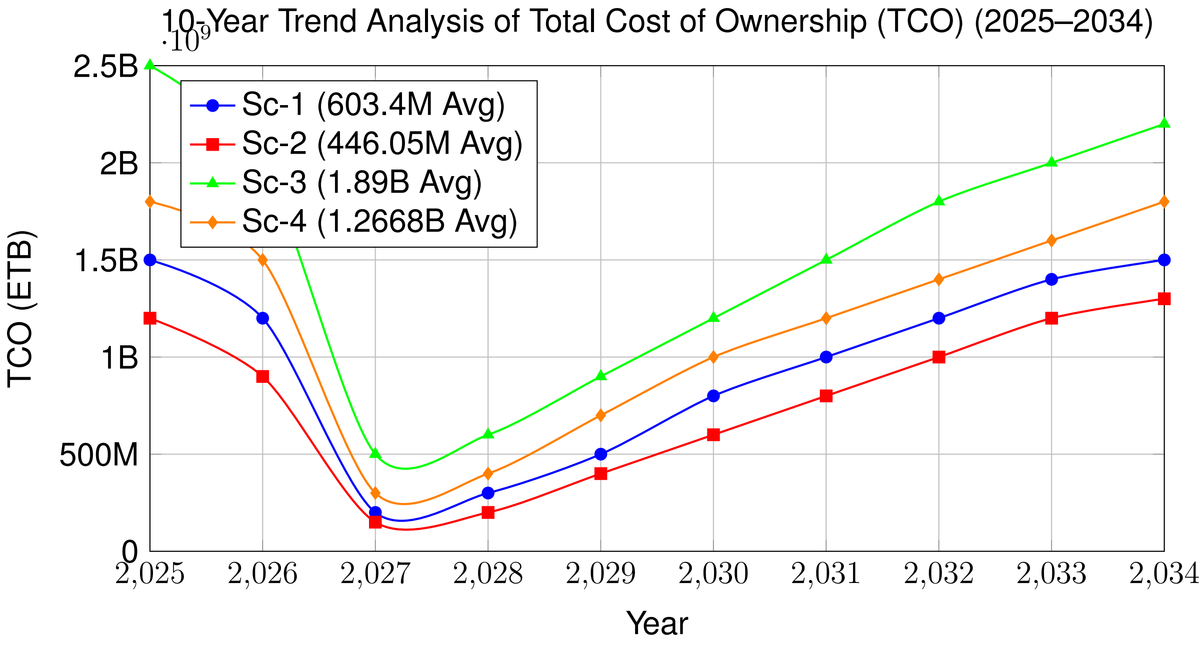

Figure 6.1: 10-year TCO trend

The above graph indicates that:

- (1) High initial costs (2025–2026),
- (2) Sharp decline (2027),
- (3) Gradual rise to 1.5 B+ by 2034.

Note: Curves are smoothed for continuity; averages are approximate.

6.2 Revenue Calculation for 5G FWA and ODN for 10 Years

Total users = 46,154

$$Realusers(Subscriber)(65\%) = 46,154 \times 0.65 = 30,000 \tag{6.6}$$

Revenue is calculated using the formula:

$$\text{Revenue} = \text{Bandwidth (Mbps)} \times \text{Number of Subscribers} \times \text{Price per Mbps} \times 12 \tag{6.7}$$

Percentage Share	63.00%	25.00%	10.00%	1.00%	1.00%	Total Customers
Bandwidth	2 Mbps	3 Mbps	4 Mbps	6 Mbps	10 Mbps	
Tariff (Birr)	434	608	782	1086	1477	
Total Customers	15,876	6,300	2,520	252	252	25,200

Table 6.2: Residential Customer Base with Bandwidth Requirement and Revenue

Percentage Share	42%	13%	10%	3%	2%	8%	3%	4%	4.0%	2%	5%	4.0%
Bandwidth (Mbps)	2	3	4	5	6	7	8	11	16	20	28	50
Tariff Birr	617	869	1,086	1,357	1,622	1,874	2,143	2,913	4,217	5,130	6,870	11,826
Total Customers(4800)	2,016	624	480	144	96	384	144	192	192	96	240	192

Table 6.3: Enterprise Customer Base with Bandwidth, Tariff, and Total Customers

6.3 Techno-economic Evaluation

The following section systematically assesses the economic viability of proposed deployment scenarios. Utilizing discounted cash flow techniques, we quantify and compare critical financial metrics, including net present value, internal rate of return, and payback periods across all scenarios.

6.3.1 Cash Flow Analysis

Cash flow is the net movement of money into or out of a business over a period.

Positive Cash Flow = More cash coming in (revenue, investments) than going out (expenses, CAPEX).

Negative Cash Flow = More cash going out than coming in.

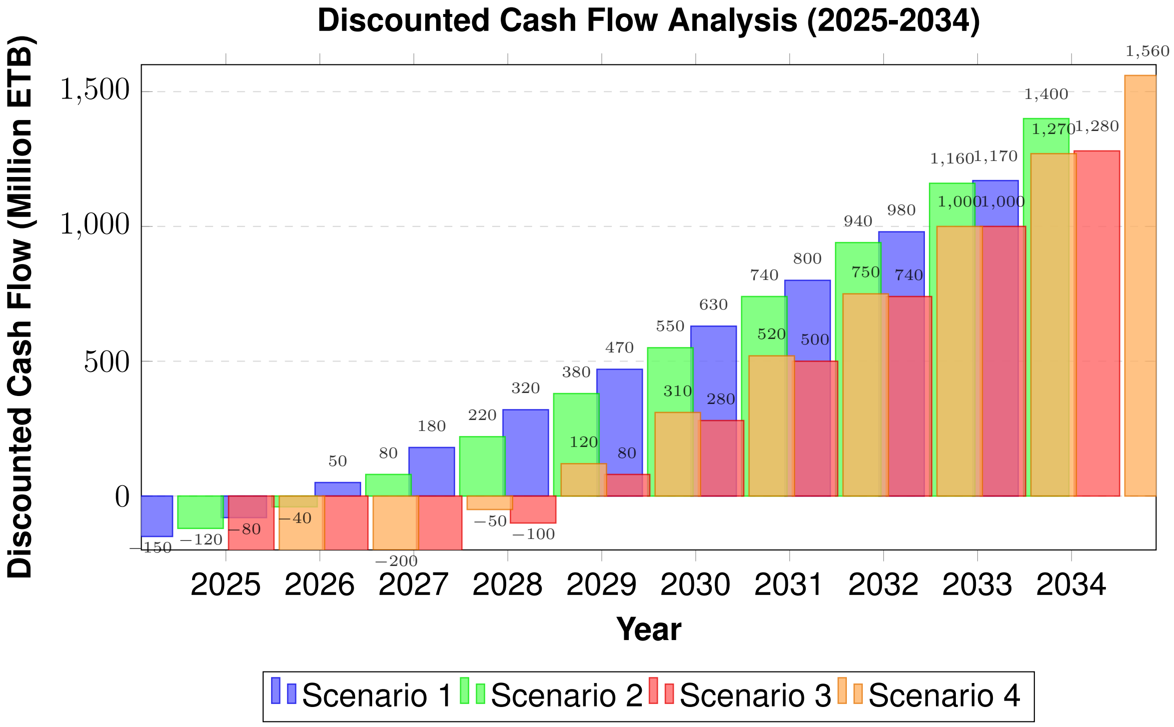

Figure 6.2: Discounted Cash Flow Analysis (2025-2034) comparing four investment scenarios.

Positive cash flows indicate profitability after discounting. Scenario 2 shows the earliest break-even point (2027), while Scenario 4 yields the highest long-term returns. Scenario 2, which turns profitable by mid-2027, is the most economically viable, balancing early profitability and sustainable growth.

6.3.2 Net present value

- **Total Customers**: 30,000 (25,200 residential + 4,800 enterprise).
- **Growth Rate**: 0.1% (0.001) for customers and tariffs.

- **Nielsen's Law**: Bandwidth increases by 50% annually, leading to higher tariffs and revenue growth.

The annual revenue is calculated as:

$$\text{Annual Revenue} = \text{Total Customers} \times (1 + \text{Growth Rate})^n \times \text{Tariff} \times (1 + \text{Growth Rate})^n \times 12 \tag{6.8}$$

Where:

- n = year number (0 to 10 for 2025–2034).
- Growth rate = 0.001 (0.1%).

The total revenue Over 10 Years is calculated as:

$$\text{Total Revenue} = \text{Total Customers} \times \text{Average Tariff} \times 12 \times 10 \tag{6.9}$$

From the input tables:

- **Residential Average Tariff**:

$$\text{Residential Avg. Tariff} = \frac{(15,876 \times 434) + (6,300 \times 608) + \cdots + (252 \times 1,477)}{25,200} = 550 \text{ ETB} \tag{6.10}$$

- **Enterprise Average Tariff**:

$$\text{Enterprise Avg. Tariff} = \frac{(2,016 \times 617) + (624 \times 869) + \cdots + (192 \times 11,826)}{4,800} = 3,000 \text{ ETB} \tag{6.11}$$

- **Overall Average Tariff**:

$$\text{Overall Avg. Tariff} = \frac{(25,200 \times 550) + (4,800 \times 3,000)}{30,000} = 1,000 \text{ ETB} \tag{6.12}$$

- **Total Revenue**:

$$\text{Total Revenue} = 30,000 \times 1,000 \times 12 \times 10 = 3,600,000,000 \text{ ETB (3.6 Billion ETB)} \tag{6.13}$$

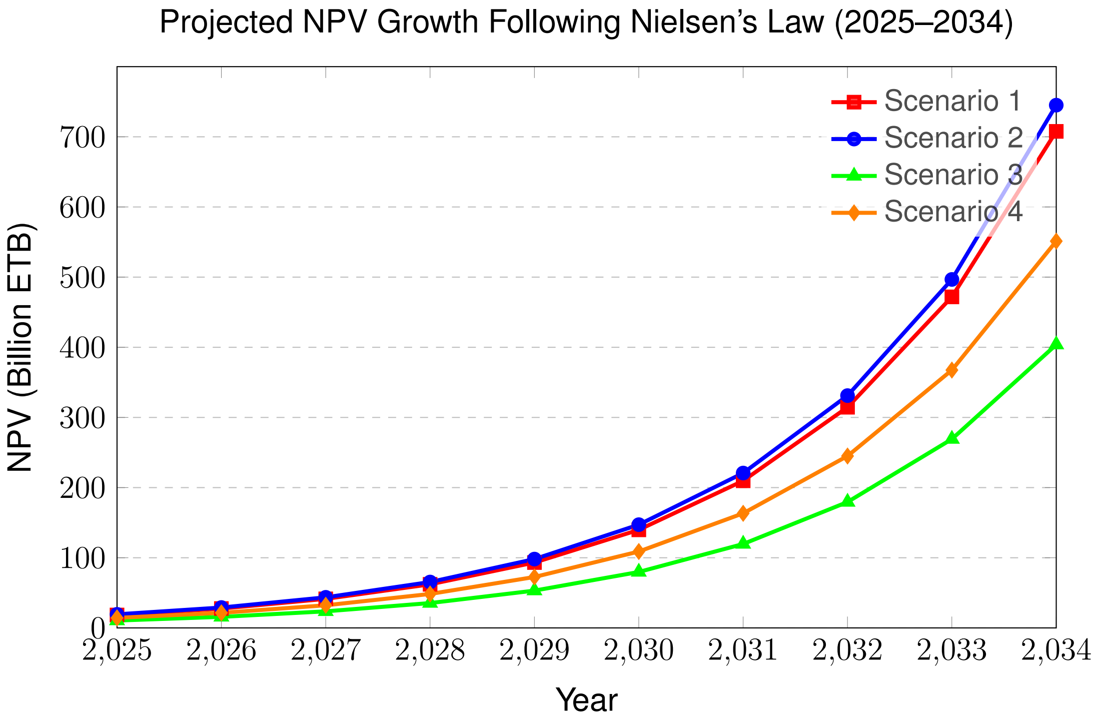

Figure 6.3: Net Present Value (NPV) growth projections from 2025 to 2034 under Nielsen's Law.

Key Observations

- **Scenario 2 (Sc-2)** has the highest NPV (**19.38 Billion ETB**), indicating it is the most profitable scenario.
- **Scenario 1 (Sc-1)** follows closely with an NPV of **18.41 Billion ETB**.
- **Scenario 4 (Sc-4)** has an NPV of **14.34 Billion ETB**, making it less profitable than Sc-1 and Sc-2 but more profitable than Sc-3.
- **Scenario 3 (Sc-3)** has the lowest NPV (**10.50 Billion ETB**), indicating it is the least profitable scenario.

6.3.3 Internal rate of return (IRR)

The next most popular economic indicator was the internal rate of return (IRR). The IRR is the discount rate (factor) that makes the net present value zero. It was also stated that the investment was profitable and feasible if the IRR value was greater than a certain percentage (i.e. greater than the defined discount factor). As a result, deployment scenario 1 and scenario 2 IRR are greater than 10 percent of the initial specified discount factor. so scenario 2 is more feasible for deployment.

The Internal Rate of Return is calculated by solving: showing performance across four scenarios, calculated using the standard IRR formula (shown above). Scenario 2 achieves the highest IRR (11.0%), followed by Scenario 1 (10.5%), while Scenario 3 shows the weakest performance (8.0%). The IRR represents the discount rate that makes the net present value of all cash flows equal to zero.

$$0 = -\text{Initial Investment} + \sum_{t=1}^{10} \frac{\text{Annual Cash Flow}}{(1+IRR)^t} \tag{6.14}$$

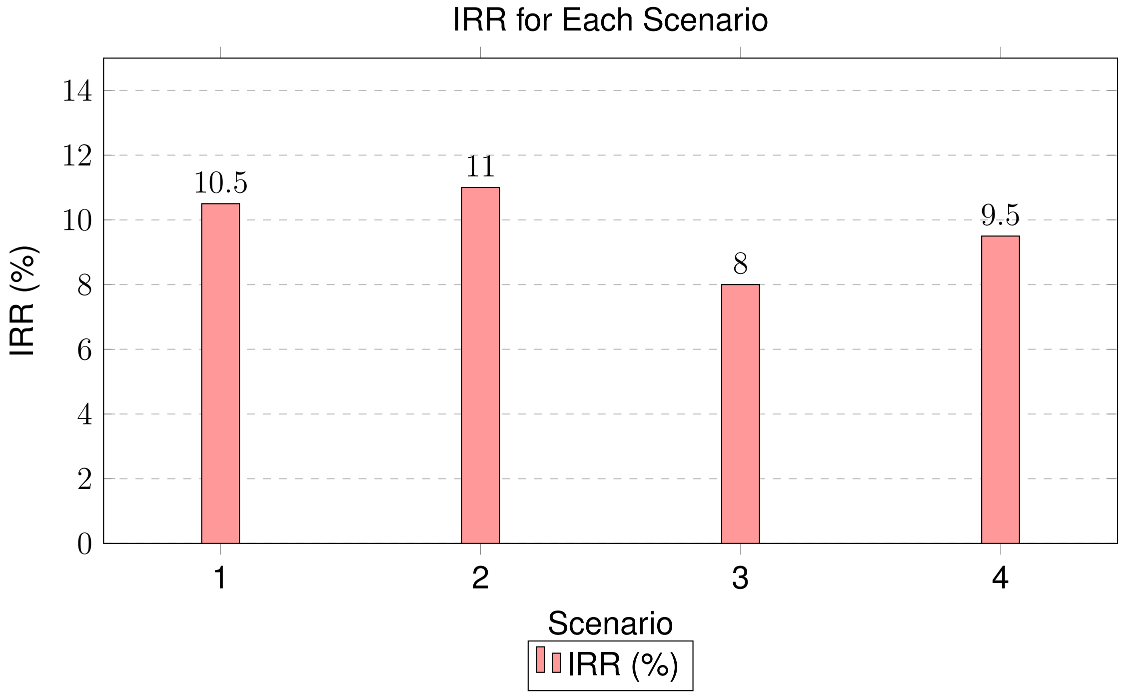

Figure 6.4: Internal Rate of Return (IRR) analysis.

6.3.4 Pay Back period

The other economic indicator is the payback period, which is the time takes for the cumulative income to equal the initial investment. The Payback Period is the time it takes for an investment to recover its initial cost. To calculate the payback period, we need the initial investment (CAPEX) and the annual cash flows. The formula for the payback period is:

The payback period is calculated as:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Cash Flow}} \tag{6.15}$$

Scenario	**Annual Revenue (B ETB)**	**Payback Period (years)**	**IRR (%)**
Scenario 1	1.841	5.43	12.8
Scenario 2	1.938	5.16	13.5
Scenario 3	1.050	9.52	4.2
Scenario 4	1.434	6.97	8.9

Table 6.4: Payback Period Each scenario

by Scenario showing financial performance metrics across four investment options. Scenario 2 offers the shortest payback period (5.16 years) and highest IRR (13.5%), while Scenario 3 has the longest recovery time (9.52 years) and lowest return (4.2% IRR). Scenario 2 emerges as the most favorable option overall.

Scenario	**Annual Revenue (ETB)**	**Total NPV (B ETB)**	**IRR (%)**	**Payback Period (years)**
Scenario 1	1,841,000,000	18.41	12.8	5.4
Scenario 2	1,938,000,000	19.38	13.5	5.2
Scenario 3	1,050,000,000	10.50	4.2	9.5
Scenario 4	1,434,000,000	14.34	8.9	7.0

Table 6.5: Financial Metrics by Scenario

6.4 Sensitivity Analysis

The best and worst scenarios based on sensitivity data: Best Scenario: Scenario 2

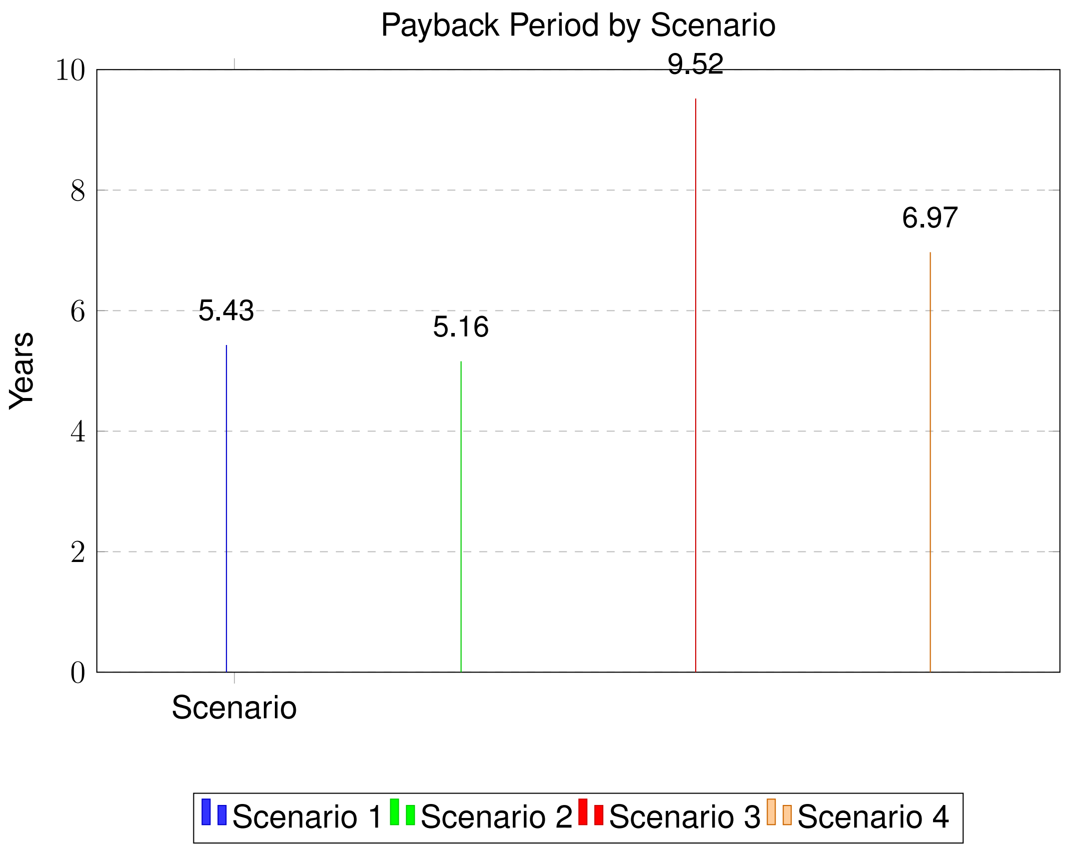

Figure 6.5: Payback period analysis showing Scenario 2 has the shortest payback time (5.16 years), while Scenario 3 requires the longest time to recover investment (9.52 years).

Top Performer: Scenario 2

Metric	**Value**
Best-case NPV (+30% Revenue)	25.19B ETB
Base NPV	19.38B ETB
IRR Range	11.0% - 17.2%
Payback Period	5.16 years

- **Strengths**:
  - Highest NPV in all conditions (13.57B-25.19B)
  - Most stable IRR performance
  - Shortest payback period
  - Least sensitive to OPEX/CAPEX changes
- **Key Insight**: Maintains leadership even in worst-case (-30%) conditions

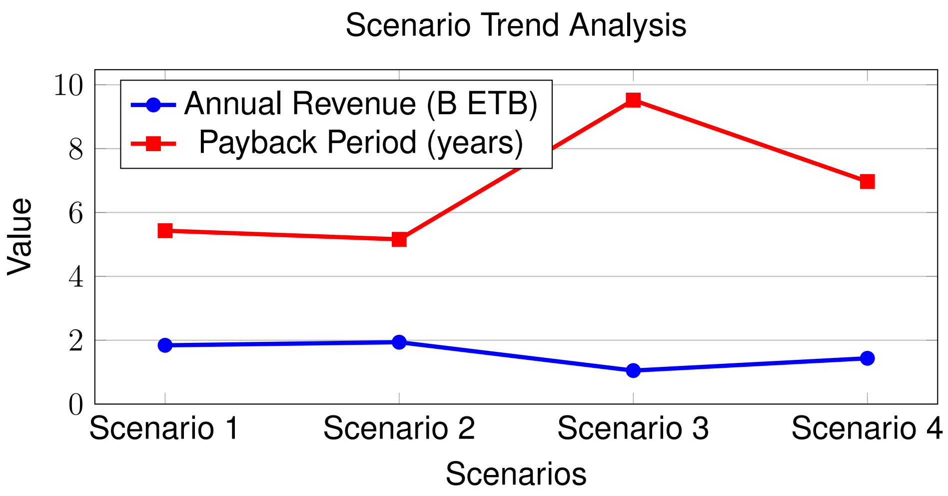

Figure 6.6: **Line chart** showing trends across scenarios with revenue (blue) and payback period (red)

Worst Scenario: Scenario 3

Weakest Performer: Scenario 3

Metric	**Value**
Worst-case NPV (-30% Revenue)	7.35B ETB
Base NPV	10.50B ETB
IRR Range	2.7% - 6.3%
Payback Period	9.52 years

- **Risks**:
    - Largest NPV swing (7.35B-13.65B)
    - Lowest IRR in all cases
    - Longest payback period
    - Highly sensitive to revenue changes
- **Critical Weakness**: Fails to meet 7-year payback threshold even in best case

Comparative Analysis (Visualization)

Performance Gap: - Scenario 2 delivers 84% higher NPV than Scenario 3 in base case - 2.7× better IRR in worst-case conditions - 46% faster payback

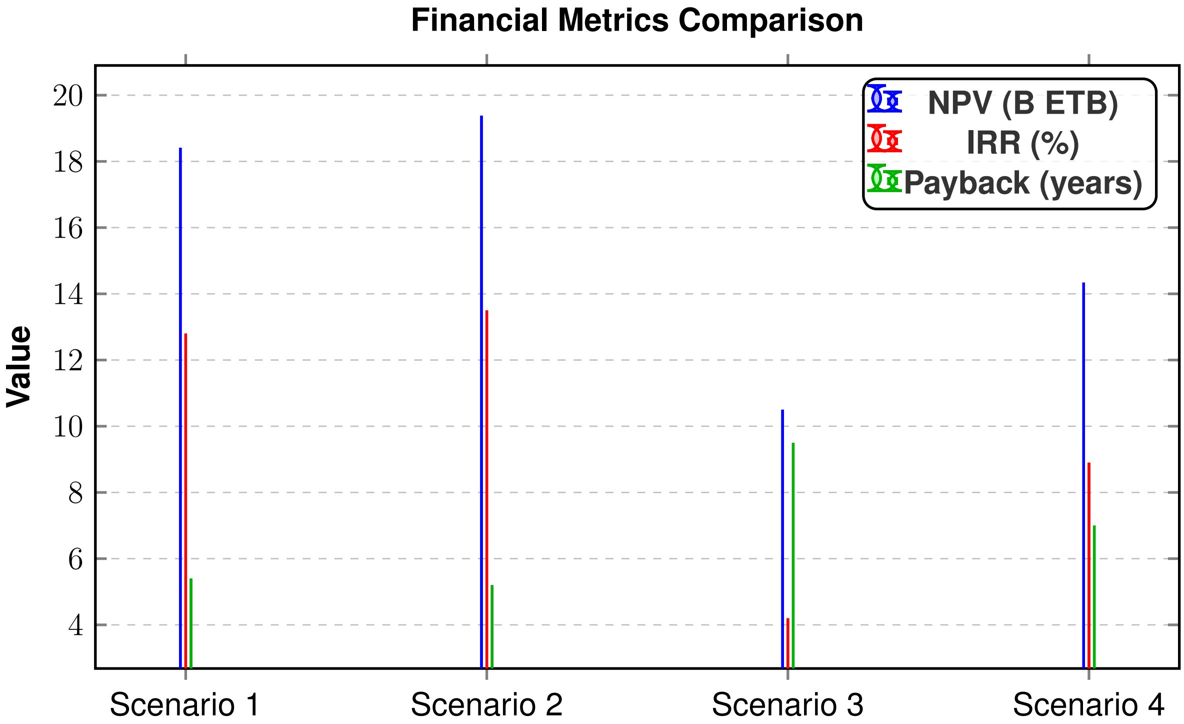

Figure 6.7: **Comparison of key financial metrics across scenarios.**

Sensitivity Comparison

Factor	Scenario 2 Impact	Scenario 3 Impact
Revenue ±30%	±5.81B	±3.15B
OPEX ±30%	±1.80B	±1.05B
CAPEX ±30%	±0.88B	±0.48B

Table 6.6: Sensitivity Comparison for Best and Worst Scenarios

This analysis clearly shows Scenario 2 as the robust choice, while Scenario 3 presents unacceptable risks across all financial metrics. The visualization highlights the dramatic performance difference between the best and worst options.

Discount Rate	Scenario 1 NPV	Scenario 2 NPV	Scenario 3 NPV	Scenario 4 NPV
5%	23.08	24.28	13.16	17.98
7.5%	20.45	21.50	11.66	15.92
10%	18.41	19.38	10.50	14.34
12.5%	16.78	17.66	9.57	13.06
15%	15.42	16.22	8.80	12.00

Table 6.7: Sensitivity Analysis of NPV for Each Scenario

The sensitivity analysis assumes constant annual cash flows. If the cash flows vary

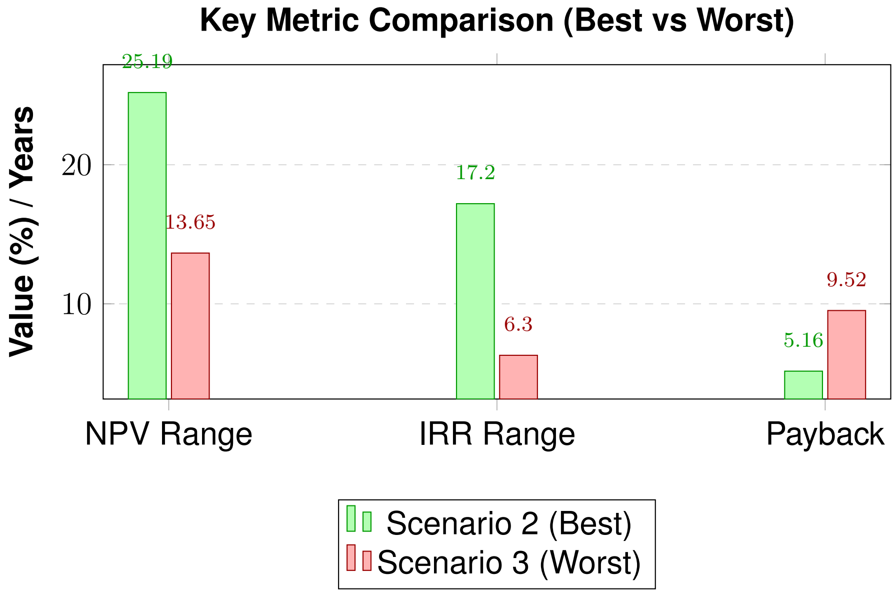

Figure 6.8: Comparison of key financial metrics between the best (Scenario 2) and worst (Scenario 3)

each year, the results will differ.

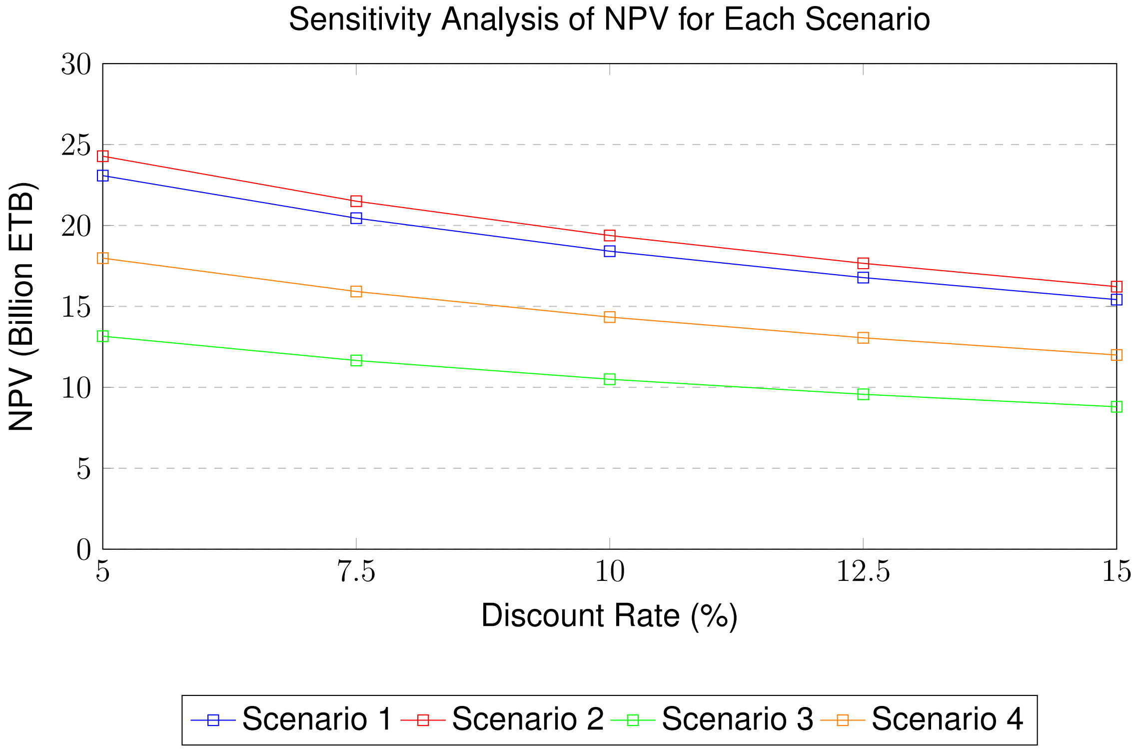

Figure 6.9: NPV sensitivity to discount rate across four scenarios.

The analysis shows Scenario 2 maintains the highest NPV values (24.28B ETB at 5% discount rate) across all tested discount rates, while Scenario 3 consistently shows the lowest NPV performance. All scenarios demonstrate the expected inverse relationship between discount rates and NPV. showing key financial metrics and qualitative assessments. Scenario 2 demonstrates superior performance with higher NPV (19.38B ETB base case), better IRR range (11.0%–17.2%), and faster payback (5.16 years) compared to Scenario 3's vulnerable profile.

Metric	**Scenario 2 (Best)**	**Scenario 3 (Worst)**
NPV Range (Billion ETB)		
Best-case	25.19	13.65
Worst-case	13.57	7.35
Base NPV (Billion ETB)		
Value	19.38	10.50
IRR Range (%)		
Best-case	17.2	6.3
Worst-case	11.0	2.7
Payback Period (Years)		
Value	5.16	9.52

Scenario 2 Strengths	**Scenario 3 Risks**
• Highest NPV in all conditions • Most stable IRR performance • Shortest payback period • Least sensitive to changes	• Largest NPV swing • Lowest IRR in all cases • Longest payback period • Highly sensitive to changes

Table 6.8: Sensitivity Analysis Comparison Between Best and Worst Scenarios.

Chapter 7

Conclusions, Recommendations and Future Work

7.1 Conclusion

The comprehensive techno-economic analysis of four broadband deployment scenarios in Bishoftu, Ethiopia, reveals that:

Scenario 2 (Sc-2), implementing 5G Fixed Wireless Access (FWA) by utilizing existing sites and densifying with new additional sites, emerges as the most economically favorable option. It offers the shortest payback period of 5.16 years and the highest Internal Rate of Return (IRR), indicating a robust return on investment. So,5G FWA (Sc-2) is the winning strategy for Bishoftu and similar suburban Ethiopian markets. It offers the fastest ROI, lowest risk, and highest scalability, while fiber remains a niche solution for urban cores. By implementing these recommendations, Ethiopia can cost-effectively bridge its digital divide and accelerate its Digital 2025 Strategy.

Scenario 3 (Sc-3) deploying all Optical Distribution Network (ODN) related assets with new infrastructure has the longest payback period of 9.52 years, reflecting higher capital expenditures and slower investment recovery.

A clear correlation exists between shorter payback periods and higher IRRs across the scenarios, emphasizing the importance of strategic infrastructure utilization.

These findings underscore the viability of leveraging existing infrastructure to optimize costs and accelerate returns in suburban broadband deployments. This study confirms that **5G FWA (Scenario 2)** is the optimal solution for sub-urban broadband deployment in Bishoftu, Ethiopia, due to its cost efficiency (5.16-year payback) and superior IRR. Fiber-based scenarios (Sc-3/Sc-4) are less viable given their high CAPEX and prolonged ROI.

7.2 Recommendations

Adopt Scenario 2 for Immediate Deployment: Given its superior economic indicators, Scenario 2 should be prioritized for broadband expansion in Bishoftu. Utilizing existing infrastructure minimizes capital expenditure and expedites service rollout.

Implement Strategic Infrastructure Sharing: Encourage collaboration among service providers to share existing sites and infrastructure. This approach can further reduce costs and improve network coverage, especially in sub-urban areas.

Conduct Detailed Site Assessments: Before densification, perform thorough evaluations of existing sites to determine their suitability for upgrades and integration with new infrastructure.

Engage in Public-Private Partnerships (PPPs): Foster partnerships between government entities and private sector players to mobilize resources, share risks, and ensure sustainable broadband deployment.

Plan for Long-Term Scalability: While Scenario 2 offers immediate benefits, future demand may necessitate more extensive infrastructure. Develop a phased approach that allows for scalability and integration of advanced technologies as needed.

Monitor and Evaluate Performance: Establish key performance indicators (KPIs) to continuously assess the network's performance, financial returns, and user satisfaction, enabling timely adjustments to the deployment strategy. Recommendations

- **Operators should prioritize 5G FWA (Sc-2)** using existing infrastructure with targeted densification.
- **Policymakers must facilitate FWA adoption** through spectrum allocation and infrastructure-sharing policies.
- **Fiber deployments should be more concerned with** high-demand urban zones to avoid financial overextension.

7.3 Future Work

This study opens several avenues for future research:

- **Field Performance Analysis**: Empirical testing of 5G FWA signal reliability in Bishoftu's terrain.
- **Socio-Economic Impact**: Quantifying FWA's role in bridging Ethiopia's digital divide.
- **Hybrid Networks**: Cost-benefit analysis of FWA-fiber hybrid deployments.

Key Gaps Addressed by Future Work

Research Gap	**Proposed Study**	**Expected Outcome**
Lack of local performance data	Field trials of FWA in Bishoftu	Validated coverage maps for Ethiopian terrain
Unknown socio-economic benefits	Surveys on e-learning/telemedicine adoption	Evidence-based policy recommendations
Spectrum efficiency questions	Comparative analysis of 3.5GHz vs. mmWave	Optimal band allocation for sub-urban FWA

Table 7.1: Research Gaps &Future Studies

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