



Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

**Techno-economic Comparison of Mid-band 5G Fixed Wireless
Access and GPON-based Optical Distribution Networks**

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A Thesis Submitted to the School of Electrical and Computer
Engineering in Partial Fulfillment of the Requirements for the Degree
of Master of Science in Communication Engineering

June 2023

Addis Ababa, Ethiopia

Addis Ababa University

Addis Ababa Institute of Technology

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Thesis Title

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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 used in the thesis have been properly cited.

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Abstract

The popularity of broadband Internet services has increased significantly over the past few years. Similarly, the development of mobile network technologies has seen rapid growth. Due to these trends, Fifth Generation (5G) Fixed Wireless Access (FWA) networks have been proposed as a potential competitor to other broadband access technologies, such as Optical Distribution Network (ODN). However, technological advancement itself cannot show the performance, acceptance, or economic viability of an investment without a detailed technical and economic feasibility assessment of possible broadband deployment alternatives.

This thesis conducts a techno-economic comparison between 5G FWA at mid-band frequency range and Gigabit Passive Optical Network (GPON) based ODN to provide broadband services for residential users. It presents a techno-economic analysis of four possible deployment scenarios: namely, two scenarios (Sc-1) and scenario (Sc-2) based on 5G FWA using new and existing infrastructure, respectively. The other two scenarios (Sc-3) and scenario (Sc-4) are GPON-based ODN using new and existing infrastructure, respectively. These scenarios are evaluated in the context of the capital city of Ethiopia, Addis Ababa, around an area called Tulu Dimtu. Data collected from the operator, ethio telecom, serves as main source of information. For the evaluation, the most popular and widely used techno-economic tool, called Techno-economic Results from the Advanced Communications Technology and Services (TERA), is modified and implemented including network dimensioning, revenue modeling, cost modeling, and economic analysis. For all analyses, 10-years study period and 10% discount rate are considered. The analyses were evaluated using standard economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP). MATLAB and Microsoft Excel are used for the implementation.

Achieved result shows that the PBP of the scenarios are: 4.48, 3.75, 4.63 and 4.37 years for Sc-1, Sc-2, Sc-3, and Sc-4, respectively. Based on NPV results, all scenarios have positive NPV for the study period and greater IRR value than the defined discounted rate. Sensitivity analysis shows that revenue is the most sensitive parameter over the other parameters. The findings indicate that all scenarios are deployable, but they should be deployed based on requirements.

Keywords: 5G FWA, GPON, ODN, TERA, Techno-economic Analysis, and Broadband.

Acknowledgments

First, I want to begin by thanking the Almighty God for giving me the help and strength necessary to complete this thesis.

Second, I would like to express my sincere thanks to Dr. -Ing. Dereje Hailemariam, who served as my advisor and invested his time with me, for his precise guidance, constant support, and unwavering encouragement, I am extremely happy, and I consider working with him to be one of my best opportunities. Through my academic studies, I have acquired a lot of knowledge and experience, which will help me in my career and life. Without his essential help, it would not have been possible to reach the study's intended outcome.

Along with my advisor, I would like to thank the other members of my thesis committee: Dr. Ephrem Teshale, Prof. Mohammed Abdo, Dr. Yihnew Wondie, Dr. Beneyam Berehanu and Dr. Murad Ridwan. I appreciate all of their wise advice and support, as well as the critical questions they posed that motivated me to broaden my research from various perspectives.

Moreover, I want to express my sincere gratitude to all my friends and classmates who have continuously supported and motivated me to complete this thesis. In addition, I would like to express my heartfelt gratitude to the ethio telecom staff for providing me with the necessary data and information. It is also my pleasure to thank staff members of the School of Electrical and Computer Engineering of the Addis Ababa Institute of Technology, Addis Ababa University, for their support and assistance in getting me the necessary knowledge and facilities.

Finally, I would like to extend my deepest thanks to my beloved wife Shasho Dame, my kid Kena Tujuma, my father Bayisa Tafa, and my mother Gadise Mekonnen. My success is a result of their continuous encouragement, unconditional love, and precious time. I owe them so much in terms of time and love.

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List of Abbreviations

2G	Second Generation
3G	Third Generation
3GPP	Third Generation partnership project
4G	Fourth Generation
5G	Fifth Generation
5G FWA	Fifth Generation Fixed Wireless Access
ACTS	Advanced Communication Telecom services
ADSL	Asymmetric Digital Subscriber Line
AHP	Analytical Hierarchy Process
ARPU	Average Revenue per User
BH	Busy Hour
BS	Base Stations
BW	Band Width
CAPEX	Capital Expenditure
CCF	Cumulative Cash Flow
CF	Cash Flow
COST	Cooperation of Scientific and Technical Research
CPE	Customer Premises Equipment
dB	decibel
DCF	Discounted Cash Flow
DL	Down Link
DOCSIS	Data Over Cable Service Interface Specifications
DSL	Digital Subscriber Line
ECOSYS	Techno-Economics integrated Communication Systems and Services
EPON	Ethernet Passive Optical Network
ETB	Ethiopian Birr
FDD	Frequency Division Duplexing
FWA	Fixed Wireless Access
GB	Giga Byte

Gbps	Giga Bit Per Second
GE-PON	Gigabit Ethernet-Passive Optical Network
gNodeB	Next generation NodeB
GPON	Gigabit Passive Optical Network
IEEE	Institute of Electrical and Electronics Engineers
IRR	Internal Rate of Return
ISP	Internet Service Providers
ITU	International Telecom Union
I-UPF	Intermediate- User Plane Function
Kbps	Kilo bit per second
KHz	Kilo Hertz
LoS	Line of Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution -Advanced
MAPL	Maximum Allowable Path Loss
MATLAB	Matrix Laboratory
MB	Mega Byte
Mbps	Mega Bit Per Second
Mhz	Mega hertz
MIMO	Multiple Input Multiple Output
MSAN	Multi-Service Access Node
NLoS	Non Line of Sight
NPS	Net Promoter Score
NPV	Net Present Value
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Domain Multiple
OLT	Optical Line Terminal
ONT	Optical Network Terminal
OPEX	Operational Expenditure
PBP	Payback Period

PDSCH	Physical Downlink Shared Channel
PON	Passive Optical Network
PRB	Physical Resource Block
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature phase Shift Key
RACE	Research in Advanced Communications in Europe
RAN	Radio Access Network
RF	Radio Frequency
RLB	Radio Link Budget
ROI	Return on Investments
SAAZ	South Addis Ababa Zone
SDL	Super high speed Down Link Network
SDR	Software Defined Radio
SDSL	Symmetric Digital Subscriber Line
SEAMCAT	Spectrum Engineering Advanced Monte Carlo Analysis Tool
SINR	Signal interference to Noise Ratio
SOHO	Small Office Home Office
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TEA	Techno-economic Analysis
TERA	Techno-Economic Results from ACTS
TITAN	Tool Introduction Scenario and TE Evaluation of Access Network
TONIC	Techno-economics of IP optimized networks and services
UL	Up Link
VDSL	Very High Digital Subscriber Line
VoIP	Voice over Internet Protocol
WiMAX	Worldwide Interoperability for Microwave Access
WMAN	Wireless Metropolitan Area Network
WTTH	Wireless to the Home

CHAPTER ONE

1. Introduction

The rapid growth of internet services creates new opportunities and challenges for industry stakeholders. At the same time, technological advancements in both wireless and fixed broadband technologies are also highly increasing [1]. In today's competitive market, it is clear that no single network architecture or technology would seem to be the obvious choice, and no single broadband access technology will win over the entire market; it will shift over time. In many cases, the choice of broadband access technology is driven by the legacy network infrastructure of the network provider. As a result, each access technology has its own areas of dominance in terms of geography, cost, coverage, reliability, bandwidth, as well as political and regulatory decisions [2].

Globally when we look at these technologies trends, the Fixed Wireless Access (FWA) market is growing quickly, especially with the evolution of Fourth Generation (4G) and Fifth Generation (5G) mobile networks. Deloitte global predicts that the number of FWA connections will grow from about 94 million in 2023 to 103 million in 2026, with 5G FWA representing almost 39% of the total (see Figure 1.1) [3].

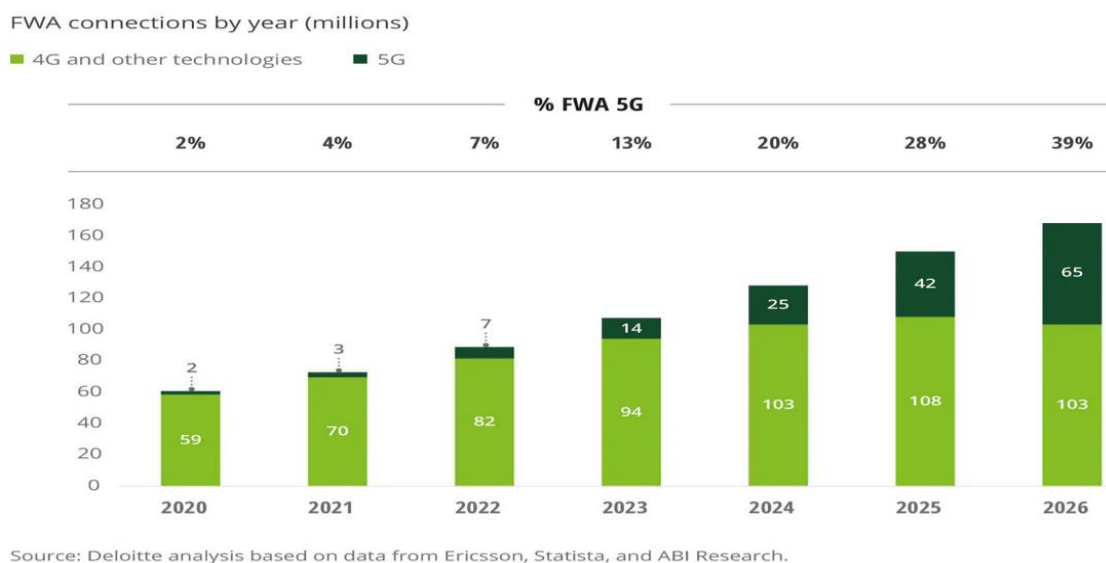


Figure 1. 1 The number of global FWA connection is growing rapidly, with 5G expected to make up an increasing share [3].

In Ethiopia, these broadband access trends have also experienced significant growth during the past few years. In just four years, the number of fixed and wireless broadband users subscribing to the services has increased from 17.9 million to 26.1 million from 2018 to 2021/2022 [4]. From this, the number of users subscribing to fixed broadband services similarly increased from 66.2 thousand to 506.8 thousand see Figure 1.2, and the growth trend seems to continue in the coming years.

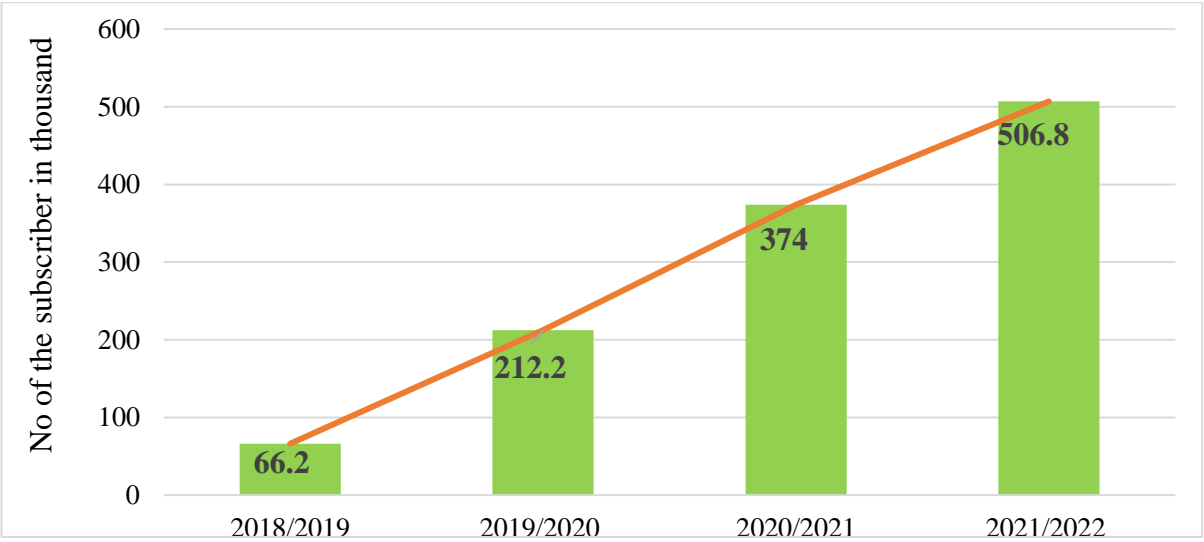


Figure 1. 2 Fixed broadband subscriptions in Ethiopia (from 2018 to 2021/2022) [4].

ethio telecom has implemented several telecom projects to meet this rising subscription demand. However, due to low feasibility assessments of technologies before implementation, the efficiency (in technical and economic aspects) and the choice of access to network technologies for these projects raises many questions after deployment [5].

Broadband access is vital to socio-economic development. However, most of these services are provided by wire line-based technology. Even economically deploying broadband services over a fixed wire line requires huge capital expenditure and a medium to long-term investment. Currently, fixed-line technology is not the only option to deliver broadband service. FWA has become an innovative solution, enabling easy and rapid deployment of broadband networks. With the introduction of 4G and 5G mobile networks, FWA has gained popularity as an alternative to fixed broadband service for providing broadband access [3].

As we can see from Figures 1.1 and 1.2, though from local and global data sources, the subscriptions per year are increasing in both fixed broadband and FWA. To meet these ever increasing demands in an economical and technically efficient manner, network operators should model the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) of various deployment scenarios before entering the market. Therefore, a detailed investigation of techno-economic analysis needed to be a cost-effective and flexible deployment under different scenarios with different points of view.

1.1. Statement of the Problem

The telecommunications sector is experiencing rapid growth in terms of services, technologies, and business models. However, each of these services, technologies, and architectures varies in complexity, network functionality, and overall network costs [6]. On the other hand, data traffic volume increases in both wireless and fixed networks due to the continuous improvement of devices, applications, and many other data-consuming devices.

The data growth trend is the same in the Ethiopian context and to meet this demand, ethio telecom, the main telecom operator, is investing heavily in fixed and wireless networks to provide services to its customers. The company began deploying ODN projects across the country in 2020 [7]. The deployment of this project requires high investment costs for obtaining permission, right-of-way issues, installations, and civil work, to mention some. Due to this process, most of the fixed network users are unhappy because they must wait for installation until deployment and have numerous complaints regarding maintenance after deployment.

Again, from the wireless network side, the company launched a 5G pre-commercial network in May 2022 [7]. When we see the device distribution, from the connected devices of 75.8 million, only 110 thousand devices, which is only 0.001% of the total devices, support 5G [7]. Therefore, it is preferable to adapt the 5G early use cases and carry out thorough localized techno-economic assessments prior to project implementation.

On the other hand, these investments are affected by the relative performance levels of alternative technologies, existing infrastructure, and regulatory decisions. However, deploying new technologies without a detailed study and decision of techno-economic analysis will lead

to many complications. Such investments lead to resource waste, underutilization, and revenue loss, as well as require high CAPEX and OPEX. Similarly, the impact of a lack of proper assessment ranges from the individual to the national level, as the benefits of mobile broadband range from personal development to a high contribution to the country's development.

Additionally, technological advancement makes it difficult to select the appropriate technology based on the requirements; for example, the upcoming 5G FWA is presented as a challenger to fiber-based networks [8]. Therefore, examining the feasibility of broadband deployment scenarios based on 5G FWA and ODN and exploring their viability by applying techno-economic analysis is very significant before deployment. Finally, this study answers the following questions:

1. What are the limitations of ODN and 5G FWA-based broadband access deployment?
2. What is the use case for the upcoming 5G network to provide broadband?
3. What scenarios of broadband deployment take a high share of the network cost in each deployment scenario?
4. What factors of technical and economic viability are we considering when deploying ODN and 5G FWA networks?
5. Can 5G FWA compete with ODN?

1.2. Objective

1.2.1 General Objective

The general objective of the study is to evaluate and compare the techno-economic feasibility of mid-band 5G FWA and GPON-based ODN deployment to provide broadband services under different scenarios.

1.2.2 Specific Objectives

- To formulate broadband deployment scenarios for the targeted area;
- To dimensioning 5G FWA at mid-band (3.5 GHz) in terms of coverage and capacity;
- To model CAPEX and OPEX of 5G FWA and ODN deployment scenarios;
- To implement the TERA, framework model for the techno-economic evaluation;
- To evaluate the feasibility of each scenario via economic indicators;
- To evaluate the techno-economic analysis of broadband deployment with MATLAB;
- To recommend a more feasible technical and economic scenario for its deployment.

1.3 Methodology

This thesis initiated from the current ongoing ODN project and pre-commercialized 5G services in Ethiopia by ethio telecom. The methodology and procedures followed in the thesis presented in Figure 1.3 below.

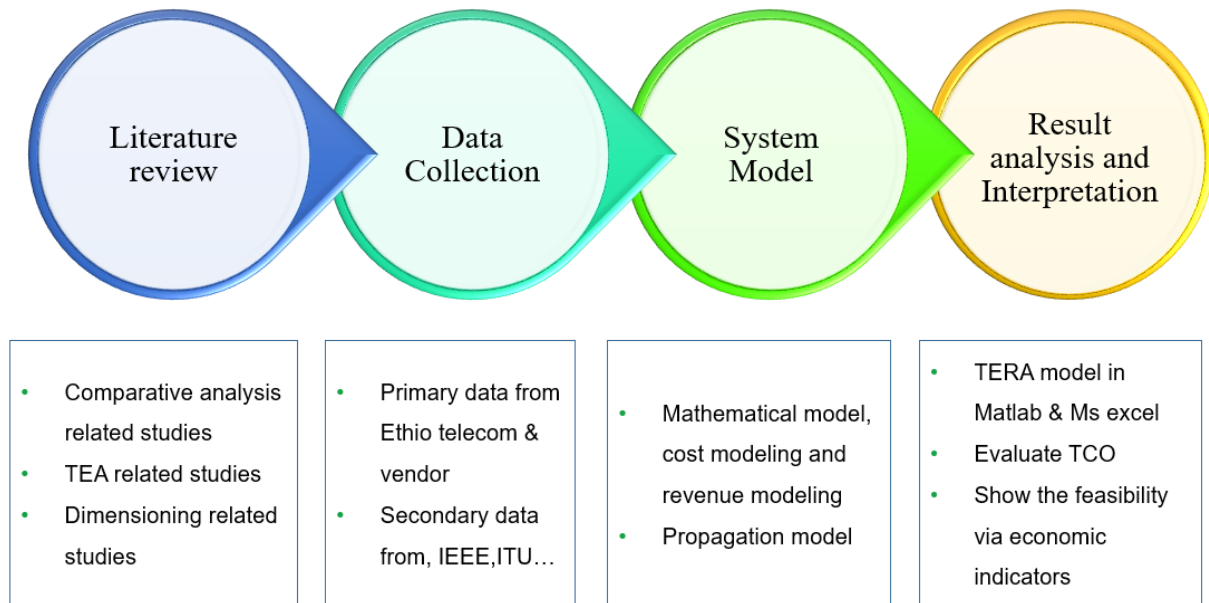


Figure 1. 3 Proposed methodology.

For the proposed methodology, detailed components described as follows:

Literature Review

In this thesis related, study categorized into three segments.

- i. Comparative Analysis Related Studies:** Which focused on the study that investigates the deployment of Fiber to the Home (FTTH) and FWA to provide broadband access under various scenarios.
- ii. Techno-economic Analysis (TEA) Related Studies:** Focused on TEA modeling tools and an assessment of several TEA-related studies.
- iii. Designing Related Studies:** Concentrated on studies relating to 5G radio network dimensioning, propagation models selection, coverage, and capacity dimensioning.

Data Collection

- The primary data source has been collected from ethio telecom and vendors.
- Secondary data based on Third Generation Partnership Project (3GPP) documentation, Institute of Electrical and Electronics Engineers (IEEE) articles and journals, International Telecommunication Union (ITU) publications, and TEA-focused studies.

System Model

- Mathematical modeling.
- Radio network dimensioning phase, propagation model, coverage, and capacity dimensioning.
- CAPEX, OPEX, and revenue modeling.

Evaluation

- Techno-economic evaluation system based on the prepared mathematical model in Microsoft Excel and MATLAB.
- Evaluating the techno-economic with a modified TERA model depending on the objective of the analysis.

Results Analysis and Interpretation

- Compare the Total Cost of Ownership (TCO) of each selected broadband deployment scenario.
- Show the feasibility of each deployment scenario via economic indicators.
- Sensitivity analysis to see if their input estimation affects the output results.

1.4. Scope and Limitations

1.4.1 Scope

From the technology point of view, the scope of the thesis is limited to point-to-multi-point 5G FWA network dimensioning at a mid-band frequency of 3.5 GHz, and ODN dimensioning follows the ITU G.984.2 GPON-based class B+ standard.

From a service perspective, the study's focus is solely on broadband data services for residential users; voice services and enterprise users are not taken into account.

From the network operator perspective, most OPEX and CAPEX cost estimations are based on ethio telecom data in the case of Ethiopia, Addis Ababa, around an area called Tulu Dimtu suburban area.

1.4.2 Limitations

Documents and TEA model deliverables tools are available only to project sponsors and members of the project. These may in turn exclude from deep understanding and being familiar with the parameters. There is also a lack of detailed documents related to TEA and 5G networks in ethio telecom. The analysis excluded the impact of tariff trends and variable pricing.

1.5. Literature Review

The author in [9] starts with the objective to clarify the debate on the FWA versus fixed-line broadband access. Techno-economic analysis of optical fiber-based solutions versus 3 FWA-based scenarios using existing commercial macro cells, newly installed millimeter (mm) Wave small cells, and hybrid macro and small cells over a 10-years study period are evaluated. This study is based on a case in Sweden to achieve one of the Swedish Government's 2025 broadband goals. The Fuzzy Analytical Hierarchy Process (Fuzzy AHP) framework and pairwise comparisons are used in techno-economic modeling. The propagation model used for network dimensioning was developed by the Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT) project with 'Hata Extended'. Obtained results show that fiber-based solution is the "default" choice to achieve the Swedish goal of at least 1 Gbps per user. FWA using mm-Wave small cells is capable of achieving the 1 Gbps at 98% goal and the estimated relatively low cost in rural areas. However, the study considered only Internet speeds at a 1 Gbps level, which is not feasible in developing countries. In addition, comparing only TCO is not enough to assess the viability of each deployment scenario. As a result, the study does not take into account well-known economic decision-making tools like CF, NPV, IRR, and PBP.

The study presented in [8] compares the deployment of different broadband access technologies from a techno-economic point of view. Four deployment scenarios were taken into account for this study. Two scenarios are based on GPON, while the other two are based on FWA and are based on 4G and 5G infrastructure, respectively. A classical Erlang-B model was used for the capacity planning of FTTH and FWA. To estimate the operator's CAPEX and OPEX, the European Average Revenue Per User (ARPU) is used. The authors address that FTTH is most of the time less expensive and more profitable for the long term and in rural areas. FWA is more economical than FTTH, as installing new fiber requires a high CAPEX. From a technical

perspective, the classical Erlang-B model used for network dimensioning does not show the accurate required network equipment per scenario. In this case, several parameters should be considered, especially from the (Radio Access Network) RAN side. In addition, the most popular economic feasibility tools were also not taken into account from an economic perspective. Finally, European mean ARPU used in the study is not feasible in all countries, especially developing countries.

Author in [10] investigated suitable scenarios of link capacity enhancing techniques for delivering broadband services at wireless backhaul. Particularly, this work presents four scenarios for techno-economic analysis. A techno-economic evaluation was performed using the TERA model, which consists of cost and revenue models and was implemented in Microsoft Excel and MATLAB. TEA's assessment and evaluation methods applied are discounted cash flow, cash flow, net present value, internal rate of return, payback period, and sensitivity analysis are used. According to the results of the five-year study period, mm-wave multiple input, multiple output (MIMO) is the more profitable scenario, and the millimeter-wave band is the scenario that has the shortest return on investment. There are several challenges with mm-wave to meet expected results, but they are not identified here as well as optical fiber backhauling is efficient and less expensive, but not included in the comparison.

The author in [11] conducted a techno-economic analysis to find out whether the emerging standards-based FWA networks raise opportunities or threats to the current broadband business of operators, due to the rapid development of wireless technologies. The cost structures of FWA and Digital Subscriber Line (DSL) networks compared and a techno-economic analysis was carried out to determine the feasibility and competitiveness of IEEE 802.16 a-based FWA networks in providing broadband internet access to residential customers. The networks were analyzed using a techno-economic TERA framework and tools that were developed in several European research projects. The results from the analysis show that the cost structure of FWA networks is not currently competitive with DSL in densely populated urban and suburban areas. The results show FWA networks will also provide access to portable and mobile terminals in the near future, making the business case more favorable. However, the investigation did not; evaluate the deployment of FWA using a different technological choice that provides a higher data rate than DSL.

The author [12] starts with the motivation of qualifying a dynamic professional in the field of network dimensioning and design areas, to satisfying an ever-increasing demand while improving coverage and capacity in existing networks. The significance of basic requirements has been demonstrated using mathematical analysis, radio network planning, and optimization tools in WinProp software. To predict received power and path loss, WinProp ray-optical propagation and empirical models were used. At the dimensioning stage, the required gNodeBs for coverage planning and capacity planning were obtained by mathematical modeling. Based on mathematical modeling and simulation results the close-in propagation model has high path losses relatively compared with the rest, and the dominant path loss model has lower path losses than the others. As stated in the study title, the network dimensioning at least for mid-band frequency range not carried out, as well as the expected 5G data rate was not obtained in the simulation section.

1.6. Contributions

Technology choices and investment decisions are major challenges in the telecommunications industry in providing broadband access, which incurs high investment costs. This study combines technical and economic perspectives to provide a comprehensive view by addressing this challenge and contributes in a way that necessitates pre-deployment optimization to reduce extra costs during network deployment.

Through our analysis, we identify limitations in the current deployment of ODN, address challenges in broadband access deployments, and forecast the open many types of businesses for the telecommunications industry with the upcoming fifth-generation mobile network. Additionally, to establish a clear path regarding modifications to business models, capacity issues, and potential overlap with existing implemented solutions, particularly in the context of broadband access deployment.

For the techno-economic analysis, a modified TERA model is used to enhance the modeling quality for expressive analysis and meaningful forecasts for future users and services. Furthermore, it is used as an input for advanced research and investment decisions.

1.7. Thesis Layout

There are seven Chapters in this thesis. The first Chapter explains the introduction, problem statement, objective, methodology, scope, limitations, literature reviews, and contributions of the thesis. The second Chapter deals with a general overview of broadband access network technology, network architecture, and access network alternatives. Chapter three discusses techno-economic modeling and evaluation methods, cost modeling, revenue modeling and investment decision-making tools within their mathematical approach.

In Chapter four, the general principles and methods for 5G FWA network dimensioning and ODN dimensioning basic approach are introduced. The chapter also discusses path loss model selection, general capacity, coverage, and frequency planning principles, to estimate the required number of gNodeBs for 5G FWA and Multi-Service Access Node (MSAN) for ODN. The implemented TEA framework, network dimensioning, cost modeling, and revenue modeling are all explained in Chapter five. Chapter six clarifies the obtained results from techno-economic modeling and interpretation for each scenario's feasibility. Finally, conclusion and future works are explained in Chapter seven.

CHAPTER TWO

2.1 Background of the Broadband Access Network

The traditional access network consists of point-to-point wireline connections between telephone subscribers and an electronic multiplexing or switching system. Data access to the telephone network began with the introduction of voice band modems, which could transmit data as a modulated signal within the nominally 4 kHz voice band pass-band frequency. The maximum data capacity of this voice band modems was limited to 33.6 kbit/s, or 56 kbit/s under special circumstances [2].

As out-of-band technologies are introduced to transmit signals over the copper line other than the voice band DSL technology is employed to send digital information into the out-of-band signals. With the introduction of broadband access, network providers became interested in alternative ways to offer broadband access to its subscribers. The two main competing technologies for delivering these services are fixed wire line access and wireless radio frequency connections. The first DSL-based broadband service, derived from fixed wireline access, offers transmission speeds ranging from several hundred Kbps to Mbps. DSL enhances technology like Asymmetric Digital Subscriber Line (ADSL), Symmetric Digital Subscriber Line (SDSL), Very High Digital Subscriber Line (VDSL), and G.fast, which can offer several Mbps to Gbps rates.

On other hand, the advancement of optical fiber technology over the past few decades has enabled fixed networks to deliver high-speed broadband services. When compared to other mediums, fiber optic cables have a much lighter weight, a smaller diameter, and the ability to avoid corrosion and rust due to their non-metallic construction. Fiber optics are at the top of the list for communications in today's world because of these characteristics. It enables data transmission speeds never seen before in previous technologies, with transmission speeds measured in Gbps [13].

On the other hand, wireless mobile networks have grown in popularity, and new technologies and protocols have been developed. This is particularly convincing in areas that lack a legacy fixed line infrastructure capable of evolving broadband services [2]. From the fixed wireless

side, Worldwide Interoperability for Microwave Access (WiMAX) is the commercialization of the IEEE 802.16 standard for FWA technology, which has been developed for a long time. Many operators have already upgraded WIMAX to Forth Generation Long Term Evolution (4G LTE). With the evolution of 4G and the arrival of 5G, 4G/5G FWA provides users with speeds up to 100Mbps and even Gbps and becomes an alternative to FTTH [14]. Fortunately, with the introduction of 5G and abundant bands of under-used, high-frequency mm-wave above 6 GHz, the speed of FWA is now comparable to fiber. In addition, technological advancement has made even the below-6 GHz spectrum more feasible for fixed wireless by applying massive MIMO technologies [15].

2.2 Access Technologies

As bandwidth demands for multimedia applications increase continuously, users require broadband and flexible access with higher bandwidth and lower cost. To meet these growing demands, new broadband access technologies are emerging. In addition, there is strong competition among several technologies created between: digital subscriber line, hybrid fiber coax, wireless, and FTTH. In the meantime, FTTH and wireless networks have become very promising access technologies, which is the best solution for broadband and mobile access services in the future [2]. Figure 2.1 shows the most common fixed broadband access technology under different scenarios in various circumstances.

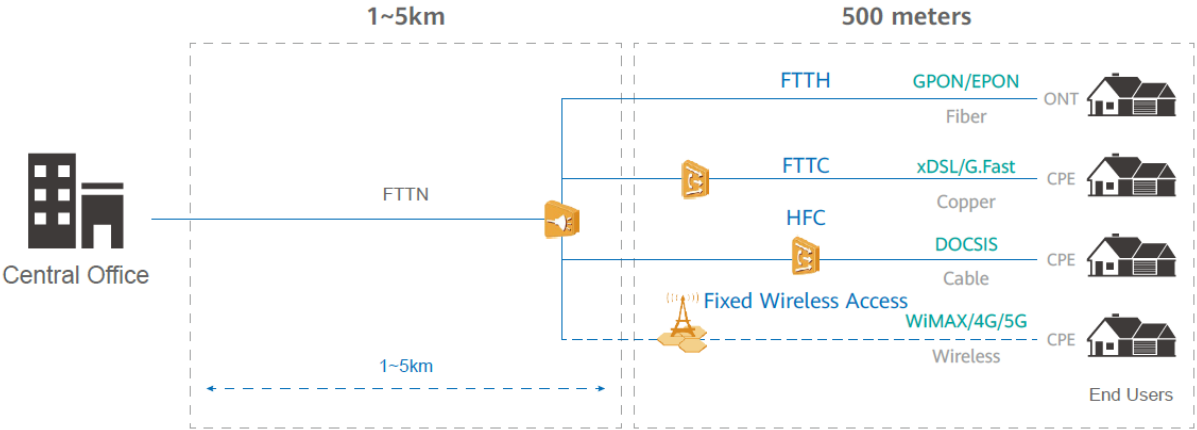


Figure 2. 1 Fixed broadband access technologies [16].

2.2.1 Digital Subscriber Line and G.fast

DSL is a wired technology that uses a traditional copper cable to provide internet speeds ranging up to 100 Mbps. However, in real networks, most xDSL broadband speeds are below 10 Mbps as the speed is dependent on the Fiber to the Node (FTTN) network and the distance from home to the exchange. The copper line quality and the lack of record of copper also result in high maintenance costs [16].

G. Fast technology enables delivery of gigabit speeds over copper loops for distances up to 100 m using Orthogonal Frequency Division Multiplexing (OFDM) in a 212-megahertz (MHz) frequency spectrum [1].

2.2.2 Cable Modem

Coaxial cables are used by cable modems to deliver images and sound to television sets. A cable modem is an external device with two connections: one to the cable wall outlet and one to a computer. Cable operators use the Data Over Cable Service Interface Specifications (DOCSIS) standard to provide internet access over their Hybrid Fiber-Coaxial (HFC) infrastructure. It can provide maximum internet speeds of 1.2 Mbps and 10 Mbps with DOCSIS 3.0 and 3.1, respectively [16].

2.2.3 Fiber to the Home

The majority of FTTH solutions are based on Passive Optical Network (PON) architectures, which have no active elements outside fiber plants and share capacity of single fiber core up to 32, 64, 128 or 256 subscribers via a tree or branch. From the PON families' time division-multiplexing PON, includes GPON, Gigabit Ethernet-PON (GE-PON), XG-PON, and 10G Ethernet Passive Optical Network (EPON), which connect multiple users or optical network units to a single optical line termination port via a passive splitter [1].

GPON Based ODN

The ODN is one of the FTTH families that splits and distributes the signal traveling along the PON between the Optical Line Terminal (OLT) and Optical Network Terminal (ONT) [17]. It

is the most cost-effective way of delivering services via Point to Multi Point (P2MP) distribution.

The ITU-T G.984 series specifies that the GPON-based ODN can provide a 20-km reach with a 28dB optical budget by using class B+ optics with a 1:64 split ratio [18]. The GPON ODN consists of a single-mode optical fiber cable, optical fiber ribbon cables, splices, optical connectors, and passive branching components.

The ODN functionally consists of two points and three segments, that is, optical distribution point, user access point, feeder optical cable, distribution optical cable, and drop cable [7].

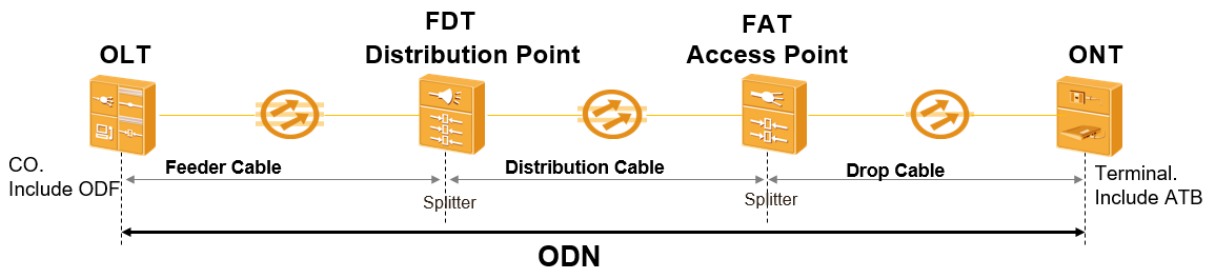


Figure 2. 2 ODN network structure [7].

2.2.4 Fixed Wireless Access

FWA is a type of wireless broadband data communication that takes place between two fixed locations that are linked by fixed wireless access devices and equipment.

The following are the most common FWAs:

i) 4G/5G FWA

Both technologies use the same infrastructure for mobile broadband and fixed wireless access, which means that the expertise of infrastructure vendors and mobile operators can be reused rather than developing a completely new technology [19]. Any technical specification adheres to the standards of both technologies, and Customer Premises Equipment (CPE) serves as the user terminal, receiving the 4G/5G signal from the nearest network equipment and providing fixed Ethernet connectivity to the Local Access Network (LAN), thus the CPE represents the 4G/5G FWA equivalent of a cable or DSL modem [20] [21].

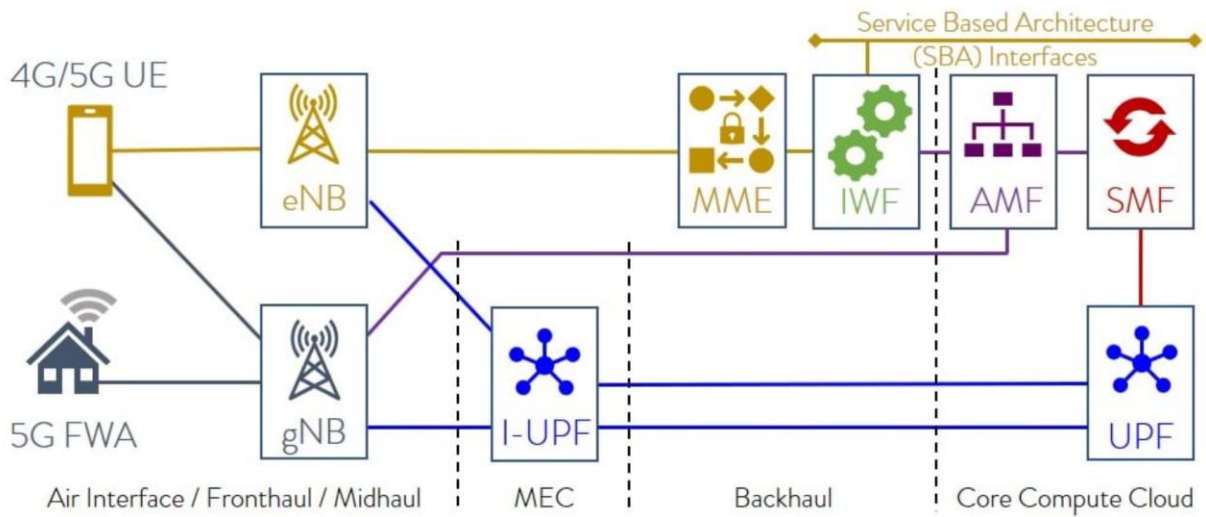


Figure 2. 3 5G FWA architecture with 4G interworking to a 5G core [21].

As shown in Figure 2.3, the main functions of the components in the architectures are presented as follows:

User Equipment (UE): In 3GPP, user equipment is defined as any devices which are used directly by the end user for communications. They can be hand held devices like smartphones or data cards, or they could be embedded into a laptop or tablets. The UE contains the Universal Subscriber Identity Module (USIM), which is an application placed into a removable smart card called the Universal Integrated Circuit Card (UICC). The USIM derives security keys for protecting, identifying, and authenticating the users in radio interface transmission [5].

Evolved Packet Core (EPC): It is a framework standardized in 3GPP Release 8 for providing data and converged voice on a 4G LTE network.

Next-generation NodeB (gNodeB): The 5G Base Station uses New Radio (NR) technology and is referred to as a gNodeB. It is a radio features Software Defined Radio (SDR) with various MIMO options, including 2×2, 4×4, 8×8 and Massive MIMO options for higher capacities [12].

Intermediate- User Plane Function (I-UPF): 5G UPF deployed within a highly automated Multi-access Edge Compute (MEC) cloud environment with dynamic scaling and autonomous network slicing. 5G systems compliant with the 3GPP R16 standard allow for I-UPFs in the 5G Core Network (CN) architecture [21].

User Plane Function (UPF): It has a role to connect all actual data coming over the RAN to the Internet.

ii) WIMAX Based FWA

WiMAX is a technology standardized by IEEE 802.16 series standards, which aims to provide Wireless Metropolitan Area Network (WMAN). This standard aimed to provide high throughput wireless data, last-mile broadband, to fixed users, which forms a real competitor to DSL and cable data providers [22].

WiMAX forum certified systems can be expected to deliver up to 40 Mbps per channel for fixed and portable access applications. Initially, the IEEE 802.16 standard was approved for frequencies ranging from 10 to 66 GHz. Again, to address the disadvantage of the Line-of-sight (LoS) requirement between transmitters and receivers, the IEEE 802.16a standard was approved in 2003 to support Non Line of Sight (NLoS) links at frequencies ranging from 2 to 11 GHz [23].

2.3 5G FWA Spectrum

The 5G NR can be deployed in two main frequency ranges, which were defined by 3GPP in the Release 15 [24].

Table 2. 1 NR frequency ranges [24].

Frequency range designation	Corresponding frequency range
FR1	450 MHz - 6000 MHz
FR2	24250 MHz - 52600 MHz

Frequency Range 1 (FR1): is contains all existing and new bands below 6 GHz or changed to 7.125 GHz [15].

Frequency Range 2 (FR2): Contains new bands in the range of 24.25 – 52.6 GHz. At the same time, 3GPP defined the operating bands, corresponding to different frequency ranges for downlink and uplink [15]. Table 2.2 and 2.3 describes the summary of key parameters and operating bands for 5G New Radio of FR1 and FR2 respectively [24].

Table 2. 2 NR operating bands in FR1 [12] [24].

NR Operating Band	Upload Link (UL) operating and BS receive / UE transmit	Downlink (DL) operating band	Duplex mode
n1	1920 MHz - 1980 MHz	2n0 MHz - 2170 MHz	FDD
n2	1850 MHz - 1910 MHz	1930 MHz - 1990 MHz	FDD
n3	1710 MHz - 1785 MHz	1805 MHz - 1880 MHz	FDD
n5	824 MHz - 849 MHz	869 MHz - 894 MHz	FDD
n7	2500 MHz - 2570 MHz	2620 MHz - 2690 MHz	FDD
n8	880 MHz - 915 MHz	925 MHz - 960 MHz	FDD
n12	699 MHz - 716 MHz	729 MHz - 746 MHz	FDD
n20	832 MHz - 862 MHz	791 MHz - 821 MHz	FDD
n25	1850 MHz - 1915 MHz	1930 MHz - 1995 MHz	FDD
n28	703 MHz - 748 MHz	758 MHz - 803 MHz	FDD
n34	2010 MHz - 2025 MHz	2010 MHz - 2025 MHz	TDD
n38	2570 MHz - 2620 MHz	2570 MHz - 2620 MHz	TDD
n39	1880 MHz - 1920 MHz	1880 MHz - 1920 MHz	TDD
n40	2300 MHz - 2400 MHz	2300 MHz - 2400 MHz	TDD
n41	2496 MHz - 2690 MHz	2496 MHz - 2690 MHz	TDD
n50	1432 MHz - 1517 MHz	1432 MHz - 1517 MHz	TDD
n51	1427 MHz - 1432 MHz	1427 MHz - 1432 MHz	TDD
n66	1710 MHz - 1780 MHz	2n0 MHz - 2200 MHz	FDD
n70	1695 MHz - 1710 MHz	1995 MHz - 2020 MHz	FDD
n71	663 MHz - 698 MHz	617 MHz - 652 MHz	FDD
n74	1427 MHz - 1470 MHz	1475 MHz - 1518 MHz	FDD
n75	N/A	1432 MHz - 1517 MHz	SDL
n76	N/A	1427 MHz - 1432 MHz	SDL
n77	3300 MHz - 4200 MHz	3300 MHz - 4200 MHz	TDD
n78	3300 MHz - 3800 MHz	3300 MHz - 3800 MHz	TDD

n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n86	1710 MHz – 1780 MHz	N/A	SUL

Table 2. 3 NR operating bands in FR2 [24].

NR operating band	UL and DL operating band	Duplex Mode
n257	26500 MHz - 29500 MHz	TDD
n258	24250 MHz - 27500 MHz	TDD
n260	37000 MHz - 40000 MHz	TDD
n261	27500 MHz - 28350 MHz	TDD

As illustrated in Figure 2.4 below, there are three layers for the 5G deployment scenario based on their frequency band; coverage layer (low-bands), coverage and capacity layer (mid-bands), and super data layer (high-bands). C-band (mid-bands) is the primary band for the introduction of 5G, which is the most appropriate for FWA providing superior coverage and moderate throughput [25].

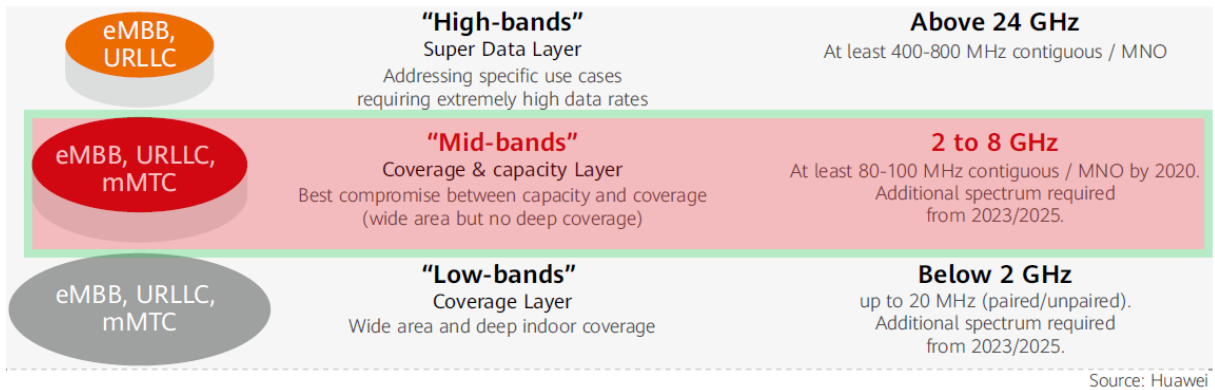


Figure 2. 4 Multi-layer frequencies band approach for 5G usage scenarios [25].

2.4 5G FWA CPE and Access Level Scenarios

Customers have a choice of access to either indoor or outdoor CPE depending on their home environment [16]. As shown in the below Figure 2.5 there are three levels of FWA to address different classes of target subscriber requirements.

Entry-level: This is a cost-effective broadband data scenario for low-income users. It cannot guarantee high speeds during peak hours, but the price is much lower when compared with fixed or mobile broadband. CPE will be either indoor or portable in this case.

Basic-level: It can provide a peak rate of up to 600 Mbps at the near point, and an average rate of 10–20 Mbps during busy hours. At this level, CPE will be installed with a high performance, indoor or outdoor CPE.

Professional-level: This scenario can provide a peak speed rate of greater than 1G bits/s. In this case, outdoor CPE is preferable to indoor devices because it provides more stable broadband connections.

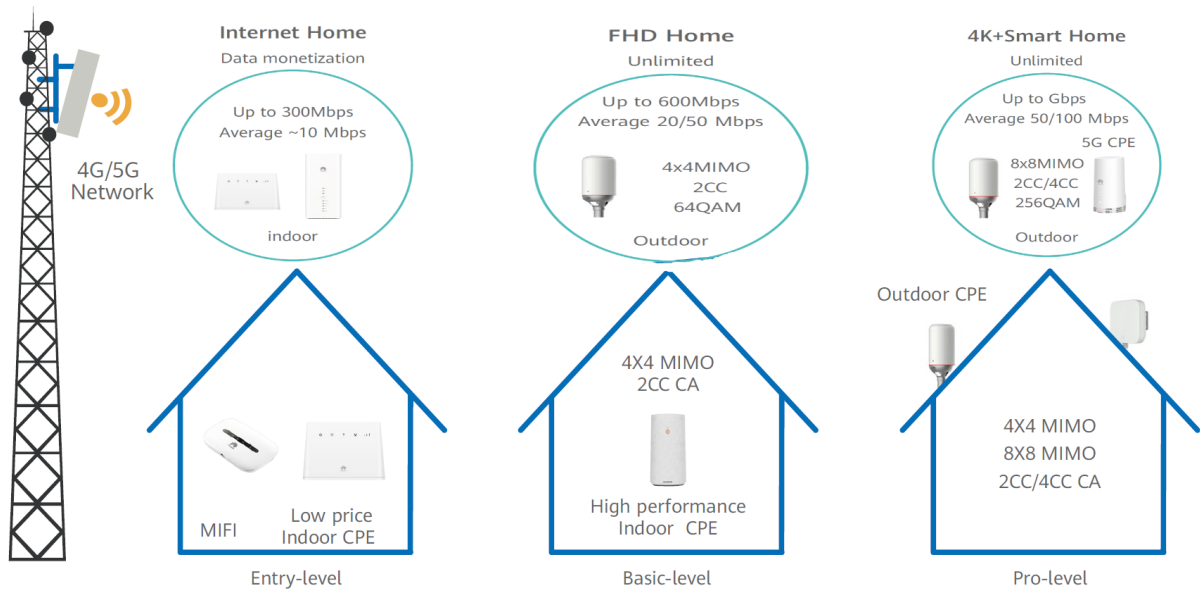


Figure 2. 5 4G/5G access level [16].

2.5 Challenges with FTTH and FWA Deployments

The majority of broadband connections are delivered using wire-based technology. However, economically deploying broadband services over a fixed wire line demands large capital expenses and long-term investment.

Technologically, FWA is an innovative solution, which enables easy and rapid deployment of broadband networks. It allows operators to meet the increasing demand for high-speed broadband services from time to time and more cost-effectively [5]. Subscribers can enjoy a broadband experience just as they would with FTTH, without the hassle of paying and waiting for a contractor to dig up their front lawn to bury a physical fiber line in their home. Figure 2.6 shows the deployment time and process for both technologies, thus FWA greatly reduce CAPEX/OPEX.

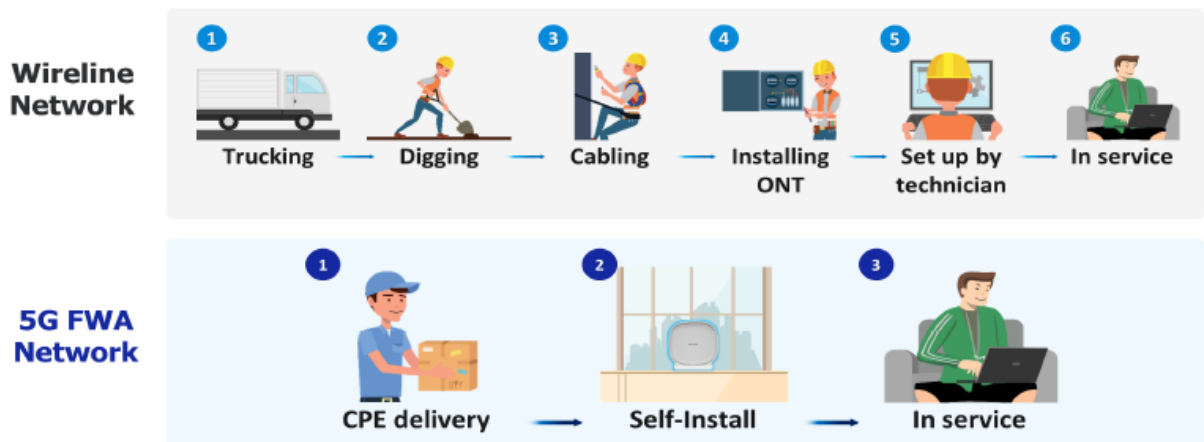


Figure 2. 6 Process to deploy Wireline and 5G FWA network [20].

5G FWA is one potential solution to improve the highly increased demand and enable the convergence between fixed and wireless. Traditionally, different operators offered fixed broadband and mobile services over separate technologies. However, recently, a convergence between mobile and fixed network has started to emerge via 5G mobile network [26]. As we can see in Figure 2.7, it becomes possible to provide alternative services with the 5G network, as illustrated below.

5G AS COPPER/FIBER ALTERNATIVE

- › Desire to offer 100 Mbps – 1Gbps access to buildings and households
- › Subscribers can easily be added 'on request'
- › No digging to the buildings needed – only simple mounting of a customer premises equipment = 5G terminal

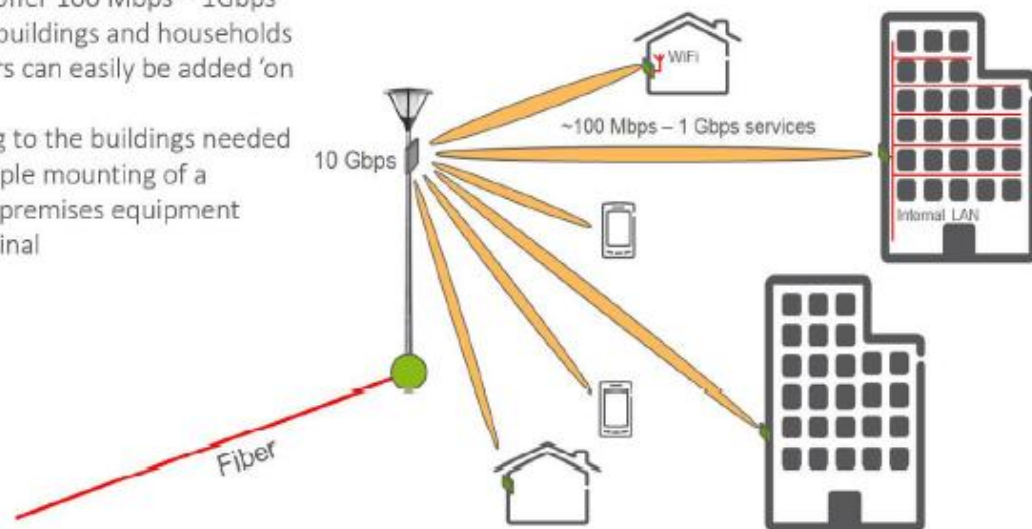


Figure 2. 7 5G as copper / fiber alternative (Ericsson 2015, 1), slightly adapted [19].

Alongside the benefits, there are also several challenges with FWA, where the signals are susceptible to various losses, including propagation losses, distance from wireless infrastructure, dense tree foliage, and other impairments that directly affect the system's signal strength. In contrast, fiber offers better performance, higher throughput, symmetric traffic, and predictable traffic [27]. Table 2.8 summarizes the differences between FWA and ODN-based networks.

Table 2. 4 Comparative summary between FWA and ODN [27].

Category	FWA		ODN	
	Pros	Cons	Pros	Cons
Deployment	Quick market entry	The characteristics of propagation (foliage, material, and clutter) have an impact on range	Can be deployed in any terrain	required long term and permitting are required
Quality of Service		Variable depending on location	Consistent and Predictable	
Throughput Availability		Decreases proportionally to distance, varies depending on obstructions in the signal path traffic is asymmetric in favor of the down link	Constant and predictable traffic; traffic can be symmetric	Service disruption caused by a fiber cut
Number of users	Cell densification is required for capacity to support a higher throughput number of users	Variable depending on deployment scenario and other factors	Linearly and scalable	

CHAPTER THREE

3. Techno-economic Analysis Modeling and Evaluation Methods

3.1 Introduction to Techno-economic Analysis (TEA)

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]. 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, many European research projects have used and extended the below-mentioned methodologies in the telecom industry within their application areas, as listed in Table 3.1 [11].

Table 3. 1 TEA models and their application areas [6] [11].

Model	Area	Example
Techno-Economic Results from ACTS (TERA)	Comparing broadband radio and satellite system fixed such as access networks, fixed and wireless technology (Second Generation (2G), Third Generation (3G) and LTE) multimedia broadband services on the system	Fixed WiMAX vs. ADSL
Techno-economics of IP Optimized Networks and Services (TONIC)	New business models to offer IP based mobile services (competitive scenario) Mobile IP service provisioning ,in 3G mobile and IP service over fixed networks	Feasibility study, broadband over cable TV network
Techno-economics of integrated Communication Systems and Services (ECOSYS)	General telecommunication projects emerging mobile: technology, services and business	Virtual service operator, TV on mobile, broadband service on fixed WiMAX

TEA is an integrated evaluation of the technological performance and economic feasibility of a new process or value chain, with the most important underlying parameters for its economic feasibility [28].

The following are the main objectives of TEA:

- To find the optimal choice for a different technology;
- Is a decision-making tool used to evaluate available technology;
- To study feasibility of emerging different technologies and services;
- Is used to evaluate investment feasibility economically and technically;
- To know a cost-effective network deployment and find efficient technology;
- Check the viability of investments before entering a new or existing market and
- Identify scenarios in deploying new technology or utilizing available resources.

3.2 Techno-economic Result from ACTS (TERA) Framework

TERA is the most widely used and popular techno-economic tool in the telecom industry. It was developed during the fourth program of scientific research and development as part of the European Union's Advanced Communications Technologies and Services (ACTS) program (1994-1998) [29].

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 investments 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].

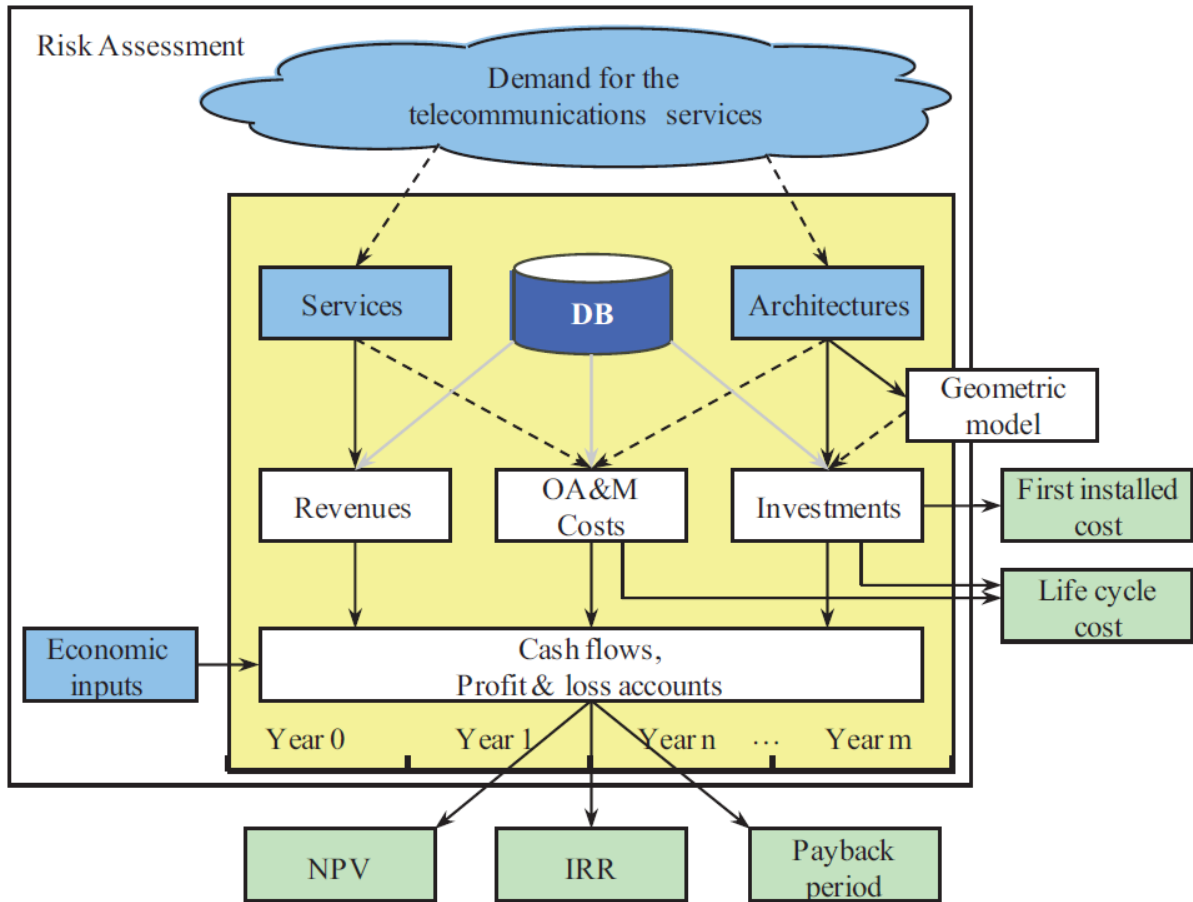


Figure 3. 1 TERA Framework [6] [10].

3.3 Cost Modeling

Generally, costs can be divided into two categories: investments and operational costs, or CAPEX and OPEX. In this study, two types of cost modeling approaches were used. The first one is top-down modeling. It begins with reference values from a similar project or business as inputs. It uses observed CAPEX, OPEX, and service usage levels to calculate costs per service or customer [29]. The second is bottom-up modeling, in this approach, all costs upward, starting at the bottom and accounting for each expected cost of labor, equipment, indirect and direct costs. It is the most accurate means of estimating total costs. The bottom-up method is preferred and frequently used when calculating investments in techno-economic modeling. Operational costs are commonly modeled using a combination of the two approaches [31].

3.3.1 Capital Expenditure (CAPEX)

CAPEX is the initial investment cost in network deployment for equipment, infrastructure, or upgrading costs [32]. These costs are calculated based on the results of network dimensioning, which determines the number of network equipment required for ODN and 5G FWA deployment. CAPEX is mathematically modeled by using the following formula [33].

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

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

The key components of the ODN CAPEX model are divided into three categories. Such as, costs of installation work, civil work, and equipment costs. The 5G FWA is also divided into five major categories. These include equipment costs, site build-out costs, installation, fiber backhaul costs, and power-related costs.

This model considers cost information from vendor databases, well-known industry price catalogs, and ethio telecom project documents when deploying ODN, LTE/LTE-A and 5G in Addis Ababa. In addition, some literature related to ODN and 5G FWA cost modeling are considered.

3.3.2 Operational Expenditure (OPEX)

OPEX is the cost associated with network deployment that is necessary for the ongoing operation of the business [32]. Typically, OPEX related costs are modeled using the calculated number of required network elements as inputs. This includes maintenance and operational costs, site rental costs, and energy consumption costs [33]. Mathematically, the CAPEX can be expressed as:

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

Where: j customer driven and network driven costs, $N_j^{(i)}$ is the numbers of item j type elements operated during in year i , C_j^{opex} is per unit operating cost for each asset j in the first year, P_j^{opex} is yearly price trends and $OPEX^{(i)}$ is the operational expenses in year i .

ODN OPEX was calculated using the actual project proposal. Accordingly, monthly reports produced by the operators and related literature are used to estimate the annual OPEX for the study.

3.3.3 Total Cost of Ownership (TCO)

TCO is the overall cost associated with the network's investment, operation, and maintenance throughout its lifetime [34]. It can be calculated using the following general formula.

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

Where: TCO is total cost ownership of the network, CAPEX is capital expenditures cost resulted from dimensioned network result and OPEX is operation expenditures cost assumed for the system.

3.4 Revenue Modeling

A revenue model specifies how much an operator will charge customers for a service in order to generate revenue and it is based on the number of subscribers, the ARPU, and the market share [32] [35]. The revenue of each scenario can be calculated by the following formula.

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

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

Where: R_T is the total revenue generated, N_S is the predicted number of subscribers, ARPU is the average revenue per user and M_S is the broadband market share.

3.5 TEA Evaluation Method

One of the most important things in TEA is to determine whether a project is profitable or not. For techno-economic evaluation, Cash Flow (CF) and Discounted Cash Flow (DCF) are used, and the most common economic decision-making tools used to measure a project's profitability are its NPV, IRR, and PBP, which are applied in this study.

3.5.1 Cash Flow (CF)

CF refers to the amount of cash received and disbursed within the study period. Based on the outputs from the costs and revenue model, it can be modeled mathematically by the following formula [36].

$$CF = \sum_i^T (R_T - C_T)_i \quad (3.6)$$

Where: CF is the cash flow, R_T Total revenue, C_T Total cost of the network (TCO) and T is the study period.

3.5.2 Discounted Cash Flow (DCF)

Using a discounted rate, the discounted cash flow method (DCF) determines the present value of a company's future cash flows to arrive at a current estimate of its fair value. DCF is modeled mathematically, as shown in the below formula [32] [10].

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

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

3.5.3 Investment Decision Making Metrics

3.5.3.1 Net present value (NPV)

The NPV is the difference between the present value of cash inflows and cash outflows over a given period. NPV is used in capital budgeting and investment planning to analyze the profitability of different network deployment scenarios. In general, projects with a positive NPV

are worthwhile, whereas those with a negative NPV are not. NPV obtained as shown in below formula [37].

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

Where: NPV is Net Present Value, T is the study period, CF_i is the cash flow occurring in time T and r is discount rate.

3.5.3.2 Internal Rate of Return (IRR)

IRR is a metric used in financial analysis to calculate the profitability of potential investments. In a discounted cash flow analysis, it makes a discount rate of the NPV all cash flows equal to zero. This makes the present value of the cash flow stream equal to the initial value of the investment [37]. IRR can be calculated by using the following formula:

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

Where: NPV is Net Present Value, T is total number of study period, IRR is Internal Rate of Return, and CF is cash flow.

According to the IRR principle, the higher the IRR, are the more desirable deployment, and it considered as the best and would be undertaken first.

3.5.3.3 Pay-back Period (PBP)

PBP is the amount of time it takes for an investment to reach its breakeven point. Shorter payback periods indicate more attractive investments, whereas longer payback periods indicate less desirable investments [32] [37]. The PBP can be expressed mathematically as follows:

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

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

3.5.4 Sensitivity Analysis

Sensitivity analysis is conducted to identify how much variation in input values for a given variable affects the results of an output [10]. The results can be visualized by a sensitivity analysis graph with a tornado diagram and the sensitivity of each input is mirrored by the change or variation in output within the normal value to examine how changing input assumptions affects the prediction [38].

CHAPTER FOUR

4. Network Dimensioning

Network dimensioning is the first stage of the network-planning phase, used to calculate the necessary site density and site configuration data for the target area to fulfill the coverage and capacity requirements [5]. Dimensioning activities include calculating cell range, sector throughput, and estimating the amount of network equipment needed. The results obtained in this phase are used as input for TEA to estimate the required resources and cost of the network. Two values were obtained during this stage: one from the coverage dimensioning and the other from the capacity dimensioning. From these two results, according to the dimensioning rule, the larger of the two numbers used as the final output [29]. The overall flow chart of the network dimensioning approach applied in this thesis is shown in Figure 4.1.

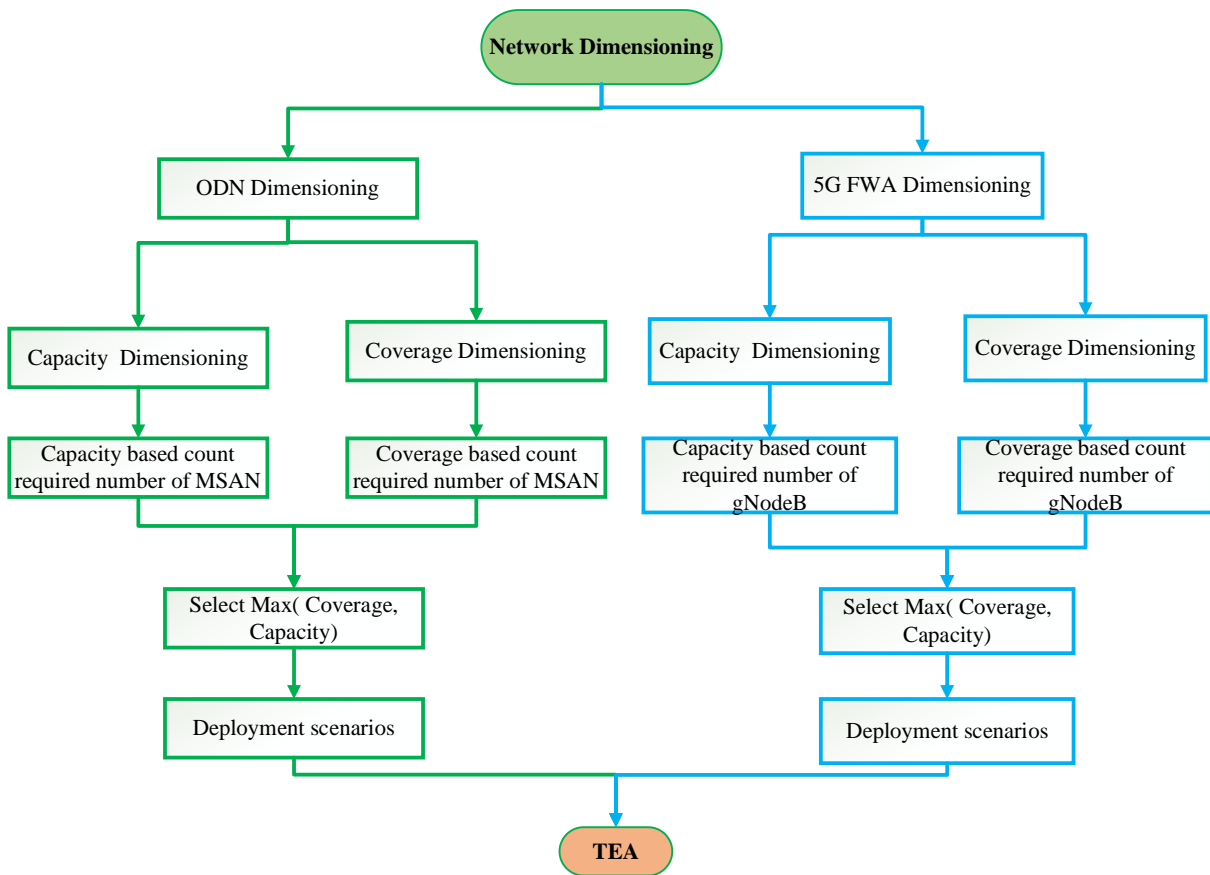


Figure 4. 1 Network Dimensioning Approach.

4.1 5G FWA Coverage Dimensioning Approach

The coverage dimensioning process begins with Radio Link Budget (RLB) calculations, which are used to calculate the path loss for the Downlink (DL) and Uplink UL radio link budgets [5]. Link budget calculations estimate the maximum allowed signal attenuation, path loss, between the User Equipment (UE) and gNodeB antennas. It also estimates the required Signal-to-Interference-Noise Ratio (SINR) level at the receiver, taking interference and shadow into account [39]. The procedure of 5G FWA coverage dimensioning is summarized in below Figure 4.2.

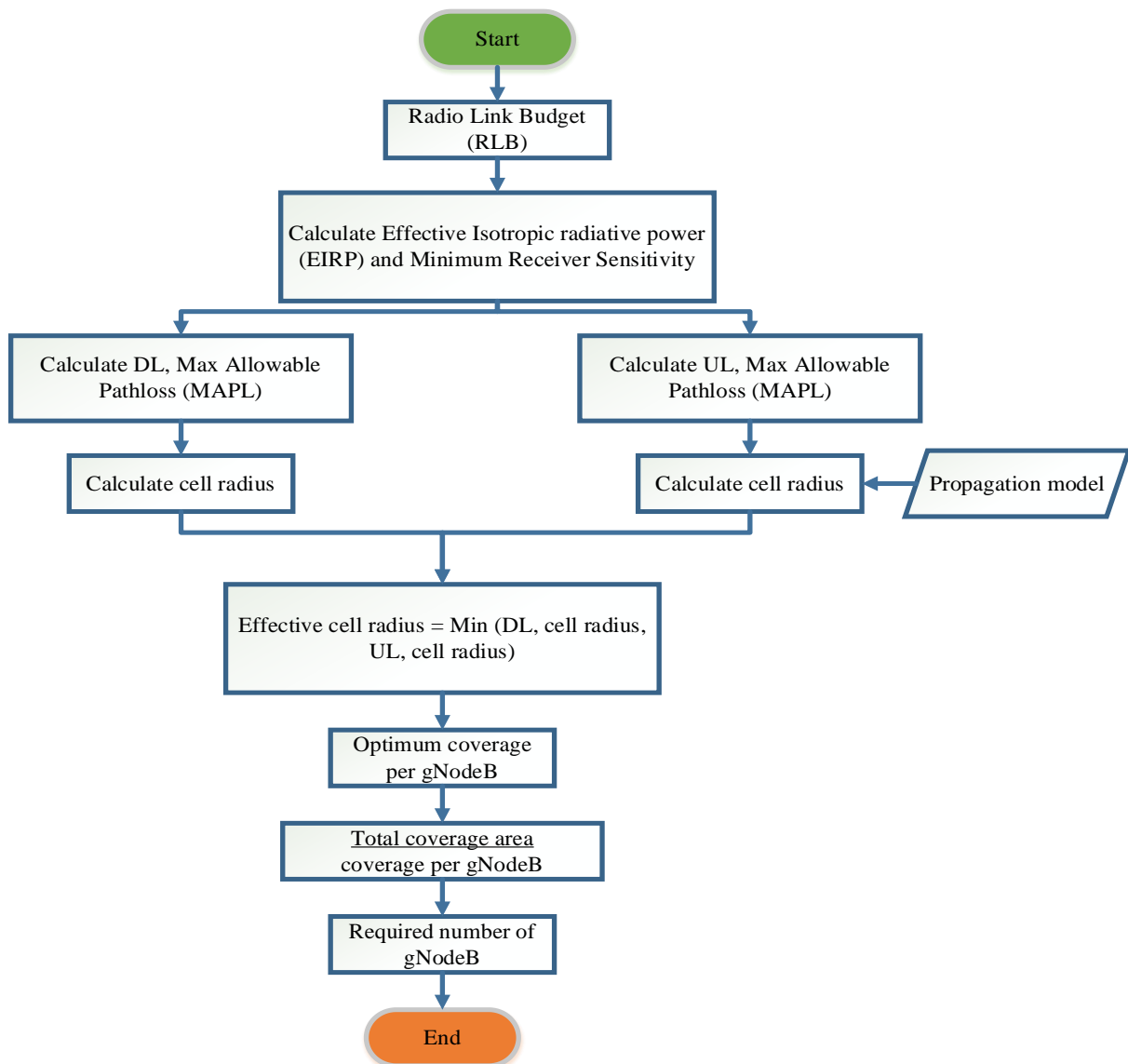


Figure 4. 2 5G FWA Coverage Dimensioning Flow Chart.

The following are the primary goals of coverage dimensioning:

- To determine the coverage area of each gNodeB;
- To calculate the maximum allowable path loss;
- Determine the estimated resources required to provide service in the deployment area;
- To ensure that the amount of base stations is enough to reach the customers in a certain area.

4.1.1 Propagation Model

Propagation models are extremely useful in network planning, particularly for feasibility studies and initial deployment. Because of a proper understanding of the propagation model is critical in the dimensioning and planning of wireless communication [40]. These models are broadly classified into three models: empirical, deterministic and stochastic models [41].

- **Empirical models:** The models solely based on observations and measurements. These models primarily used to predict the path loss.
- **Deterministic models:** The models uses electromagnetic wave propagation laws to determine the received signal power at a specific location.
- **Stochastic models:** These models are the least accurate, but they require the least amount of information about the environment and use significantly less processing power to generate predictions. It also models the environment using a series of random variables.

This thesis is mainly based on empirical propagation model. For predicting path loss in the 3.5 GHz frequency range, the several propagation models are available, including the Stanford University Interim (SUI) model, Cooperation of Scientific and Technical Research (COST)-231 Hata model, and the Okumura-Hata model [41]. The COST-231 Hata model was chosen from the empirical propagation model for this study because it can predict path loss in all environments and is appropriate for the target area [40] [42].

COST-231 Hata Propagation Model

The model was developed by the European Cooperation in the field of Scientific and Technical Research action 231 groups [43]. This model only needs the central frequency and distance

between transmitter and receiver as input variables for computation. COST-231 Hata propagation models are typically used for carrier frequencies ranging from 1500 to 2000 MHz. The same model can be used for higher carrier frequencies because we assume that the loss caused by the higher frequency is compensated by an increase in antenna gain [29]. It is a simplified model, it does not require actual geographical information about the deployment area, such as street width, building height, and building separation distance. The expression of path loss in COST 231-Hata or modified Hata model is given by [44];

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

Where: PL is path loss (dB), f is the frequency used in MHz, h_{BS} is Base Stations (BS) antenna height(m), d is the distance (Km) between the transmitter and receiver antenna, h_{ue} is UE antenna height(m), C_o is 0 dB for suburban and 3 dB for urban areas.

In addition, the following formulas are used to express the UE antenna height correction factor for urban, suburban, and rural areas.

$$\text{Urban area: } a(h_{UE}) = 3.2[\log(11.75 * h_{UE})]^2 - 4.79 \quad (4.2)$$

$$\text{Suburba(rural)area: } a(h_{UE}) = 1.1 \log(f) - 0.7h_{UE} - (1.5 \log(f) - 0.8) \quad (4.3)$$

4.1.2 Operating Frequency and Bandwidth

The primary inputs considered when dimensioning coverage are the operating frequency band and bandwidth. Operating frequency band was chosen based on 3GPP Release 15 recommendations for 5G New Radio (5G NR) deployment [24]. Bands 77 and 78(3300-4200 and 4400-5000 MHz), also known as C-bands are developing as the primary frequency bands for the deployment of 5G, providing an optimal balance of coverage and capacity for cost-effective implementation. It employs massive MIMO, Time Division Duplex (TDD), and the availability of at least 100 MHz channels and bandwidth per 5G network to increase peak, average, and cell edge throughput [25].

In most cases, higher frequency is used for coverage improvements, whereas lower frequencies are preferred for wider coverage areas [25]. A multi-layer spectrum approach divides this range into three scenarios based on their requirements [24]:

Coverage and Capacity Layer: In this layer frequency range from 2 GHz to 6 GHz are used to provide optimum capacity and coverage.

Super Data Layer: It utilizes frequencies above 6 GHz, such as 24.25-29.5 and 37-43.5 GHz, to handle particular use cases requiring extremely high data rates.

Coverage Layer: It uses spectrum below 2 GHz, such as 700 MHz, to provide extensive and in-depth indoor coverage.

Table 4. 1 The summary of selected frequency bands and propagation models for this thesis.

Propagation Scenario	Frequency band (GHz)	Propagation model	Bandwidth	Mode
Urban (small city)	C band (3.5)	COST-231 Hata	100MHz	TDD

4.1.3 Radio Link Budget Parameters Modeling

The basis of the radio link budget in 5G is the same as in previous mobile systems; the path loss is estimated based on key parameters, taking into consideration the set of gains and losses. The RLB determines the Maximum Allowable Path Loss (MAPL) between the transmitter and receiver in both the UL and DL directions. The cell radius can be calculated for various terrain morphologies by comparing the MAPL with the path loss of the appropriate propagation model. The RLB takes into account a number of factors that influence the final cell coverage. To calculate all gains and losses, these factors include building penetration loss, feeder loss, antenna gain and radio link interference margins [45]. Several parameters used to estimate the radio link budget are described below;

- **gNodeB Transmitter Power:** It is the maximum transmission power per each branch of the transmitter having a typical value of 46dBm [12] [46].
- **gNodeB Antenna Gain:** The antenna gain is proportional to the antenna size and beam width of the horizontal or vertical antenna patterns. The antenna gains and beam width are chosen based on the type of clutter and the required coverage [12]. A low gain antenna (15-17dBi) can be used in dense urban and urban clutters, whereas a high gain

antenna (18-20dBi) can be used to extend Radio Frequency (RF) coverage in rural areas and highways [46].

- **UE Maximum Total Transmitter Power:** Denotes the UE transmit power, which is dependent on the UE power class and has a typical value of 23dBm [46].
- **Loss:** Includes cable and body loss at both the gNodeB and UE. The cable loss value is determined by the cable length, it varies from 1-6 dB for gNodeB. Body loss occurs when the UE is held close to the user's head, and it is nearly 2-3 dB in practical planning [39].
- **Effective Isotropic Radiated Power (EIRP):** It is used to specify how much transmitted power is radiated in the desired direction and includes the gain of the transmitter antenna as well as the losses in transmission cables and connectors. It can be calculated using the following formula [42]:

$$EIPR = P_{Tx} + G_{Tx} - \sum Total T_x losses \quad (4.4)$$

Where: P_{Tx} is the transmitter power (dBm), G_{Tx} is the transmitter antenna gain (dBi) and Total T_x losses is cable and other losses on the transmitter side (dB).

- **Cell Edge User Throughput:** It is the lowest net single UE target throughput required at the cell edge. Typically, the network operator will provide this parameter based on the necessary services at the cell edge.
- **Thermal Noise:** Thermal noise is a loss caused by heat and can be expressed as [12]:

$$N = KBT \quad (4.5)$$

Where: K is Boltzmann constant = $1.38066 * 10^{-23}$ J/K, T is absolute temperature at a value of 290 K and B is channel bandwidth which is 100MHz for this study and N is Thermal noise (dB).

- **Noise Figure:** It is the ratio of the SINR at the receiver input end to the SINR at the receiver output end and used to evaluate the receiver's performance. The typical value of the noise figure is between 6 and 8 dB [46].

- **Signal to Interference Noise Ratio (SINR):** The value of SINR depends on the receiver design, which is derived from the outcomes of system-level simulations. Thus, SINR parameter is based on vendor specifics.
- **Receiver Sensitivity:** It indicates the minimum signal strength required for decoding by the gNodeB or UE receiver in the absence of interference and is expressed as [42]:

$$R_s = N_F + SINR + N \quad (4.6)$$

Where: R_s is receiver sensitivity (dBm), noise figure (dB), SINR is signal-to-interference-noise ratio (dB) and thermal noise (dB).

Slow/Shadow Fading Margin: It is the fading caused by the blocking of a natural feature.

The slow fading difference is determined by the standard deviation of slow fading, and shadow fading is caused by location changes. Depending on the nature of the clutter, the slow fading standard deviation ranges from 5 to 12 dB.

- **Body loss:** Is loss results from signal delay and immersion when a terminal antenna is close to the body.
- **Transmitter Power:** This includes the gNodeBs, which influences the downlink budget, as well as the terminal sides, which influence the uplink budget.
- **Feeder Loss:** It is the loss caused by various devices located along the path of the antenna to the receiver.
- **Penetration Loss:** It is the fading of radio signals caused by a building obstruction from an indoor terminal to the gNodeB and vice versa. This is determined by the nature of the buildings and the category of clutter in the targeted coverage area. Table 4.3 displays the penetration losses based on the type of clutter [42].

Table 4. 2 Penetration losses based on clutter type [42].

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

- Maximum Allowable Path Loss (MAPL):** It enables the maximum cell range to be valued with appropriate propagation models that provide the number of gNodeB sites required to cover up the target area. The maximum allowable path loss is expressed as follows [46]:

$$MAPL = EIRP - R_s - P_L - S_m - I_m + G_{RX} \quad (4.7)$$

Where: $EIRP$ is 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), and G_{TX} is the transmitter antenna gain (dBi)

Table 4. 3 5G FWA Radio Link Budget DL/UL Parameters [39] [46].

Parameters	Downlink/Uplink Budget Variable
General Link Budget Parameters	
Morphology	Urban (small city)
Data channel type	PDSCH/PUSCH
Duplex mode	TDD/TDD
User environment	Indoor, Outdoor
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

Factor A and B	0.4 and 1.1
Transmitter (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 sub carrier (dBm)	$E=A+B-C-D$
Receiver (UE) Link Budget Parameters	
UE noise figure (dB)	F
Sub carrier spacing (kHz)	I
Sub carrier	J
PRB size (kHz)	$G=I*J$
Thermal noise (dB)	$L=KBT$
Receiver noise floor (dBm)	$M=F+L$
SINR (Linear)	$N=Factor\ B*(2^{(Data\ rate/Factor\ A)}-1)$
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
Clutter Link Budget Parameters	
Shadowing fading loss (dB)	T
Cell edge coverage probability	90-95%
Interference margin (dB)	V
Indoor penetration loss (dB)	W
Maximum Allowed Propagation Loss (MAPL)	
MAPL (dB)	$MAPL=E-P-Q+R-S-T-V-W$

4.1.4 Cell Area and Site Count

After the MAPL calculated in both UL and DL, the next step is to calculate the cell radius using the proper propagation model. The COST-231 Hata model is used in this study to compute the path loss for cell radius. In most network planning studies, the site coverage area is modeled as hexagonal, and we assume that the site configuration is hexagonal as well [44]. As illustrated in Figure 4.3, depending on the site arrangement, the site configuration can be Omni-directional, bi-sector, or tri-sector.

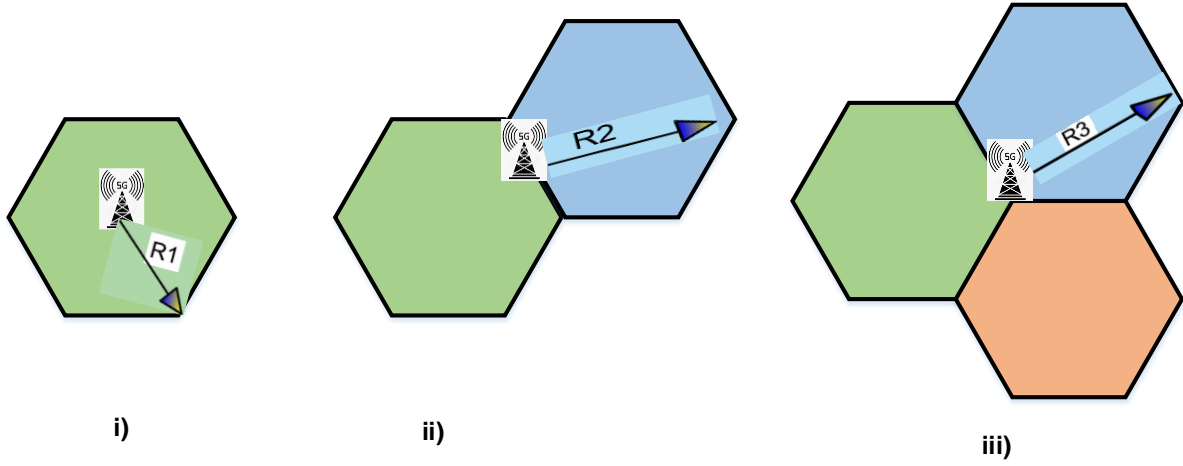


Figure 4. 3 Different types of site arrangements i) Omni-directional, ii) bi-sector and iii) tri-sector.

The site area is calculated as follows for each of the site configurations depicted in Figure 4.3:

$$\text{For Omni-directional: } SA(A_{cell}[km^2]) = \frac{3 \cdot \sqrt{3} \cdot [R_1]^2 [km]}{2} \quad (4.8)$$

$$\text{For bi-sector: } SA(A_{cell}[km^2]) = \sqrt{3} \cdot [R_2]^2 [km] \quad (4.9)$$

$$\text{For tri-sector: } SA(A_{cell}[km^2]) = \frac{9}{8} \sqrt{3} [R_3]^2 [km] \quad (4.10)$$

Where: SA is site area and R is cell radius.

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

$$T_{Ns} = \frac{T_{CA}}{SA} \quad (4.11)$$

Where: T_{Ns} is total number of sites and T_{CA} is target coverage area.

4.2 5G FWA Capacity Dimensioning Approach

Capacity dimensioning is used to estimate the resources required to support a specified offer traffic with a certain level of Quality of Service (QoS), throughput, or blocking probability. The capacity dimensioning of the 5G FWA is dependent on the required data plan per user, modulation scheme, coding and available bandwidth and SINR delivery in the cell [44]. Figure 4.4 depicts capacity-dimensioning flow charts for 5G FWA.

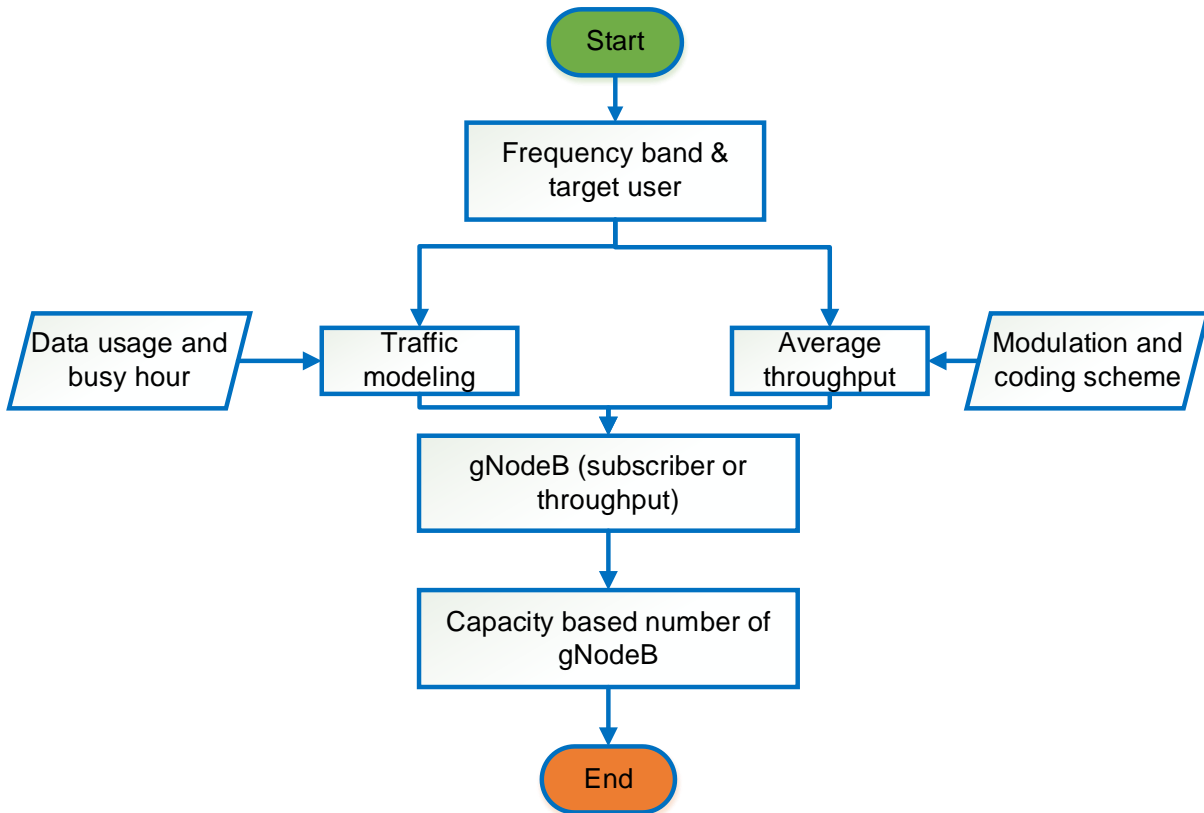


Figure 4. 4 5G FWA Capacity Dimensioning Flow Chart.

4.2.1 Aggregate Throughput or Data Rate Modeling

Throughput is the maximum data rate that a communication system can transmit, and it is defined as a quality indicator expressed as the data transfer rate of usual and non-redundant information. The main objective of the capacity planning exercise is to get an estimate of the

site count based on the capacity requirements. Where network operators establish capacity requirements based on predicted traffic and average cell throughput required to calculate the capacity-based site count [44].

The aggregate throughput is modeled based on the 3GPP TS 38.306 standard of 5G NR [47]. The maximum data transfer rate for DL and UL can be calculated by the following formula [47]:

5G NR Throughput (in Mbps)(DL and UL)

$$= 10^{-6} \sum_{j=1}^J \left(v_{Layers}^{(j)} * Q_m^{(j)} * f^{(j)} * R_{max} * \frac{N_{PRB}^{BW(j),\mu} \cdot 12}{T_s^\mu} (1 - OH^{(j)}) \right) \quad (4.12)$$

Where:

- 10^{-6} - Constant (because of Mbps).
- j - Represents the number of aggregated components carriers in a band or band combination, the maximum value of j up to 16.
- $v_{Layers}^{(j)}$ - Represents the maximum number of MIMO layers, the maximum Value is 8 in DL and 4 in UL.
- $Q_m^{(j)}$ - Type of modulation QPSK (2), 16QAM (4), 64QAM (6) and 256QAM (8).
- $f^{(j)}$ - Is the scaling factor used for medium and high mobility and should be set up per carrier. It has the possible values of 0.4, 0.75, 0.8, and 1.
- R_{max} - Is the value determined by the 3GPP 38.212 and 3GPP 38.214 encoding types. For Low Density Parity Check (LDPC), the maximum number is 948/1024
- $N_{PRB}^{BW(j),\mu}$ - Maximum number of allocated Physical Resource Block (PRB) in bandwidth per subcarrier spacing. For 100MHz bandwidth, 30 KHz subcarrier spacing and 273 PRB are used.
- T_s^μ - Represents the average duration of the OFDM symbol in a frame. For the value, μ (i) is normal cyclic prefix $T_s^\mu = \frac{10^{-3}}{14 \cdot 2^\mu} = 3.577 * 10^{-5}$
- $OH^{(j)}$ - Represent the control channel overhead. The typical value for DL and UL for FR1 is 0.14 and 0.08 respectively, whereas for FR2 it is 0.18 and 0.10 respectively.

4.2.2 Traffic modelling

The main objective of the traffic model is to describe the average subscriber behavior during the busiest time of day, known as Busy Hour (BH). The capacity of a site should base on BH because traffic is not equally distributed across 24 hours [5].

The BH is assumed to be in three different section within 24 hours of the day. The first section is between 10:00 and 11:00 in the morning, the second section is between 3:00 and 4:00 in the afternoon, and the third section is assumed to be between 8:00 and 9:00 in the evening [12]. Thus, 3 hours are considered to be the BH within 24 hours of a day, making the BH traffic 12.5% of the daily traffic. In this thesis, the daily traffic is assumed to be 12.5%. The following formula is used to calculate the average total throughput per subscriber at the BH:

$$Av. \text{ throughput at BH (in Kbps)} = \frac{\text{Monthly service package} \times 8 \text{ bit/byte}}{\text{Number of days} \times \text{Time in seconds}} \times \text{BH ratio} \quad (4.13)$$

Where: The monthly service package is based on traffic usage within a month in Gigabytes.

4.2.3 Capacity Based Site Counts

After estimating the traffic model and all capacity requirements, the capacity-based site count is calculated using the below formula;

$$\text{Max. no of sub per gNodeB (DL, UL)} = \frac{\text{Aggregate capacity throughput per site (DL,UL)}}{\text{Av.throughput per subscriber at BH}} \quad (4.14)$$

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

$$\text{Capacity based site count(DL, UL)} = \frac{\text{Total Number of subscriber}}{\text{Max. no of sub per site(DL,UL)}} \quad (4.15)$$

4.3 ODN Coverage Dimensioning Approach

The first step in the coverage dimensioning process is conduct a site survey in the target area to evaluate the environmental factors and determine whether the location is appropriate for installing fiber. The engineers choose the planning method based on the observed and gathered data; depending on the geographical topology, it may be aerial, duct, underground, or hybrid. Next, to determine the territory of the MSAN the actual environmental factors like main roads,

rivers and technical factors such as link loss or power loss limit the coverage dimensioning. Following the boundary determination, in the topology preparation stage, cable plans such as schematic plans, cable maps (cable routes), and distribution maps will be prepared by using Automatically Computer Aided Design (AutoCAD) or Geographic Information System (GIS) software planning tools.

In this thesis, the ODN network dimensioning is based on ethio telecom's actual data for the selected area, but the methodology used to dimension the network is explained here for both a coverage and capacity dimensioning approach.

Figure 4.5 depicts the ODN Coverage dimensioning approach for determining the number of MSAN required based on the actual geographic coverage.

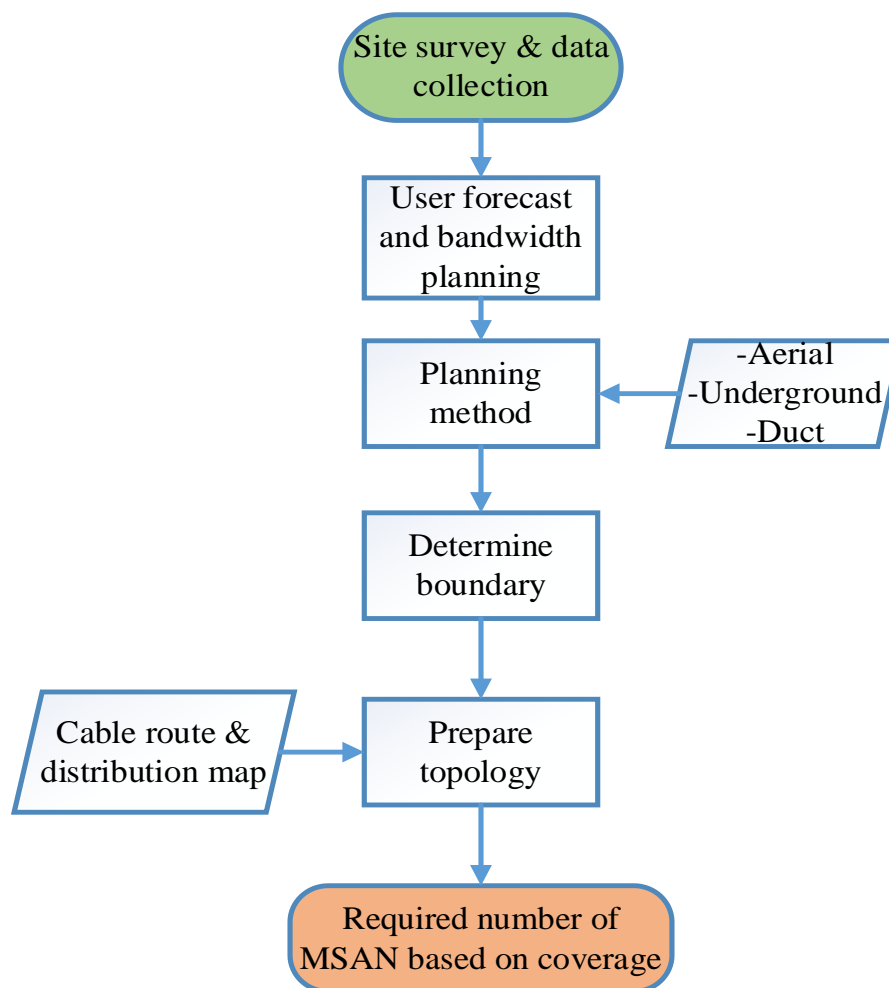


Figure 4. 5 ODN coverage dimensioning process.

4.3.1 User Forecast and Bandwidth Planning

Bandwidth planning is necessary to meet existing demand and future expansion. This will be carried out following a data collection and the identification of the target area's customer type. Typically, we are forecast users based on key information such as user growth trends in previous years, regional population, population density, quality of life, and penetration factor [7]. In addition, optical power and bandwidth are determined by a split ratio, which influences the power budget required to support physical reach.

User forecasting and bandwidth planning are done to determine the minimum data rate required per user and the physical reach in order to determine the capacity and coverage requirements. The user bandwidth required for each service type is shown in Table 4.5 below.

Table 4. 4 User forecast and bandwidth required per user [7].

Service	Service type	Bandwidth required (Mbps)
Data	Browsing the web, writing, and sending emails	5Mbps
Voice	VOIP, Video telephony and Voice conference	1Mbps
Video	Music on demand, multimedia contents	2Mbps
	Online gaming	2Mbps
	SD Digital TV	8Mbps
	HD Digital TV	15Mbps
	Netflix Full HD	25Mbps
	Amazon Prime Video	25Mbps
	Additional TV channels (i.e. 2 HDTV)	20Mbps
	Streaming videos, movies, and music	10Mbps
	Video conferencing	15Mbps

According to ITU-T G.984, the maximum differential fiber distance is 10 - 20 km physically and reaches 60 km logically. Therefore, with in this range, the engineers can determine the number of required MSAN for the target area based on the environmental condition and prepared topology.

4.4 ODN Capacity Dimensioning Approach

The capacity of MSAN is determined by GPON card type and the number of splitting ratios to be used. Fiber optic cable-based communications have a top capacity and often limited by the hardware, either type of cable itself. Because a single optical core with a GPON can be divided into ratios of 1:32, 1:64, 1:128, and 1:256. The capacity dimensioning process that needs to be carried out in ODN is summarized in Figure 4.6.

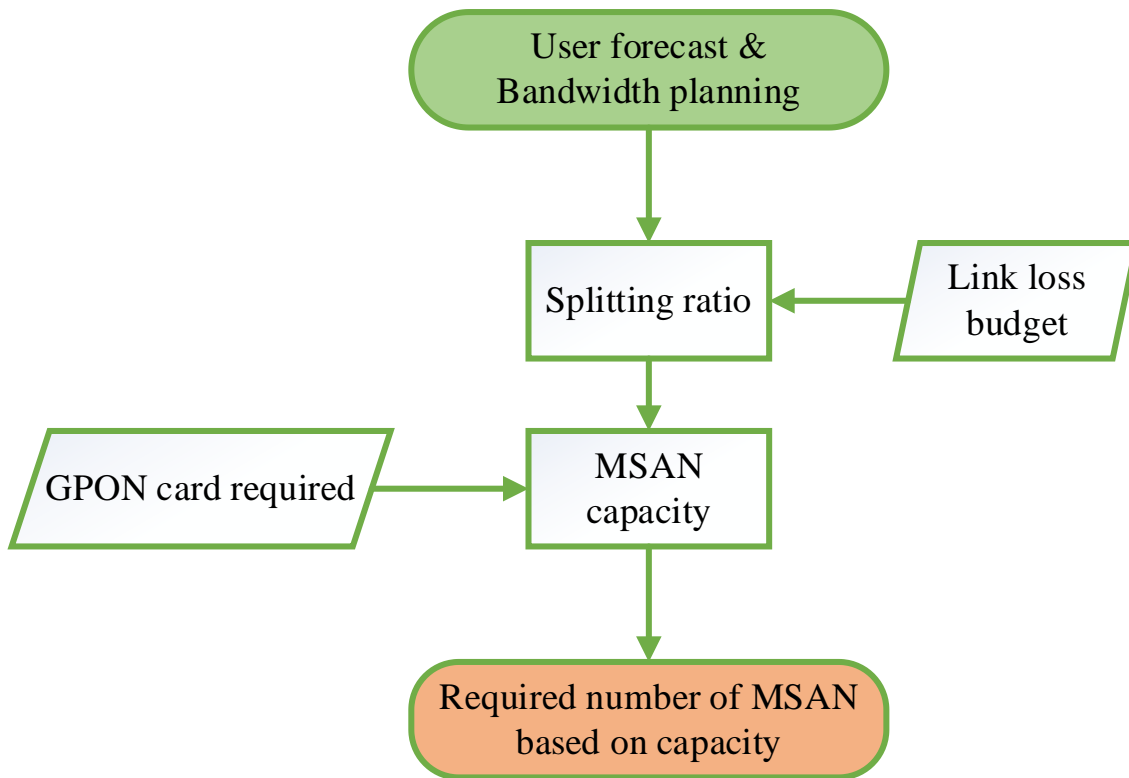


Table 4. 5 ODN capacity dimensioning process.

Optical fiber communication can reliably transmit a clear, unadulterated signal over much greater distances; however, optical fiber performance can be affected by installation loss and connector loss. Thus, the link loss budget is determined based on the chosen standard's allowed loss before beginning a capacity dimensioning approach.

4.4.1 Link Loss Budget

The link loss budget, or power loss budget, refers to the maximum amount of loss that a transmitter or receiver can tolerate in order to operate properly. This link loss is caused by cable loss, splitter loss, splicing loss, and connector loss.

Link loss modeling will adhere to the ITU G.984.2 Class B+ standard, with a maximum link loss requirement of 13dB to 28dB. To calculate the link loss budget, we will sum up all the losses in the fiber section and ensure that the planned ODN network meets the specifications. The following formula can be used to determine link loss [7]:

$$T_{loss} = L_{cable} + L_{splitter} + L_{splice} + L_{connector} \quad (4.16)$$

Where: T_{loss} is the total loss, L_{cable} is loss caused by cable type itself per length (span loss) and loop loss, $L_{splitter}$ loss caused by splitter, L_{splice} the loss due to jointing or splicing, and $L_{connector}$ is loss caused due to the mechanical connector.

The basic parameter of the ITU G.984.2 class B+ link loss requirement applied in this thesis and summarized in Table 4.5 below.

Table 4. 6 ODN link loss parameters [7].

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

Finally, after determining the link loss budget, we can calculate the capacity of MSAN, capacity of GPON card and the number of MSAN respectively as follows:

$$\text{Cap of MSAN} = \text{Splitter ratio} \times \text{No of secondary splitter} \quad (4.17)$$

$$\text{No of MSAN based on Capacity} = \frac{\text{Total number of user}}{\text{Capacity of MSAN}} \quad (4.18)$$

$$\text{Required No of GPON card} = \frac{\text{Total capacity of MSAN}}{\text{Capacity of GPON card}} \quad (4.19)$$

$$\text{No of MSAN based on Capacity} = \frac{\text{Total number of user}}{\text{Capacity of MSAN}} \quad (4.20)$$

Before we begin discussing the main components of this implemented model, we will see the site selection and deployment scenarios respectively in the next section. Because they are the primary input for the techno-economic analysis.

5.2 Site Selection

Site selection is an important step in evaluating the scenario. Because both comparison technologies are based on actual geographical conditions. As ethio telecom is the source of data for this study, the area was chosen based on expert judgments, project managers' opinions, and the ideas of various stakeholders those are directly involved in network rollout. Following these stages, Tulu Dimtu area was chosen based on ODN deployment data from various potential areas. This area is located in Ethiopian capital city, Addis Ababa under ethio telecom zone which is called, South Addis Ababa Zone (SAAZ). As illustrated in Figure 5.2, the area contains fixed and wireless resources; there are 7 existing macro base stations from the wireless side and 4 MSAN from the fixed resource side. These existing resources will be taken into account during the deployment scenario formulation.



Figure 5. 2 The selected area existing fixed and wireless network equipment with Google Maps [48].

5.3 Deployment Scenarios

Before scenario selection, it is important to note that LTE can also support fixed wireless access services. However, to deliver the fastest fiber-like internet speed and for better comparative analysis, 5G FWA-based scenarios are selected from the wireless side. In addition, we recalled that there are different types of FTTH families that deliver broadband services over optical fiber, such as PON, GPON, GE-PON, XG-PON and EPON. From this, GPON-based ODN is selected for the scenario formulation due to its better performance, and it is suitable for the selected area.

Following site selection, four scenarios were developed in this study. Thus, two scenarios are based on ODN, while the remaining two are based on 5G FWA. The basic requirements for each deployment scenario are explained below:

Scenario 1 (Sc-1): 5G FWA with New Infrastructure

In this scenario, all 5G FWA related assets will be deployed with the new infrastructure.

Scenario 2 (Sc-2): 5G FWA Using Existing Sites and Densify with New Additional Site

As shown in Figure 5.2, seven BS are currently operational. In this scenario, the operator can reuse 2G, 3G, and 4G assets like antenna and back hauling cable. Site upgrades are taken into account for the existing site's cost, and new resources are considered carefully for the additional site.

Scenario 3 (Sc-3): ODN with New Infrastructure

In this scenario, all ODN related assets will be deployed with the new infrastructure.

Scenario 4 (Sc-4): ODN with Existing and Additional New Infrastructure

The existing backhaul, duct, and other fixed network equipment can be reused in this scenario. For example, if the existing network is copper-based, the cost of upgrading to fiber considered as new.

5.4 Technical Analysis

5.4.1 5G FWA Coverage Dimensioning

The main coverage related parameters required to estimate the MAPL are RLB inputs (such as transmitter and receiver characteristics), propagation model, geographical information, and required coverage probability. The selection of the propagation model is one of the most important steps in this study. This thesis is mainly based on an empirical propagation model. Because it is a simplified model, it does not require precise geographic data about the deployment area, such as street width, building height, and building separation distance. This makes it easier to use and more accurate for the selected area. Additionally, according to my thesis's information source, the operators employ this propagation model. The following Table 5.1 provides a summary of all the standard parameters and calculated values for RLB estimation.

Table 5. 1 5G FWA DL and UL radio link budget [46].

General Parameters	DL		UL	
Morphology	Urban (Small city)			
Cell edge coverage probability	90-95%			
Propagation model	Cost-231 Hata model			
User environment	Indoor, Outdoor			
Data channel type	PDSCH		PUSCH	
MIMO Scheme	4X4		4x4	
Duplex mode	TDD		TDD	
	Value	Units	Value	Units
Operation frequency	3500	MHz	3500	MHz
Operation BW	100	MHz	100	MHz
gNodeB Transmitter Characteristics				
Data rate	100	Mbps	25	Mbps
gNodeB TX power	46	dBm	24	dBm
gNodeB antenna gain	11	dB _i	0	dB _i
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	$1.38 \cdot 10^{-23}$	J. K ⁻¹	$1.38 \cdot 10^{-23}$	J. K ⁻¹

Max number of resource block	273.000		273.000	
Sub carrier spacing (kHz)	30.000	KHz	30.000	KHz
Sub carrier	12.000		12.000	
PRB size (kHz)	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	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	dB
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	132.297	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)	0.683	km	0.538	km

The MAPL and cell radius ranges are computed for both DL and UL using Eq.4.7 and 4.2, respectively, based on the defined coverage input parameters. The obtained results for both cases are displayed in Table 5.2 below.

Table 5. 2 MAPL and cell radius range for DL and UL.

Parameters	DL	UL
MAPL(dB)	135.958	132.297
Cell radius range (Km)	0.683	0.538

5.4.1.1 Effective Radius Calculation and Coverage Based Site Count

By assuming that the gNodeB and UE antenna heights are 30 m and 1.5 m, respectively, and that all gNodeBs are three sector sites (tri-sector), the site area for DL and UL is calculated using equations Eq.4.10.

$$SA(DL) = \frac{9}{8}\sqrt{3}[R_{DL}]^2[\text{km}] = 1.949 * (0.683)^2 = 0.910 \text{ Km}^2$$
$$SA(UL) = \frac{9}{8}\sqrt{3}[R_{UL}]^2[\text{km}] = 1.949 * (0.538)^2 = 0.564 \text{ Km}^2$$

After calculating the site area, the coverage-based site count for the target area is calculated by using Eq.4.11 as follows:

$$Site\ count_{DL} = \frac{Total\ area\ to\ be\ covered\ km^2}{Area\ covered\ by\ site\ km^2\ (DL)} = \frac{4.5\ Km^2}{0.910\ Km^2} = 4.942 \approx 5\ gNodeBs$$
$$Site\ count_{UL} = \frac{Total\ area\ to\ be\ covered\ km^2}{Area\ covered\ by\ site\ km^2\ (UL)} = \frac{4.5\ Km^2}{0.564\ Km^2} = 7.976 \approx 8\ gNodeBs$$

Based on the dimensioning rule, the site area with the minimum radius is chosen. This means 8 gNodeB are taken, to meet the coverage requirements.

5.4.2 5G FWA Capacity Dimensioning

In addition to the fundamental parameters and mathematical approach described in Section 4.2, the input parameters used for the capacity dimensioning explained as follows:

5.4.2.1 Monthly Data Plan, User Category and Traffic modeling

Currently, ethio telecom offers Wireless to the Home (WTTH) wireless broadband services using LTE/LTE-A technology. These services are classified into three-user categories based on their monthly data plan; those are Gold, bronze and silver with the monthly data usage of 100 GB, 50 GB and 25 GB respectively [49].

Globally, when looking at 5G monthly data usage, Telstra's extra-large 5G plan for residential customers has 180 GB, while a large plan offering 200 GB of data is available for business users. In the six leading 5G countries, 5G smartphone users consumed between 1.7 and 2.7 times more mobile data than 4G users [50].

Based these local and global data sources, the data plan assumption per user in 5G will expected to be twice that of an LTE-A WTTW user, and the user category is divided into three categories: professional, basic, and entry level, with monthly data volumes of 50 GB, 100 GB, and 200 GB respectively.

From a practical perspective and user trends, all category cannot use 100% of the service in all time, so service usage distribution is required and assumed to be 70%, 20%, and 10% for professional, basic, and entry users, respectively, as shown in Table 5.3.

Table 5.3 User category, data plan usage and usage ratio of services.

User category	Data plan usage in GB/month	Usage ratio of the services (%)	Service type
Professional	200	70	Indoor/outdoor
Basic	100	20	Indoor/outdoor
Entry	50	10	Indoor/outdoor

Following the determination of the user category, data plan usage, and usage ratio estimation, the average BH throughput for the professional, basic, and entry user categories can be calculated using Eq. 4.13 as shown below:

$$Pro. Av. throughput at BH (DL, UL) = \frac{200 \times 10^9 \times 8 \text{ bit/byte}}{30 \times 3600} \times 12.5\% = 18.519 \text{ Mbps}$$

$$Bas. Av. throughput at BH (DL, UL) = \frac{100 \times 10^9 \times 8 \text{ bit/byte}}{30 \times 3600} \times 12.5\% = 9.259 \text{ Mbps}$$

$$Ent. Av. throughput at BH (DL, UL) = \frac{50 \times 10^9 \times 8 \text{ bit/byte}}{30 \times 3600} \times 12.5\% = 4.630 \text{ Mbps}$$

After the BH throughput for each levels are calculated, the total average throughput will be:

Total Average throughput at BH = Σ (Av. throughput service \times usage ratio of the service).

$$\begin{aligned} Total Average throughput at BH &= (18.519 \times 0.7) + (9.259 \times 0.2) + (4.630 \times 0.1) \\ &= 15.278 \text{ Mbps} \end{aligned}$$

5.4.2.2 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 summarized in Table 5.4 below [24].

Table 5. 4 DL and UL parameters used to calculate the throughputs of 5G FWA [24].

Parameters	DL	UL
Frequency	3.5GHz	3.5GHz
Bandwidth(MHz)	100MHz	100MHz
Overhead(OH)	0.14(DL) and 0.08(UL)	0.14(DL) and 0.08(UL)
Max. code rate (Rmax)	948/1024	948/1024
Number carriers(J)	8	6
Number of Layers (V)	4	4
Scaling factor/ signaled per band (f)	1	1
Max. number of Resource block	273	273
Sub-carrier per Resource block	12	12
Sub-carrier spacing	30KHz	30KHz
Average OFDM symbol duration (Ts)	$T_s^\mu = \frac{10^{-3}}{14 * 2^\mu}$	$T_s^\mu = \frac{10^{-3}}{14 * 2^\mu}$
Numerology(μ)	1	1
Bits per Symbol from modulation scheme	8	8

The maximum aggregate throughput for DL and UL in 5G NR can be calculated using Eq.4.12, as shown below:

$$DL = 10^{-6} \times 8 \times 4 \times 8 \times 1 \times \left(\frac{948}{1024} \right) \times (273 \times 12) \times \frac{14 \times 2^1}{10^{-3}(1 - 0.14)} = 18696 \text{ Mbps}$$

$$UL = 10^{-6} \times 6 \times 4 \times 8 \times 1 \times \left(\frac{948}{1024} \right) \times (273 \times 12) \times \frac{14 \times 2^1}{10^{-3}(1 - 0.08)} = 150000 \text{ Mbps}$$

Once the aggregate throughput obtained, the maximum number of users per gNodeB and total number of capacity-based site counts are calculated using Eq. 4.14 and 4.15, respectively, as follows:

$$\text{Max. no of sub per gNodeB (DL)} = \frac{\text{Throughput per site (DL)}}{\text{Av. throughput at BH}} = \frac{18696}{15.278} = 1,224 \text{ user}$$

$$\text{Max. no of sub per gNodeB (UL)} = \frac{\text{Throughput per site (UL)}}{\text{Av. throughput at BH}} = \frac{15000}{15.278} = 982 \text{ user}$$

$$\text{Capacity based site count (DL)} = \frac{\text{Total Number of subscriber}}{\text{Max. no of sub per site(DL)}} = \frac{9308}{1224} = 7.6$$

$\approx 8 \text{ gNodeBs}$

$$\text{Capacity based site count (UL)} = \frac{\text{Total Number of subscriber}}{\text{Max. no of sub per site(L)U}} = \frac{9308}{982} = 9.5$$

$\approx 10 \text{ gNodeBs}$

Finally, based on the capacity-based site count the larger number of gNodeB are taken from the DL or the UL side. Therefore, 10 gNodeB are required to meet the target area of both coverage and capacity. Table 5.5 displays the network dimensioning results as well as the best number of gNodeB required for the target area.

Table 5. 5 Summary of 5G FWA network dimensioning results.

5G FWA Dimensioning	Required number of gNodeB	Best selected number of gNodeB
Coverage	8	10
Capacity	10	

5.2.3 ODN Capacity and Coverage Dimensioning

Four MSAN are installed for capacity and coverage of the target area based on the actual geographic condition. These MSAN namely knows as, MSAN-42, MSAN-43, MSAN-44 and MSAN-45. The capacity of each MSAN determined by the type of GPON card used and the

number of splitting ratios used. By using Eq.4.17 and the data shown in Table 5.6, the capacity of each MSAN by the number of users can be calculated as follows:

$$\text{Cap of MSAN(42)} = \text{Splitter ratio} \times \text{No of sec. splitter} = 16 * 296 = 4736 \text{ user}$$

$$\text{Cap of MSAN(43)} = \text{Splitter ratio} \times \text{No of sec. splitter} = 16 * 168 = 2688 \text{ user}$$

$$\text{Cap of MSAN(44)} = \text{Splitter ratio} \times \text{No of sec. splitter} = 8 * 426 = 3408 \text{ user}$$

$$\text{Cap of MSAN(45)} = \text{Splitter ratio} \times \text{No of sec. splitter} = 16 * 218 = 3488 \text{ user}$$

Based on the existing operator's current configuration, Huawei and ZTE GPON cards are used, which can be split into 1:64 ratios theoretically. Thus, after determining the number of users per MSAN, for a 16-port GPON card with an average-splitting ratio of 1:16, the capacity of the GPON card and the capacity of the MSAN can be calculated using Eq.4.18 and Eq.4.20, respectively:

$$\begin{aligned} \text{GPON card capacity} &= \text{Number of port} \times \text{split ratio} \times \text{No of core per port} \\ &= 16 \times 16 \times 4 = 1028 \text{ user per card} \end{aligned}$$

$$\text{Req. No of GPON (MSAN - 42)} = \frac{\text{Total capacity of MSAN}}{\text{Capacity of GPON card}} = \frac{4736}{1024} = 4.6 \approx 5 \text{ GPON}$$

$$\text{Req. No of GPON (MSAN - 43)} = \frac{\text{Total capacity of MSAN}}{\text{Capacity of GPON card}} = \frac{2688}{1024} = 2.6 \approx 3 \text{ GPON}$$

$$\text{Req. No of GPON (MSAN - 44)} = \frac{\text{Total capacity of MSAN}}{\text{Capacity of GPON card}} = \frac{3408}{1024} = 3.3 \approx 4 \text{ GPON}$$

$$\text{Req. No of GPON (MSAN - 45)} = \frac{\text{Total capacity of MSAN}}{\text{Capacity of GPON card}} = \frac{3488}{1024} = 3.4 \approx 4 \text{ GPON}$$

The four MSAN are located centrally for coverage planning, to distribute the cable from the MSAN up to the customer premises, based on the actual geographic conditions. For this purpose, four types of ODN existing plan are prepared by using AutoCAD those are; duct plan with Manhole (MH) and Hand Hole (HH), pit plan, schematic diagram, and cable route plan. Samples of these plans are shown in Figures 5.3, 5.4, and 5.5 respectively.



Figure 5. 3 Sample of duct plan for civil works [48].

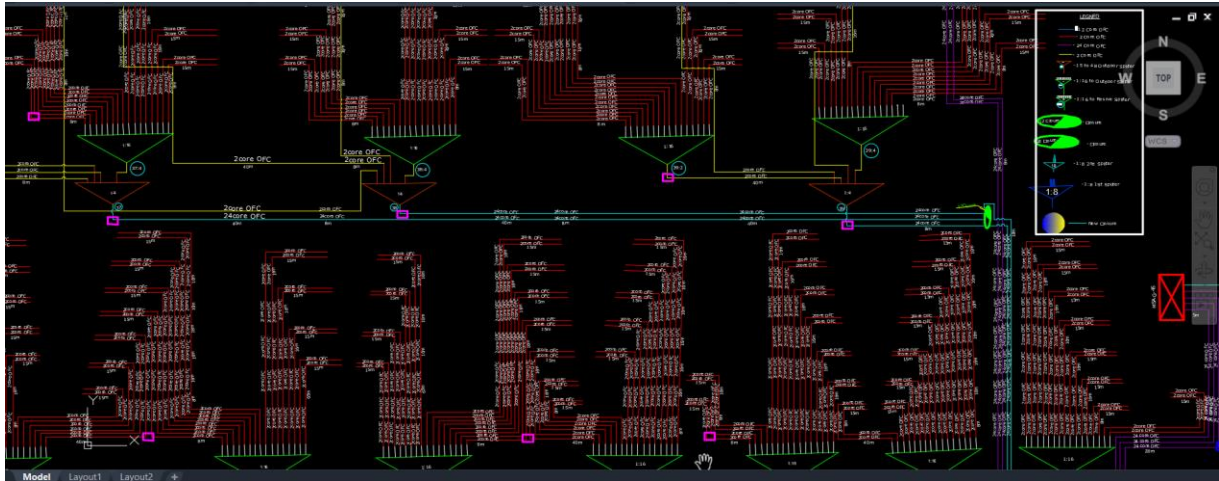


Figure 5. 4 Sample schematic plan (cable distribution) [48].

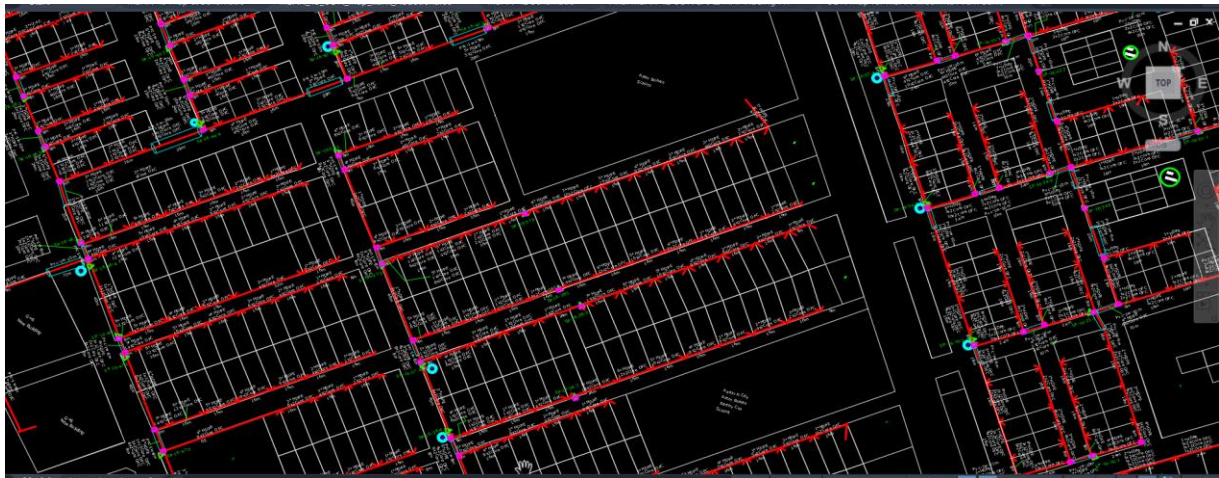


Figure 5. 5 Sample of cable map (cable route) and pit plan [48].

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.

5.5. Market Analysis

The market analysis enables the evaluation of the potential market for broadband services by defining service profiles, target markets, forecasting market penetration and revenues. The data sources considered for marketing analysis are based on the annual report of the operator (ethio telecom), business performance, user data consumption level, and pricing policy.

We recall that the targeted area is located in the capital city of Ethiopia, Addis Ababa, which is rapidly developing and has a large residential user base with the territory size of $4.5km^2$ according to google map measurement. The total number of users counted during the ODN project in the target area is around 14,320. Table 5.6 shows the total number of residential users per MSAN.

Table 5. 6 Number of user per MSAN [48].

Site Name	Secondary splitter ratio	No of splitter	Number of user per MSAN
MSAN-42	16	296	4,736
MSAN-43	16	168	2,688
MSAN-44	8	426	3,408
MSAN-45	16	218	3,488
Total number of user			14,320

5.6 Economic Analysis

The economic analysis of each scenario carried out based on the results of the market analysis and technical analysis. It primarily focuses on cost and revenue modeling for each scenario. The key components of cost modeling are CAPEX estimation, OPEX estimation, and TCO, which described in the next sub section.

5.6.1 CAPEX and OPEX Estimation

5.6.1.1 5G FWA CAPEX and OPEX Estimation

In this study, common cost sharing was used during the cost assumptions for both technologies. For instance, MSAN can support voice and data, and 5G FWA can support voice and data once the site is built out. Thus, for a fair comparison, the common costs and required cost assumptions are carefully collected based on the operator's current costs in the following subsection.

The costs for labor, site rental, and transportation are specific to the operator, and the other costs for upgrading existing BS and deploying new BS are taken from [51] [52] [53]. As some costs are in Euros, we have converted them into Ethiopian Birr (ETB) based on an exchange rate of 1 Euro=52.72 ETB (Exchange rate as of 15th July 2022). Sc-1 considers all BS deployment costs to be new, whereas Sc-2 assumes that existing sites will require upgrade costs and that additional required site costs will be new based on network dimensioning results. Table 5.7 illustrates the cost breakdown of both scenarios for the initial year CAPEX and the total OPEX over the 10-year study period.

Table 5. 7 5G FWA initial year CAPEX and the total OPEX over the 10-year study period.

Costs type	Initial year CAPEX		OPEX over 10 years		Source
	Sc-1 CAPEX (in Million ETB)	Sc-2 CAPEX (in Million ETB)	Sc-1 OPEX (in Million ETB)	Sc-2 OPEX (in Million ETB)	
5G multicarrier BS	24.357	24.357	23.197	23.893	[9] [52]
Additional carrier on current BS	8.936	8.936	10.544	10.86	
Civil works	10.702	3.211	0.535	1.07	
Fiber backhaul	11.774	11.774	2.355	3.532	
Equipment costs	26.36	7.908	7.908	7.908	[51]
Site build out costs	36.904	11.071	1.845	1.845	
Installation costs	15.816	4.745	1.582	2.372	
Power installation related costs	4.142	1.243	0.083	1.243	[48]
Site rental	-	-	24	24	[5]
Operational Costs	-	-	22.8	22.8	[48]

Power consumption costs	-	-	1.529	1.529	[9]
Total CAPEX (in Million ETB)	138.991	73.244	96.377	101.052	

5.6.1.2 ODN CAPEX Estimation and ODN OPEX Estimation

All ODN CAPEX costs are collected from ethio telecom's actual deployed network [48]. These main costs associated with ODN deployments are classified into three major categories: civil costs, installation costs, and equipment-related costs, as detailed in Table 5.8.

Table 5. 8 CAPEX costs for ODN deployment scenarios.

Major costs	Activity types	Scenario 3 (in Million ETB)	Scenario 4 (in Million ETB)	Source
Installation costs	ODN installation	77.15	77.15	[48]
	Ring protection installation	0.84	-	
Civil costs	Duct, MH & HH construction	41.91	24.07	
	PIT construction	13.68	13.68	
Equipment costs	Equipment costs	7.92	7.92	
Total CAPEX (in Million ETB)		141.5	122.82	

The labor costs and expenses associated with operating and managing networks are included in the OPEX cost. These costs depends on the operator and vendor data source. For this study, it is estimated based on an already deployed ODN project. In addition, the operating costs of each installation method used by the operators are shown in Table 5.9.

Table 5. 9 Operational cost percentage for different Installation method [7].

Installation method	Plant life	Operational cost % of capital cost
Aerial cables	15 -20 years	2%
Ducts	30-40 years	0.50%
Cable in ducts	20-30 years	1%
Direct buried cable	20-30 years	1%

OPEX estimation is divided into three major costs: maintenance and operational costs, site rental costs, and energy consumption related costs. As most cost assumptions are based on vendor and operator-dependent assumptions, their accuracy may vary significantly based on different factors, such as market conditions, regulatory requirements, and customer needs. The cost estimation for each scenario for the first year and the entire 10-years study period are shown in Table 5.10 and 5.11, respectively.

Table 5. 10 ODN OPEX for the first year.

Major cost type	Cost assumption	Sc-3 OPEX (in Million ETB)	Sc-4 OPEX (in Million ETB)	Source
Maintenance and Operational costs	ODN Installation 2% of CAPEX	1.413	1.413	[48]
	Duct, MH & HH construction 0.5%, 1% of CAPEX for Sc-3 and Sc-4 respectively	0.21	0.419	
	PIT construction 0.5% of CAPEX	0.068	0.068	
	Ring protection installation 1%, 2% of CAPEX for Sc-3 and Sc-4 respectively	0.008	0.017	
	Card 2% of CAPEX	0.158	0.158	
	Sales, advertising, billing and customer care related cost	1.5	1.5	
	General Administration and technical team	2.1	2.1	
	Rental vehicle	0.96	0.96	
Rental costs	Site rental	0.96	0.96	
Energy consumption costs	Power consumption (OLT, GPON, Invertor and air conditioning) per subscriber	0.006	0.006	[9]
Total OPEX (in Million ETB)		7.384	7.602	

Table 5. 11 ODN OPEX over 10 years.

Costs type	Scenario 3 OPEX (in Million ETB)	Scenario 4 OPEX (in Million ETB)
Maintenance and Operational costs	64.180	66.359
Site rental costs	9.600	9.600
Energy consumption costs	0.061	0.061
Total Costs (in Million ETB)	73.841	76.020

5.6.2 TCO Estimation

To clarify the big picture and assess the possible broadband deployment, based on ODN and 5G FWA scenarios are evaluated within their costs. The required TCO is the sum of the two costs, which can be computed using Eq.3.3. These contain the overall required cost amount for the initial year CAPEX and OPEX over the study period for all scenarios are shown in Table 5.12 and Figure 5.6 below, respectively.

Table 5. 12 Initial year CAPEX and OPEX over 10 years for all scenarios.

Scenarios	CAPEX (in Million ETB)	OPEX (in Million ETB)	TCO (in Million ETB)
Scenario 1	139	96	235
Scenario 2	73	101	174
Scenario 3	142	74	215
Scenario 4	123	76	199

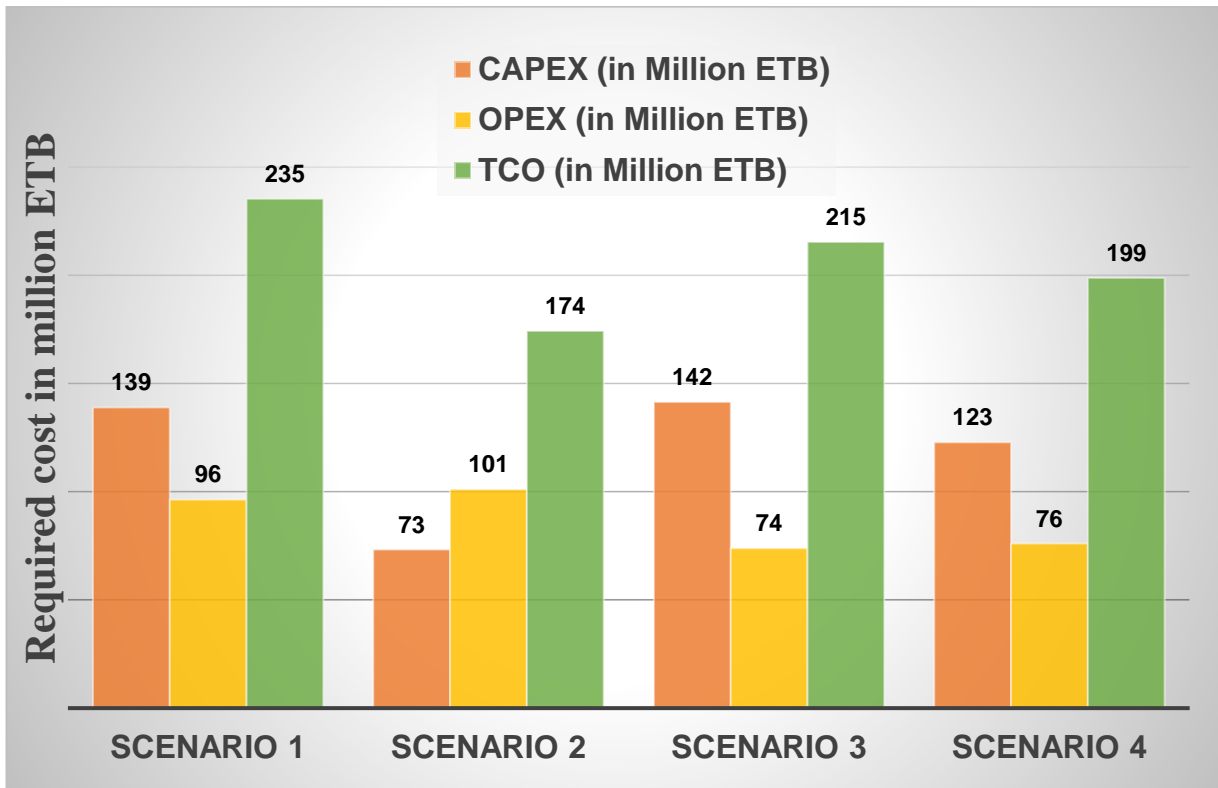


Figure 5. 6 Total CAPEX, OPEX and TCO Over 10 Years.

5.6.3 Revenue Modelling

Revenue modeling is based on service user’s monthly data consumption levels, and charging policy based on the current ethio telecom Small Office Home Office (SOHO) price per month. Other inputs required for the revenue modeling are the actual number of subscribers and the market share. Based on the ethio telecom fixed broadband market trends, 80% of users become connected to broadband services in the residential area after a certain period of network deployment. Additionally, it is assumed that Internet Service Providers (ISP) and competitors will each hold 35% of the market [7].

A well-known fact is that 5G FWA and ODN have different deployment periods; based on the actual duration of the prior projects, ODN needs at least two years, while 5G FWA can take up to a year to deliver services [48]. As a result, they begin to generate revenue at a different time after deployment.

Finally, estimating each year's bandwidth requirement is a vital step because it greatly affects the revenue generated per user.

Other basic inputs for the revenue modeling are forecasting bandwidth required. In this study, we forecast the bandwidth requirement using Nielsen's law of internet bandwidth.

Nielsen's Law of Internet Bandwidth

Nielsen's law of internet bandwidth states that a high-end user's connection speed grows by 50% per year. This law held true for 36 years and is expected to continue for the next several decades [54]. In addition, this law is widely used in a different academic research. To begin the bandwidth prediction, we used the worldwide broadband speed league estimate for 2022. They predict the average download speed in Ethiopia will be 1.8 Mbps in 2022 [55].

Based on the current ethio telecom fixed broadband price and Nielsen law of internet bandwidth the revenue generated in each scenarios during the estimated deployment period are clarified in the following Table 5.13.

Table 5. 13 Revenue for each formulated scenario over 10 years.

Years	Nielsen's Law of Internet Bandwidth in Mbps	Price per month in ETB	Revenue per year in Million ETB			
			Scenario-1 (rollout duration 1 year and 6 month)	Scenario-2 (rollout duration 1 year)	Scenario-3 (rollout duration 2 years and 6 month)	Scenario-4 (rollout duration 2 years)
2023	2.7	1,249	0.000	0.000	0.000	0.000
2024	4.1	1,560	6.970	13.940	0.000	0.000
2025	6.1	2,155	28.885	28.885	14.442	28.885
2026	9.1	2,750	61.433	61.433	61.433	61.433
2027	13.7	4,850	130.014	130.014	130.014	130.014
2028	20.5	6,400	200.159	200.159	200.159	200.159
2029	30.8	10,600	426.232	426.232	426.232	426.232
2030	46.1	15,100	877.037	877.037	877.037	877.037
2031	69.2	17,600	1494.046	1494.046	1494.046	1494.046
2032	103.8	25,000	2233.920	2233.920	2233.920	2233.920
Total Revenue in Million ETB			5458.695	5465.665	5437.283	5451.725

For each user, the ARPU over ten years per scenario using Eq.3.5 can be calculated as follows:

$$Sc - 1 \text{ ARPU} = \frac{\textit{Total Revenue}}{\textit{Total Number of user}} = \frac{5458.695}{7446.4} = 0.733 \textit{ Million ETB}$$

$$Sc - 2 \text{ ARPU} = \frac{\textit{Total Revenue}}{\textit{Total Number of user}} = \frac{5465.665}{7446.4} = 0.734 \textit{ Million ETB}$$

$$Sc - 3 \text{ ARPU} = \frac{\textit{Total Revenue}}{\textit{Total Number of user}} = \frac{5437.283}{7446.4} = 0.730 \textit{ Million ETB}$$

$$Sc - 4 \text{ ARPU} = \frac{\textit{Total Revenue}}{\textit{Total Number of user}} = \frac{5451.725}{7446.4} = 0.732 \textit{ Million ETB}$$

CHAPTER SIX

6. Results and Analysis

This chapter repeatedly refers to the formulated deployment scenarios. As we described in section 5.3 of the possible option to deliver the broadband service based on wired (ODN) and wireless (5G FWA) are summarized as shown in Table 6.1.

Table 6. 1 Formulated deployment scenarios in this thesis.

Types of technologies	Broadband deployment scenario name	Abbreviations	Description of scenarios
5G FWA based	Scenario 1	Sc-1	Deployment with the new infrastructure
	Scenario 2	Sc-2	Reuse existing asset with additional new infrastructure
ODN based	Scenario 3	Sc-3	Deployment with the new infrastructure
	Scenario 4	Sc-4	Reuse existing asset with additional new infrastructure

The developed scenarios demonstrate potential broadband deployment options based on the two chosen technologies. Furthermore, each formulated deployment scenario assessed for feasibility in terms of technical and economic aspects. The techno-economic results and their analysis are illustrated in the following subsections.

6.1 Marketing Analysis

In this study, market trend analysis of ethio telecom is used to estimate the number of users comes broadband users over the study period because the chosen area is a residential area where the number of users per household is expected to be fixed over a specific study period.

However, those user’s bandwidth requirements will increase year after year. As a result, the incremental bandwidth is directly increased within the revenue generated. Thus, Nielsen's law of internet bandwidth was used to forecast bandwidth requirements for the next ten years. Based on the current broadband speed, the required bandwidth at the end of 2032 will be 103.8 Mbps, as shown in Figure 6.1.

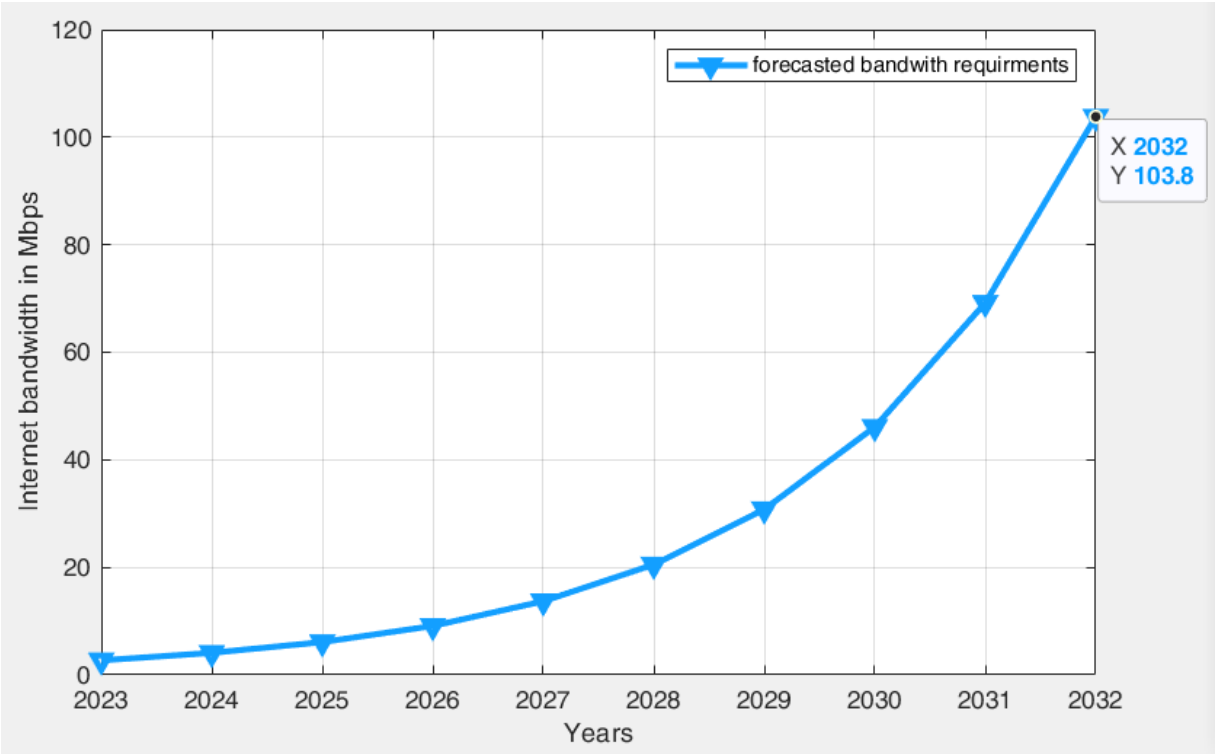


Figure 6. 1 Projected bandwidth with Nielsen's law of internet bandwidth for the study period.

Next, once the bandwidth needs are known, the viability of each scenario is assessed in terms of its economic viability in the following subsection.

6.2 Economic Analysis

The economic analysis of each scenario's CAPEX, OPEX, TCO, and revenue is covered in this section. As shown in Figure 6.2, the total estimated CAPEX costs of Sc-1, Sc-2, Sc-3 and Sc-4 are 1389M ETB, 73M ETB, 142M ETB and 123M ETB respectively. Similarly, the total estimated OPEX for Sc-1, Sc-2, Sc-3, and Sc-4 during the study period is 96M ETB, 101M ETB, 74M ETB, and 76M ETB respectively.

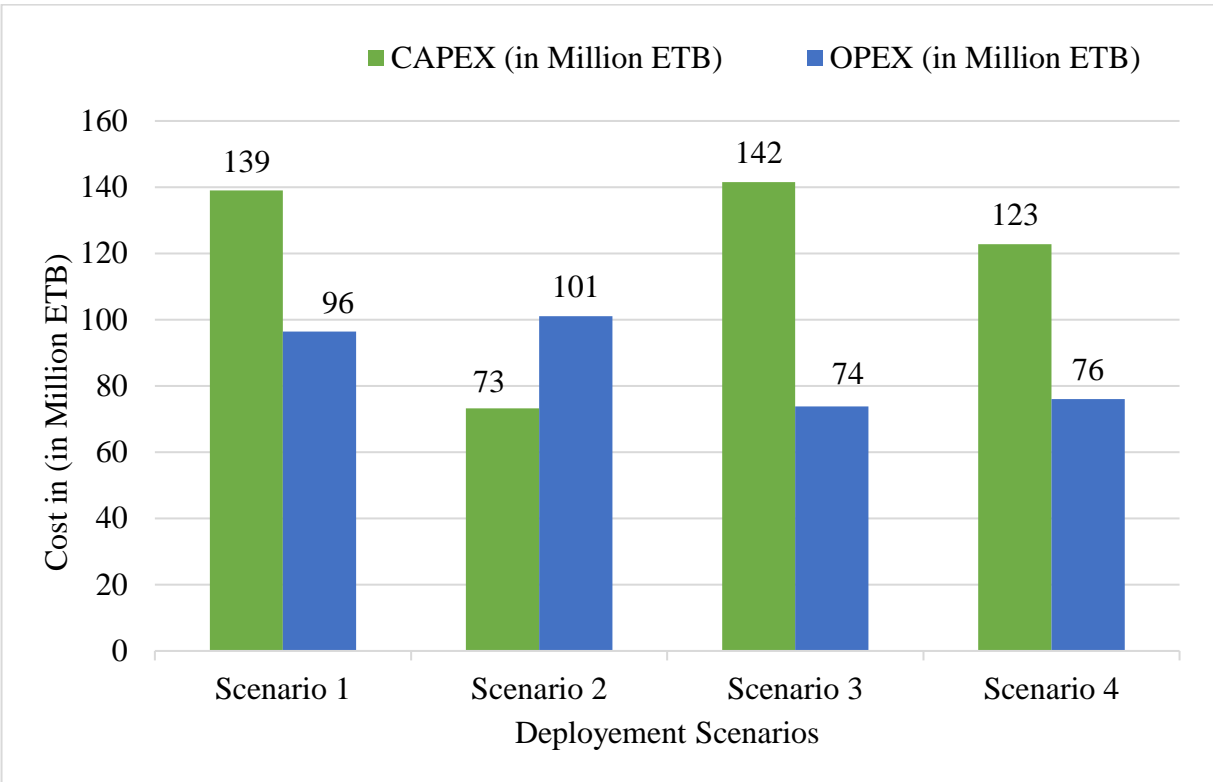


Figure 6. 2 CAPEX and OPEX estimates for each scenario over a ten-years study period.

It is clearly observed that 5G FWA based Sc-2 have lower CAPEX than the all over other scenarios. As shown in the Figure, 6.2 Sc-1 has the higher CAPEX, because the deployment of a new site and upgrade to 5G FWA requires higher costs. While ODN-based Sc-3 and Sc-4 have lower OPEX and the deployment, costs are higher even when existing infrastructures are used.

As we summarized in Table 5.10, the TCO for Sc-1, Sc-2, Sc-3, and Sc-4 is 235M ETB, 174M ETB, 215M ETB, and 199M ETB, respectively. According to the TCO trends depicted in Figure 6.3, the network cost was high for the first three consecutive years, and once the investment deployed, the only cost present was the operational cost. We notice that the TCO is the lower for the two scenarios (Sc-2 and Sc-4) that reuse existing infrastructure.

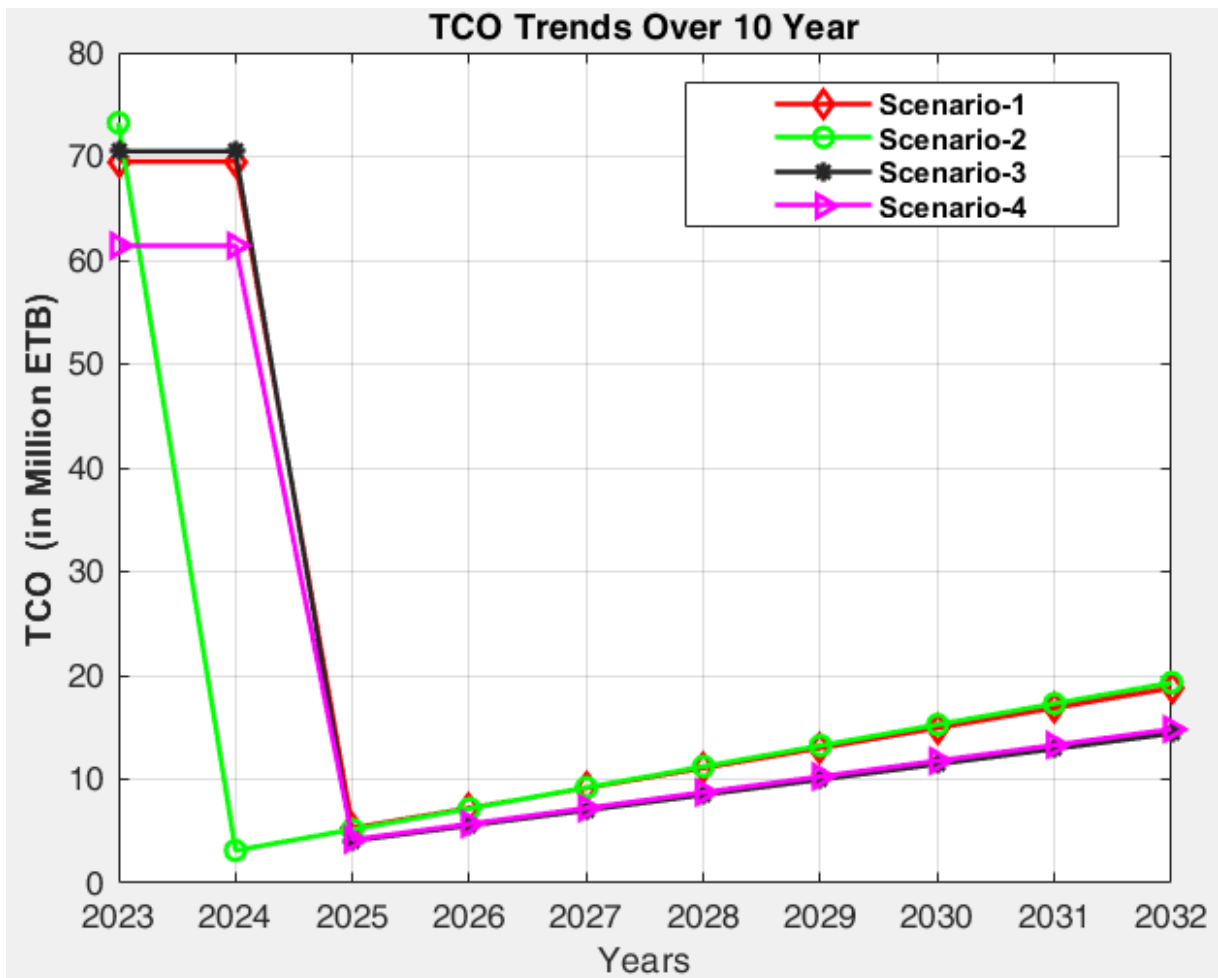


Figure 6. 3 TCO trends.

The obtained result is also quite logical. That means for the first two and three years, CAPEX costs take the high share, whereas in the rest of the years, OPEX costs take the high share.

One of the most important marketing and economic analysis parameters is revenue projections. As shown in Figure 6.4, the projected revenue is directly proportional to the bandwidth requirements of users and increases in an exponential form for all deployment scenarios during the deployment period. At the end of the study period, the projected revenue was 5,459M ETB, 5,466M ETB, 5,437M ETB, and 5,452M ETB for Sc-1, Sc-2, Sc-3, and Sc-4, respectively.

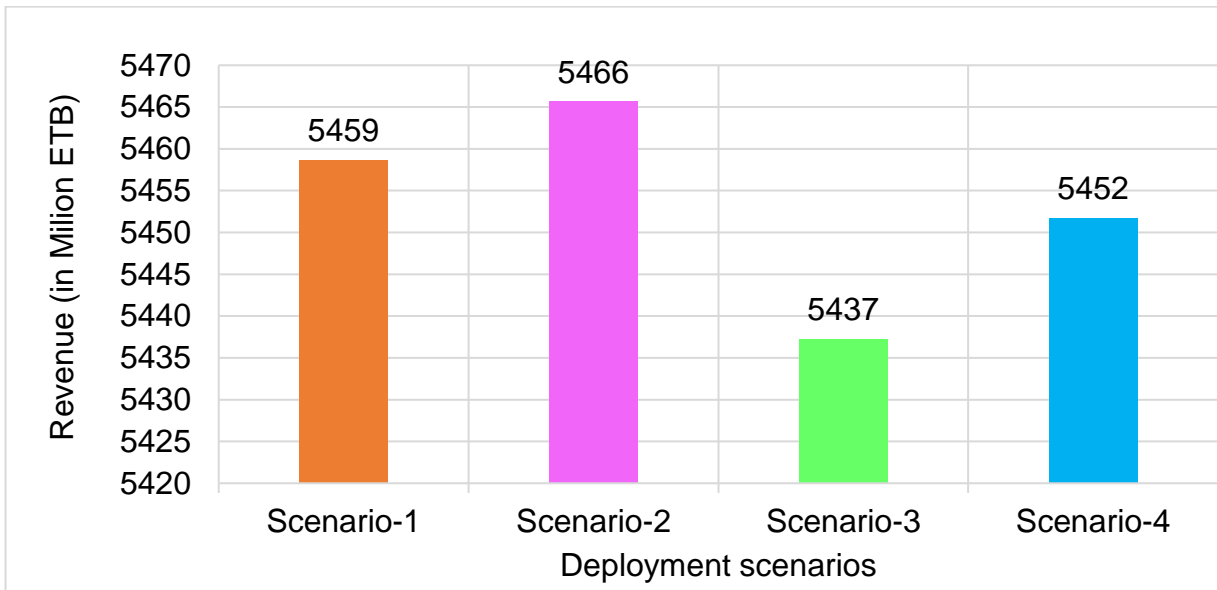


Figure 6. 4 Revenue projections for all scenarios over the study period.

Likewise, based on projected revenue, the ARPU is depicted in Figure 6.5. After the third year, the average monthly revenue per user begins to increase at an exponential rate.

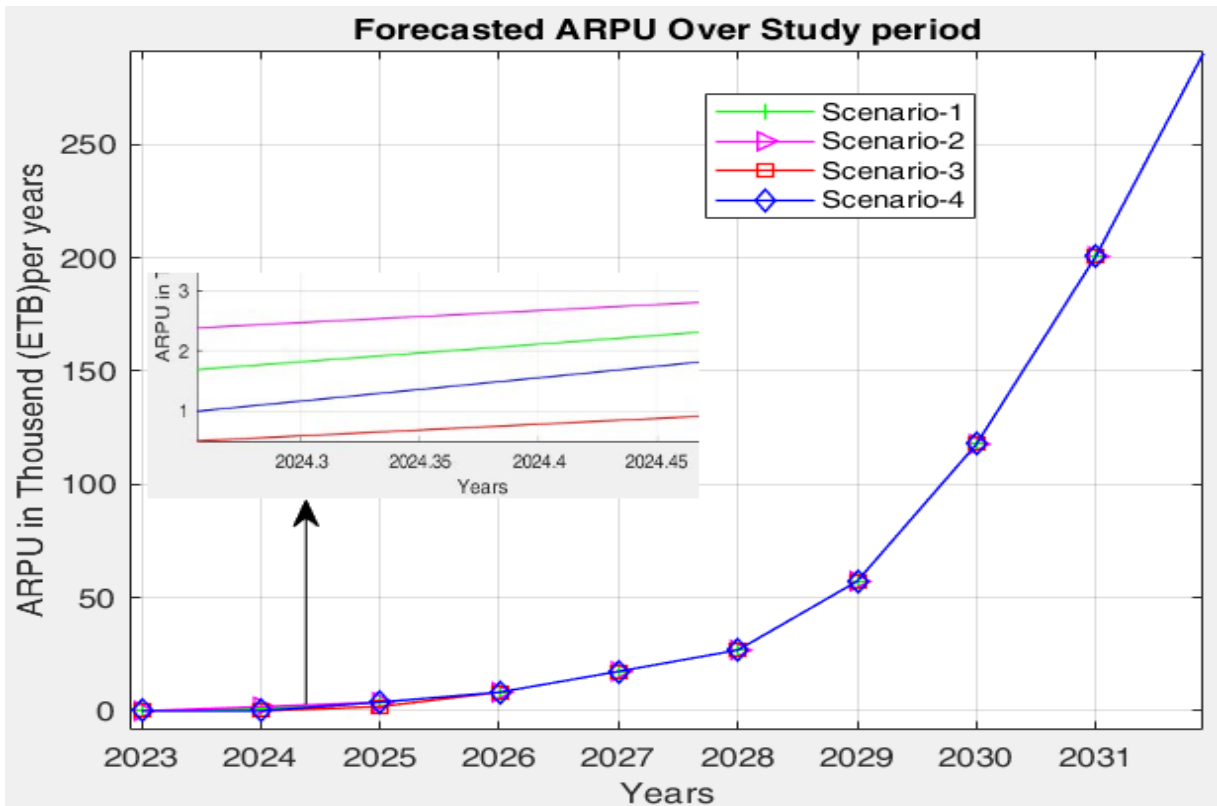


Figure 6. 5 ARPU forecasted over 10 years for all formulated scenarios.

6.3 Techno-economic Evaluation

In the following subsection, the economic feasibility of each deployment scenario is evaluated using the discounted cash flow analysis method, and with the results of each key economic parameter and indicators.

6.3.1 Cash Flow Analysis

Cash flow is the net amount of cash received or generated in a given time period by combining revenue and system costs. Most studies assume a discount factor value for new investments and the adoption of technology in the range of 10% to 15%. Accordingly, a 10% discount factor was used in this study for discounted cash flow analysis. Figure 6.6 shows that after the third year of the deployment period, the discounted cash flow increases for all deployment scenarios.

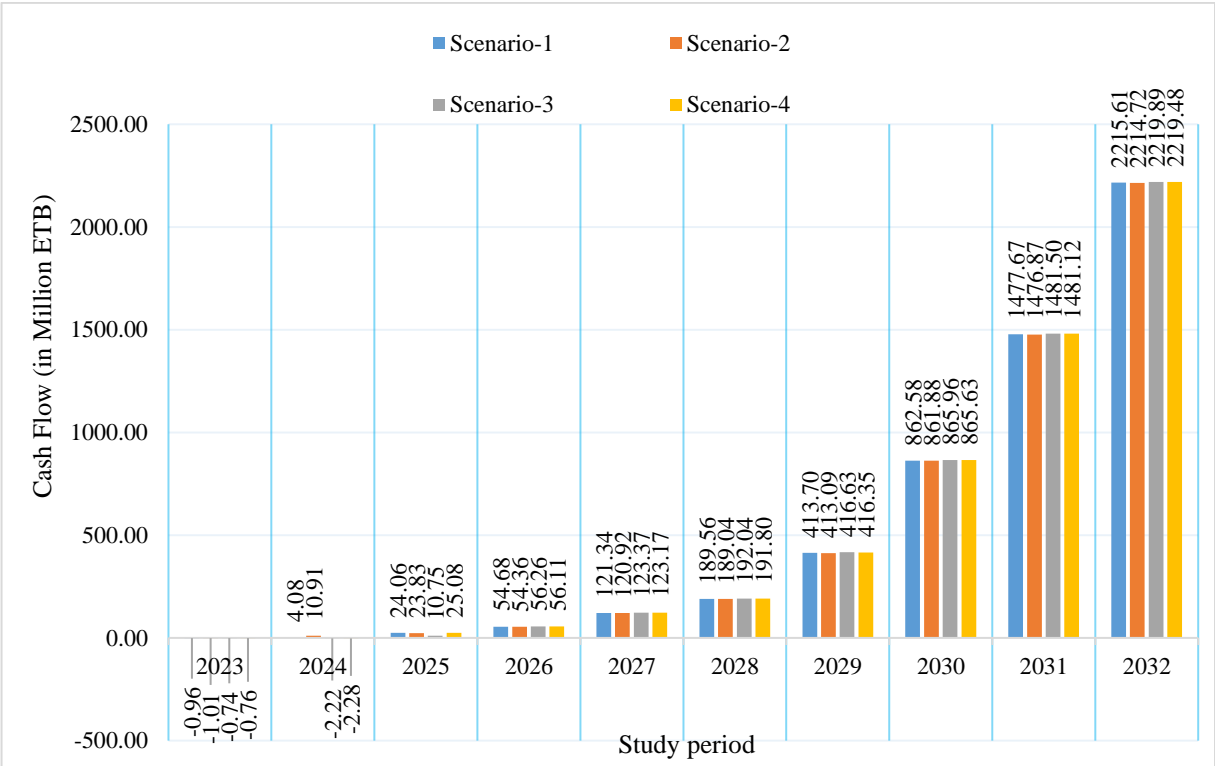


Figure 6. 6 Cash flow analysis of all scenarios over the study period.

The net discount cash flow begins in the negative during the deployment period and gradually increases from a negative to a high positive value after the second year. This trend is directly related to bandwidth requirements and projected revenue.

Following cash flow analysis, the cumulative cash flow trends for each deployment scenario over the study period are calculated and shown in Figure 6.7.

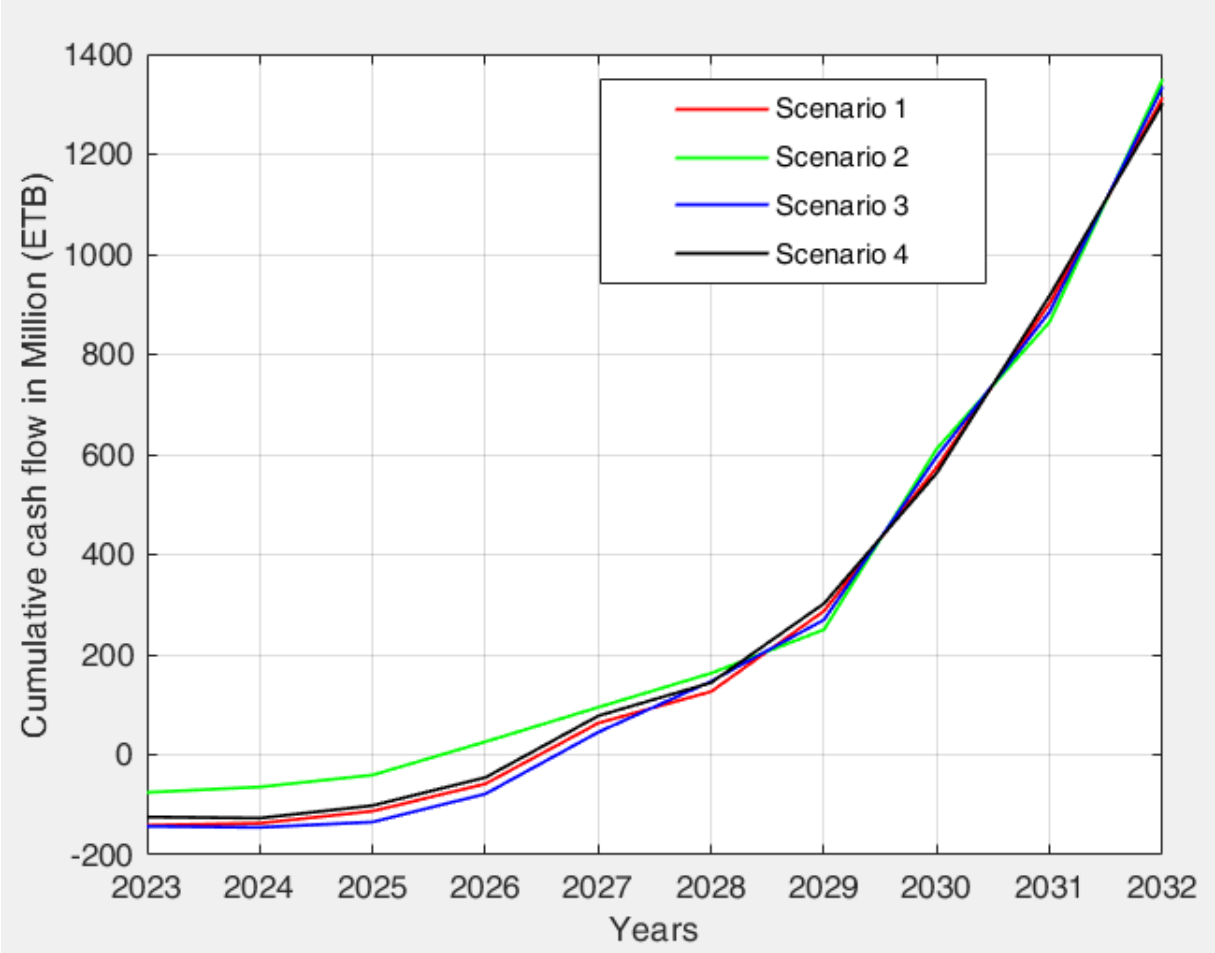


Figure 6. 7 Cumulative cash flow trends.

After the fourth year of deployment, the cumulative cash flow of Sc-1, Sc-3, and Sc-4 reaches zero and then increases exponentially for the remaining years. While the Sc-2 reaches zero after the third year, it demonstrates that lower costs are required.

As mentioned in an earlier section, the total cost of ownership and discounted cash flow were not enough to determine the feasibility of each deployment scenario. Therefore, using an economic indicator to assess the economic viability is crucial. The most commonly used economic feasibility indicators are NPV, IRR, and PBP, which are used to maximize the decision indicators.

The net present value in the 5G FWA-based scenario (Sc-1 and Sc-2) and the ODN-based scenario (Sc-3 and Sc-4) was negative for the first three and four years, respectively, but after these deployment periods, it increased exponentially to a high positive value. This indicates that, compared to the prior four years, the revenue generated per user exponentially increases after the deployment year. Furthermore, each formulated deployment scenario is economically feasible if a net present value greater than zero value is recorded.

The net present value for each year for each scenario was estimated and is shown in Figure 6.8 below.

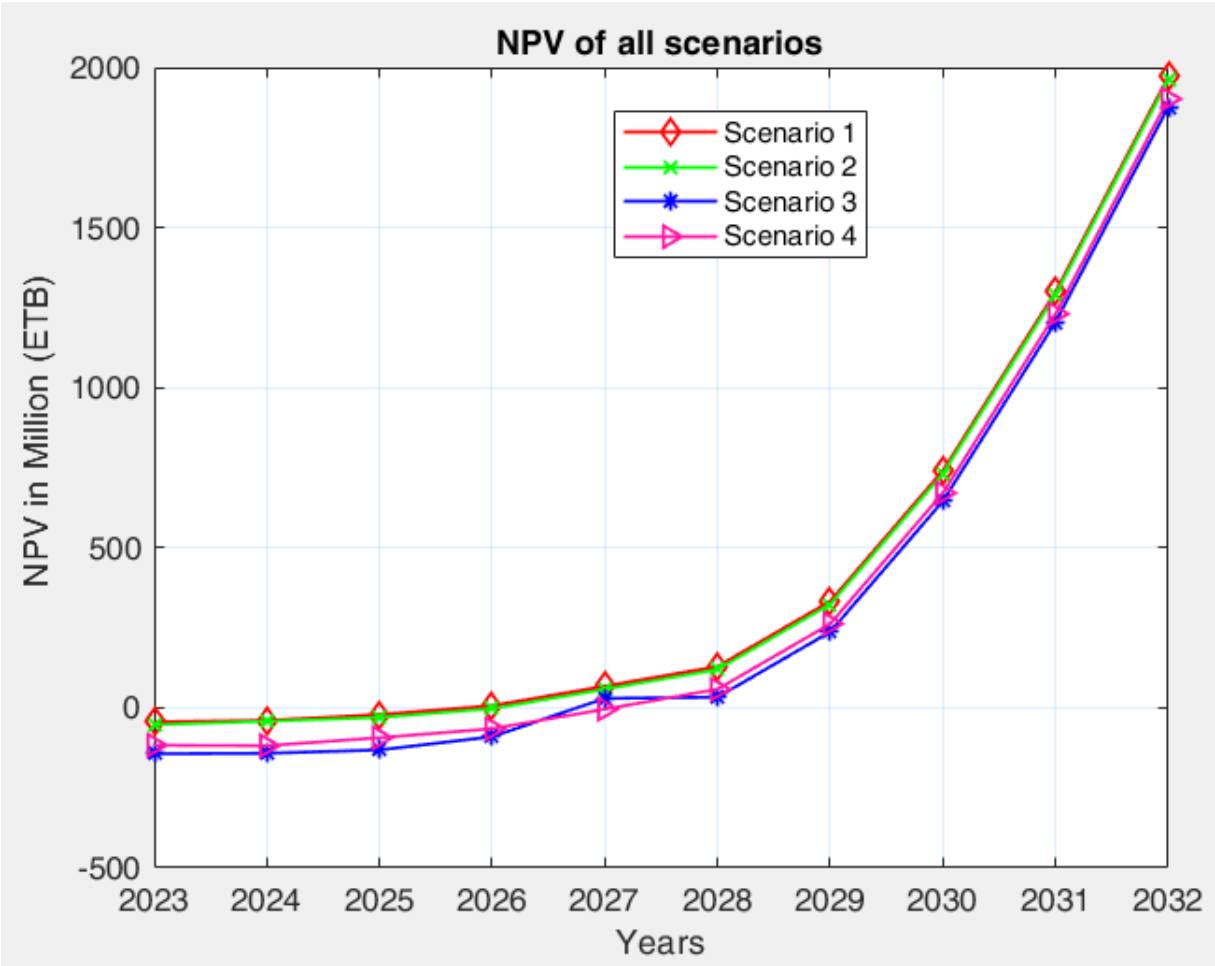


Figure 6. 8 Net present value.

The next most popular economic indicator was the internal rate of return (IRR). The IRR is the discount rate (factor) which makes the net present value to 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, all deployment scenarios IRR are greater than 10% of the initial specified discount factor, as shown in Figure 6.9. This implies that all scenarios are feasible for its deployment, and Sc-2 is more feasible than the other scenarios.

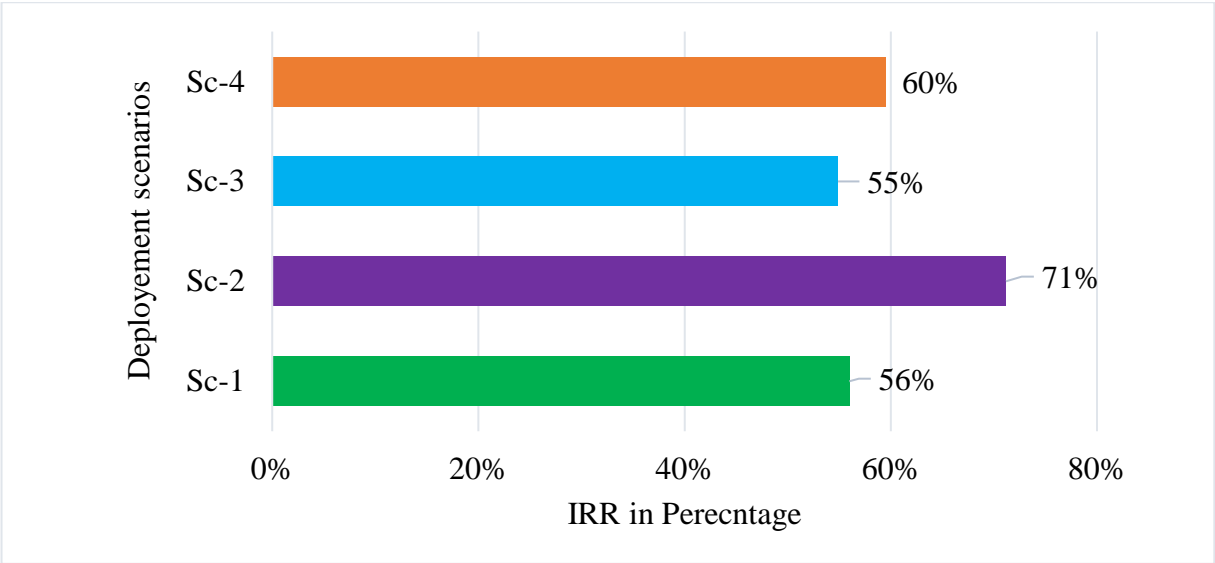


Figure 6. 9 Internal rate of return.

The other economic indicator is the payback period, which is the time takes to the cumulative income to equal the initial investment. The PBP is calculated and depicted in Figure 6.10 based on the calculated net cumulative cash flow and net discounted cumulative cash flow.

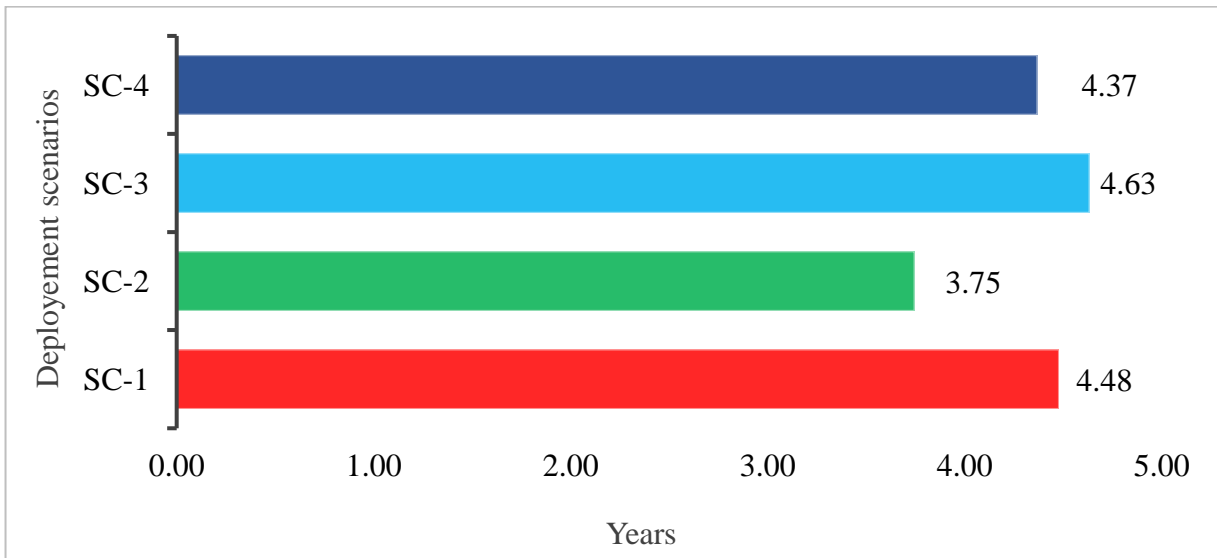


Figure 6. 10 Payback period.

The time required to return on the investment for deploying broadband services under Sc-2 was 3.75 years with the shortest return on investment. Whereas the longest year recorded to return on investment is 4.63 years under Sc-3. Similarly, the return on investment for the remaining deployment scenarios was 4.48 and 4.37 for Sc-1 and Sc-4, respectively.

From a technical point of view, scenarios based on 5G FWA internet speed cannot exceed the estimated bandwidth. To enhance this speed, an additional site will be required, which incur additional costs. The best thing regarding ODN-based scenarios is that we can still deliver the highest internet bandwidth without any additional investment. Therefore, ODN-based scenarios are preferred if a higher bandwidth is needed.

6.3.2 Sensitivity Analysis

Sensitivity analysis was used to investigate the impact of changes in input assumptions on project profitability, such as the NPV. To investigate the effect, we chose two scenarios Sc-1 and Sc-3 from 5G FWA and ODN respectively.

Considering $\pm 5\%$ as the best case and $\pm 30\%$ as the worst case, the sensitivity analysis of NPV on CAPEX, OPEX, and Revenue was performed. The results can be visualized by a sensitivity graph with a tornado diagram and the sensitivity of each input is mirrored by the change or

variation in output within the normal value. The sensitivity analysis of Sc-1 for the best case and worst case are shown in Figures 6.11 and 6.12, respectively.

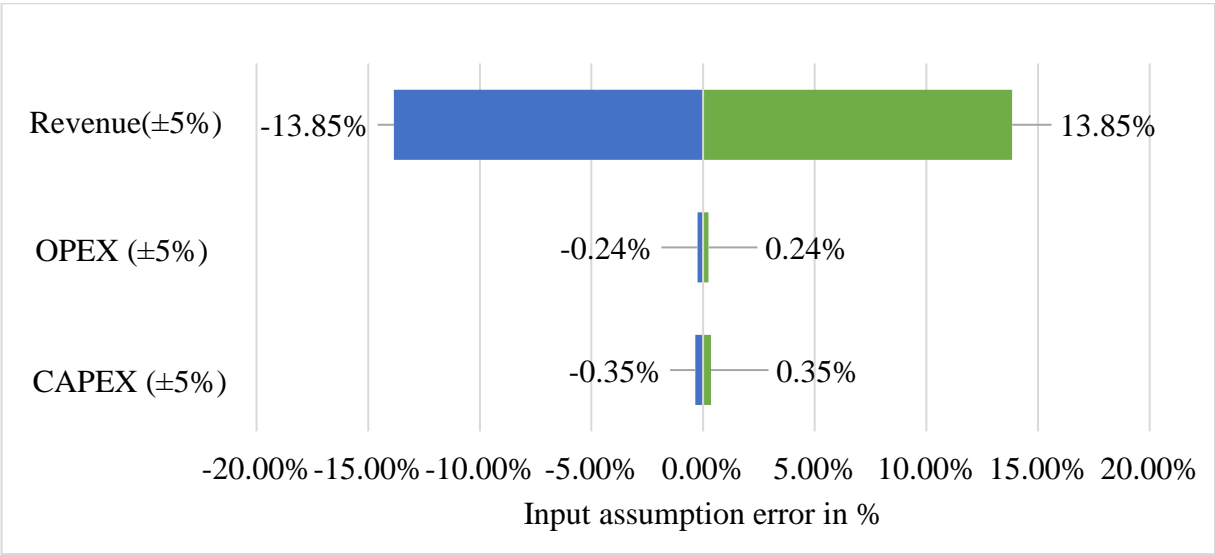


Figure 6. 11 Best case sensitivity analysis on NPV for Sc-1.



Figure 6. 12 Worst case sensitivity analysis on NPV for Sc-1.

As shown in the above figure, the sensitivity, analysis on NPV under Sc-1 implies that CAPEX and OPEX are the least affected parameters compared to revenue. Whereas, revenue is the most sensitive parameter when compared to CAPEX and OPEX, with deviation percentages of ± 13.85% and ± 83.08% in the best and worst-case scenarios, respectively.

Again, under Sc-3 the best case and worst-case sensitivity analysis are illustrated in Figures 6.13 and 6.14, respectively.

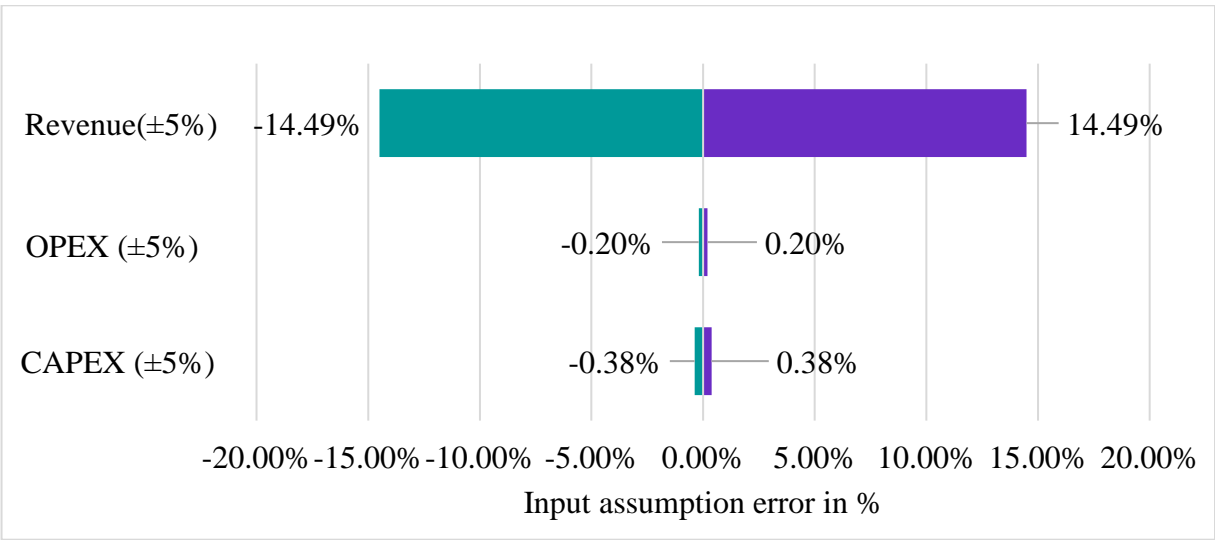


Figure 6. 13 Best case sensitivity analysis on NPV for Sc-3.

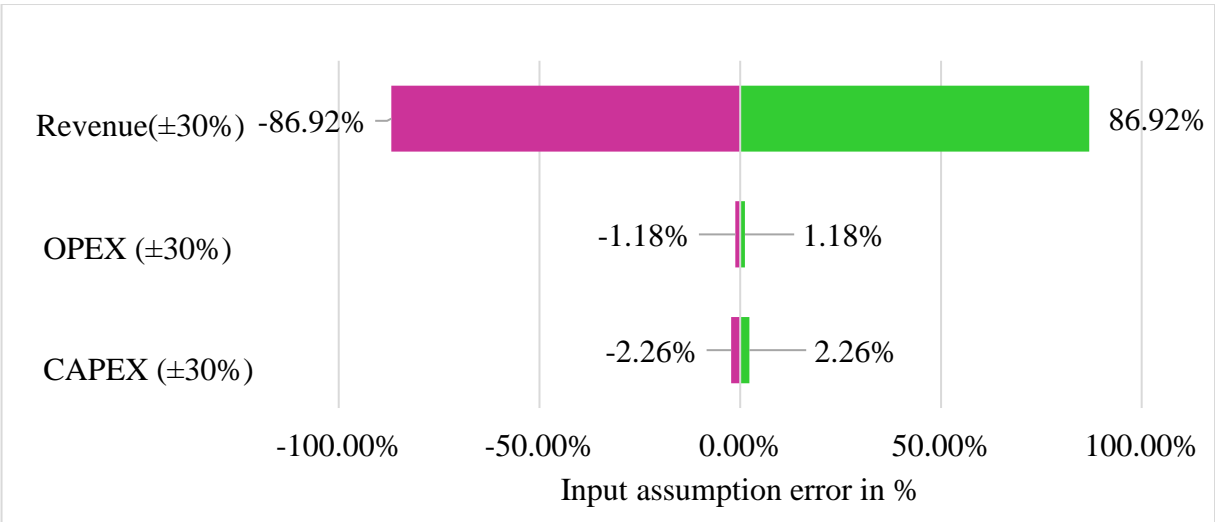


Figure 6. 14 Worst case sensitivity analysis on NPV for Sc-3.

The deviation of $\pm 5\%$ input variation on NPV from normal value affects CAPEX, OPEX and revenue by $\pm 0.38\%$, $\pm 0.2\%$ and $\pm 14.49\%$ respectively under Sc-3 for best case. Whereas, the deviation of $\pm 30\%$ input variation on NPV from normal value affects CAPEX, OPEX and revenue by $\pm 1.18\%$, $\pm 2.26\%$ and $\pm 86.92\%$ respectively under Sc-3 for best case. Again, even in the worst-case scenario, we conclude that CAPEX and OPEX have the least effect on NPV. Meanwhile, revenue is more sensitive than the other input parameters over CAPEX and OPEX.

CHAPTER SEVEN

7. Conclusions and Future Work

7.1 Conclusions

The growth of broadband users forces the operator to expand or upgrade their access networks. However, the selection of an access network scenario or technology is challenging due to the various factors to be taken into account. Capacity, performance, construction costs, quick deployment, flexibility, and strategic decisions are typically and primary determinants of providing broadband services. On the other hand, the rapid evolution and technological advancement alone cannot indicate the performance and profitability of a project. Thus, techno-economic analysis is critical for selecting technologies and evaluating technical and economic perspectives.

In this study, the techno-economic evaluation of four scenarios are considered, two from 5G FWA and two from ODN. The technical and economic viability of each deployment scenario was evaluated within their TCO and using popular economic feasibility indicators such as NPV, IRR, and PBP with a 10% discount rate. In addition, NPV sensitivity analysis was performed on CAPEX, OPEX, and revenue to see how their input estimation affects the output, with best and worst case scenarios. According to the findings, revenue is more sensitive in both the best and worst case scenarios, while CAPEX and OPEX are the least affected parameters in both scenarios. Based on the formulated scenario, (Sc-2) has the shortest Return on Investments (ROI) over the study period, and the drawback of this scenario internet speed cannot exceed the estimated bandwidth. Meanwhile, ODN-based scenarios are where we can still deliver the highest internet bandwidth without any additional investment.

In summary, the economics and technical analysis indicates scenarios should be deployed based on the requirements. From this study, we conclude that Sc-2 is suitable and cost-effective for small urban residential areas and Sc-4 is suggested if there is an existing infrastructure available for the business area where traffic data usage is rapidly increasing and exceeding the estimated data rate; otherwise, Sc-3 is preferred.

7.2 Future Work

In this thesis, a techno-economic analysis was conducted to assess the viability and competitiveness of a mid-band 5G FWA and GPON-based ODN network scenarios in delivering broadband internet access to residential customers. Likewise, the implemented techno-economic evaluation approach in this study was limited to the selected area. However, it is possible to evaluate rural and dense urban areas using a different deployment scenario and by combining the advantages of wireless and wire line technology. Furthermore, 5G FWA dimensioning was performed with mid-bands only; it can be further investigated with the low-band and mm-wave bands with a different propagation model.

Standard economic indicators like NPV, IRR, and PBP were employed in the study from an economic perspective to assess each scenario's viability. It is also possible to extend the user perspective to assess customer acceptance by utilizing tools like Net Promoter Score (NPS), mood charts, morale charts, and turnover ratio.

In the field of wireless access networks, the demand for techno-economic modeling of emerging network technologies and the ongoing evolution of mobile networks raises many critical questions. Thus, the below-mentioned questions can be investigated and answered in future works.

- When and in which geographical areas should operators start upgrading their existing networks to 5G FWA?
- What are the comparative strengths and weaknesses of the various technologies?
- How, when, and where can 5G FWA compete with optical networks?

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