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

Techno-Economic Analysis of Elastic Optical Network Deployment, in case of Ethiopia Telecom

By

Biniyam Kiflemariam

Advisor

Yalemzewd Negash (PhD)

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 Telecommunication Engineering.

October 11, 2023

Addis Ababa, Ethiopia

Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Telecommunication Engineering Graduate Program

Techno-Economic Analysis of Elastic Optical Network Deployment, in case of Ethio Telecom

By:

Biniyam Kiflemariam

Bisrat Derebssa (PhD)	______________	____________
Chairman / School Dean	Signature	Date
Yalemzewd Negash (PhD)	______________	____________
Advisor	Signature	Date
Murad Ridwan (PhD)	______________	____________
Examiner	Signature	Date
Bisrat Derebssa (PhD)	______________	____________
Examiner	Signature	Date

Abstract

This thesis offers a thorough techno-economic analysis of elastic optical networks' (EONs) implementation. In order to avoid higher operational expenditure and to create flexible communication networks, EONs have emerged as a possible alternative. This study intends to examine the technical and financial elements of EON deployment, assessing its viability, affordability, and possible advantages in the case of Ethio Telecom network.

To create a complete techno-economic model, a number of input factors are taken into account, including traffic demand, network topologies, transmission methods, spectrum allocation, equipment costs, operating expenses, revenue models, discount rate, and economic indicators. The techno-economic study examines the effects of many parameters on the effectiveness and financial sustainability of EON deployment using the proposed model. The paper also discusses the difficulties and constraints of EON implementation, including system adaptability, upgradeability, and compatibility with changing network requirements. The research's findings help decision-makers make well-informed decisions about network infrastructure expenditures by advancing our knowledge of the techno-economic elements of EON deployment.

Keywords— Elastic optical networks, Techno-economic analysis, Deployment feasibility, Cost optimization, Revenue generation, Capital expenditure, Operational expenditure, Return on investment.

Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been properly acknowledged.

Biniyam Kiflemariam

Name Signature

Date of submission

Addis Ababa

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

Yalemzewd Negash (PhD)

Advisor's Name Signature

Acknowledgements

First and foremost, I would like to thank God for giving me the strength and courage to accomplish my study.

I want to sincerely thank my adviser Yalemzewd Negash (PhD) for his unwavering support and advice with regard to my thesis work. I also want to thank my evaluators Bisrat Derebssa (PhD) and Murad Ridwan (PhD) for their helpful criticism and recommendations on how to make this study even better.

The same goes for my friends and coworkers at Ethio Telecom, who helped me with data collection and thesis writing by giving me important information about each of their respective job functions whenever I needed it.

Last but not least, I want to express my love and thanks to my family for their strength and support.

Thank you everyone!

Table of Contents

List of Figures

List of Tables

.

List of Acronyms

NW	Network
100G	Hundred Gigabit
10G	Ten Gigabit
1G	One Gigabit
40G	Forty Gigabit
5G	Fifth Generation
BFSA	Best-Fit Spectrum Assignment
CAPEX	Capital Expenditures
CDNs	Content Delivery Networks
CF	Cash flow
CLI	Command-line Interface
CO2	Carbon dioxide
DA-RSA	Distance-Adaptive routing and spectrum allocation
DCF	Discount Cash Flow
DEX	Demultiplexer
DWDM	Dense Wavelength Division Multiplexer
EA-RSA	Energy-Aware Routing and Spectrum Allocation

EDFAS	Erbium-Doped Fiber Amplifiers
EEA	Energy-Efficient Algorithms
EON	Elastic optical networks
FFSA	First-Fit Spectrum Assignment
GUI	Graphical User Interface
I-CEON	Information-Centric Elastic Optical Transport Network
IoT	Internet of Things
IRR	Internal Rate of Return
LB-RSA	Load Balancing Routing and Spectrum Assignment
M-EON	Mesh-Based EON
MUX	Multiplexer
NMS	Network Management Systems
NPV	Net Present Value
NWDM	Nyquist Wavelength Division Multiplexing
OFDM	Orthogonal Frequency-Division Multiplexing
OPEX	Operating Expenditures
OTN	Optical Transport Network
PBP	PAY BACK PERIOD

P-OTS	Packet-Optical Transport Systems
QoS	Quality of Service
R-EON	Ring-Based EON
ROADMs	Reconfigurable Optical Add-Drop Multiplexers
ROI	Return On Investment
RSA	Routing and Spectrum Allocation
SA-RSA	The Sleep-Awake RSA
SBVT	Sliceable Bandwidth Variable Transponder
SDA	Spectrum Defragmentation Algorithm
SDH	Synchronous Digital Hierarchy
SDM	Space Division Multiplexing
SDN	Software Defined Networking
S-EON	Star-Based EON
SONET	Synchronous Optical Networking
TCO	Total Cost of Ownership
TEA	Traffic Engineering Algorithms
TEA	Techno-Economic Analysis
TERA	Techno-Economic Results from the Advanced Communications Technologies and Services

TFP	Time Frequency Packing
TG-RSA	Traffic Grooming Routing and Spectrum Allocation
TP-RSA	Traffic Prediction-Based Routing and Spectrum Allocation
WDM	Wavelength Division Multiplexing
WSONs	Wavelength Switched Optical Networks

CHAPTER 1

1. Introduction

Currently, Ethio Telecom uses conventional optical transport networks (OTNs) as backbone transmission infrastructure to accommodate the rising need for high-capacity transmission connections caused by surging data traffic, broadband services, and bandwidth-intensive services. So that Ethio Telecom is investing huge amount of money for frequently network upgrading and operational expenditures, EONs may greatly increase bandwidth usage by tailoring the transmission capacity to each connection's unique needs, which improves user experience and network performance[1]. Recent research have suggested sophisticated algorithms and methods to improve EON bandwidth consumption. For example, the application of machine learning algorithms for resource allocation and traffic prediction has demonstrated promising outcomes in increasing bandwidth utilization[2]. Additionally, dynamic and effective bandwidth provisioning is made possible by EONs' use of software-defined networking (SDN) concepts[3]. These improvements in bandwidth consumption help to improve EONs' overall performance. Utilizing energy is another essential component of contemporary communication networks, since rising energy consumption creates serious problems for sustainability and operating expenses[2]. EONs have an advantage over conventional networks in terms of potential energy savings. The development of EON energy-efficient techniques has been the subject of recent study. For instance, the introduction of energy-aware routing algorithms takes into account both network element energy usage and traffic needs, resulting in optimal energy use[2]. A further factor in lowering energy usage in EONs is the adoption of energy-efficient components such low-power transceivers and amplifiers. These improvements in energy efficiency help communication networks remain sustainable in the long run by lowering operational expenses as well. Network operators and service providers are very concerned about the expense of updating network infrastructures[4]. EONs take use of the adaptability and scalability of optical spectrum allocation to offer a cost-effective solution. In order to meet the rising bandwidth needs, recent research have offered cost-effective ways for improving network infrastructures. A good example is the effective use of the current fiber infrastructure made possible by the deployment of flexible grid technology, which eliminates the need for expensive infrastructure expansions[5]. Furthermore, by utilizing reconfigurable optical add-drop multiplexers (ROADMs), it is possible to dynamically provide network resources, avoiding the need for manual intervention and lowering operational expenses. EONs are a desirable option for network operators because to developments in low-cost network infrastructure improvements. The urgent need to reduce carbon dioxide (CO2) emissions is reflected in the fact that communication networks are responsible for a sizeable amount of these emissions. EONs have potential advantages over conventional networks in terms of lowering CO2 emissions[2]. Creating green business strategies for EONs has been the subject of recent study. For instance, the use of energy-efficient parts and technologies, such as low-power transceivers and improved modulation formats, lowers the amount of energy used by EONs and, as a result, lowers their CO2 emissions. Further reducing the carbon footprint of EONs is possible through the network infrastructure's incorporation of renewable energy sources like solar and wind. The overall sustainability of communication networks is improved by these developments in CO2 emission reduction[6].

1.1 Statement of the problem

Ethio Telecom is experiencing significant growth in network traffic volume. Following this it has implemented both wired and wireless network infrastructure for its transportation services. And recently optical transport networks are the primary choice for handling high volume traffic. However, the whole existing transportation systems are not flexible or upgradable, leading to high costs for frequent network upgrades. Ethio Telecom also incurs high operational costs for spare parts, energy, and maintenance.

1.2 Objective

1.2.1 General Objective

The main objective of the study is to analysis the techno-economic feasibility of Elastic Optical Network deployment in the case of Ethio Telecom.

1.2.2 Specific objective

The specific objective of this research is

- To evaluate operational cost of all possible systems
- To perform cost modeling for each technology
- Using feasibility indicators, assess the technical and economic viability
- To compare the existing optical transmission network (i.e., fixed-grid DWDM) with elastic optical network (EON) and recommend the one with lower CAPEX and OPEX value

1.3 Methodology

- **Literature Review:**

Literature, including books, journals, online sources, and other references, will be used.

- **Data Collection:**

Data of Optical Channels Configuration and each service type data has been gathered.

- **Model Development:**

By using the TERA model, the cost modeling has been done for the two architectures (i.e. fixed grid DWDM and EON).

- **Model Evaluation:**

By using economic indicators (i.e., NPV, IRR, PBP), comparison has be done.

- **Finally**, the better technical architecture/technology has been recommended.

1.4 Literature Review

The inability of current optical communication networks, in particular Dense Wavelength Division Multiplexing (DWDM), to effectively handle diverse and fluctuating traffic needs is discussed in[7].

EONs provide an adaptable and flexible infrastructure to manage the rapidly growing data traffic more effectively and economically.

The elastic optical network (EON), which is intended to meet the rising need for line rates over 100 Gb/s in metro/core optical networks, is the main topic of[8]. The EON provides several advantages, including increased spectrum efficiency thanks to rate-adaptive super channels and distance-adaptive modulation. Additionally, it permits cost- and energy-effective traffic grooming in the optical domain[9].

According to [1]a promising approach that offers higher effectiveness, adaptability, and scalability is elastic optical networks. In comparison to DWDM-based networks, elastic optical networks considerably increase network usage efficiency by using narrow slots and spectrum allocation depending on client bandwidth requirements. These networks are a possible substitute for WDM-based networks to meet future needs for high-speed optical connections since they also allow for the adjustment of transmission characteristics including optical data rate, modulation format, and wavelength spacing.

The information-centric elastic optical transport network (i-CEON), a unique network design that intends to improve content delivery effectiveness, is introduced in the study of[10]. Establishing optical transport network topologies appropriate for content delivery becomes essential as video traffic grows in volume. The authors expand the idea of information-centric networking to include elastic optical networks in order to solve this.

The paper[11] offers a thorough analysis of elastic optical network technologies based on OFDM. Broadband wireless and wireline communication systems frequently use the modulation technique known as orthogonal frequency-division multiplexing (OFDM). High spectrum efficiency, robustness against interference, and flexibility to changing channel circumstances are benefits of using multiple spectral-overlapped subcarriers, which also enable high-speed data transfer. A possible method for extremely high-speed optical communication is optical OFDM (O-OFDM). A flexible and elastic optical network architecture that can handle a range of services and keep up with the quick increase in internet traffic may be built by utilizing O-OFDM[11].

According to[12] EONs enable operators to effectively address the various demands of their clients by providing flexibility and flexible data rates. Although Wavelength Switched Optical Networks (WSONs) currently have a reliable control plane, EONs need further development before they can use conventional WSON control plane solutions. Because of this, current research has concentrated on creating control plane designs expressly for EONs, frequently suggesting enhancements to current systems.

EONs boost spectrum utilization by balancing data rates with available bandwidth and enhancing spectral efficiency with multi-carrier and high-order modulation techniques, according to the paper[13]. The architecture and important technologies for the physical layers of EONs are the main topics of the essay. It specifically suggests using bandwidth-variable optical transponders based on optical combs and optical switching nodes that permit software specification. Experimental demonstrations are made of a number of crucial technologies for the physical layer of elastic optical networks, such as bandwidth-variable add/drop, sub band switching, spectrum conversion, defragmentation, and multicasting for optical super-channels[14].

1.5 Scope and Limitation

1.5.1 Scope of the study

Geographic Scope:

This study focus just on Addis Ababa Optical Network in other word it does not cover out of this area.

Network Type Scope:

This study focus just on Back Bone Optical Network and it does not include access side network.

Technological Scope:

This study focus just on some equipment and techniques that can be used to realize Elastic Optical Networks.

Economic Scope:

The study focus just to assess the economic aspect of deploying elastic optical network. Such as initial investment costs, operational expenses, and potential revenue streams.

1.5.2 Limitation of the study

The research makes certain assumptions on network configurations and cost factors, which could not correctly reflect the wide range of scenarios that might arise in actual deployments.

The possible difficulties and constraints involved with integrating current legacy systems with the suggested elastic optical network architecture are not taken into account in the research. The possible effects of market dynamics and regulatory regulations on the viability and sustainability of the deployment of elastic optical networks are not examined in the study.

1.6 Contribution of the study

This thesis examines how traffic demand patterns and traffic grooming techniques affect the price and efficiency of EONs, offering important insights for the planning and optimization of upcoming network installations.

The study also advances knowledge of the trade-offs between network performance and expense, empowering network operators and decision-makers to decide on the deployment of EONs based on their unique needs and financial restrictions.

Last but not least, this study offers a thorough techno-economic analysis framework that incorporates the proposed cost model and network assessment methodology, offering a complete way for determining the practical and economic viability of EON deployment in real-world settings.

1.7 Thesis layout

Chapter one provides an overview of the research, including the problem statement, objectives, methodology, literature review, scope, limitations, and contributions.

Chapter two explores the evolution of optical transport networks, including conventional optical networks and the unique features of EONs. It discusses the types of EONs, their benefits, scenarios for their use, challenges, and the architecture of EONs.

Chapter three focuses on techno-economic analysis (TEA) and assessment models. It introduces the TERA model and discusses cost modeling, revenue modeling, and evaluation metrics such as cash flow, discounted cash flow, net present value, internal rate of return, and payback period.

Chapter four explores the deployment options of EONs, including star-based, ring-based, and mesh-based EONs. It also discusses network dimensioning for each type of EON.

Chapter five presents a modified TEA framework and describes the techno-economic analysis model inputs.

Chapter six provides a technical analysis, including the number of components and traffic forecasting. It also includes an economic analysis, covering capital expenditures, operational expenditures, and total cost of ownership. Additionally, it presents the techno-economic analysis results, including cash flow, discounted cash flow, net present value, internal rate of return, and payback period.

Chapter seven concludes the research and discusses future work that can be done in this field.

CHAPTER 2

2. Optical Transport Network Overview

The Optical Transport Network is a standardized hierarchical network architecture that enables the efficient transport of large volumes of data across long distances. It is designed to meet the ever-increasing bandwidth requirements of modern communication networks. OTN employs wavelength-division multiplexing (WDM) techniques, allowing multiple signals to be transmitted simultaneously over a single optical fiber. This technology has significantly increased the capacity and efficiency of data transmission, making it an ideal solution for high-bandwidth applications.

2.1 Key Components of OTN:

1. Optical Transceivers: These devices convert electrical signals into optical signals and vice versa. They play a crucial role in transmitting and receiving data over the optical network.

2. Optical Multiplexers/Demultiplexers: These components combine or separate multiple optical signals of different wavelengths, enabling the transmission of multiple data streams over a single fiber.

3. Optical Amplifiers: As data travels long distances, it tends to weaken. Optical amplifiers boost the optical signals, compensating for the signal loss and extending the reach of the network.

4. Optical Cross-Connects: These devices allow the switching and routing of optical signals, enabling flexible and dynamic network configurations.

2.2 Benefits of OTN

1. High Capacity: OTN offers enormous capacity, capable of transmitting terabits of data per second. This high capacity is crucial for bandwidth-intensive applications such as video streaming, cloud computing, and data centers.

2. Scalability: OTN provides a scalable solution, allowing network operators to easily expand their infrastructure to accommodate growing data demands. It supports the addition of new wavelengths and the integration of multiple network elements.

3. Reliability: Optical fibers used in OTN are highly reliable and less susceptible to electromagnetic interference. This ensures a stable and secure data transmission, minimizing the risk of data loss or corruption.

4. Cost Efficiency: By consolidating multiple data streams onto a single fiber, OTN reduces the need for extensive cabling infrastructure. This leads to cost savings in terms of equipment, maintenance, and power consumption.

5. Role in Revolutionizing High-Speed Data Transmission:

OTN has revolutionized high-speed data transmission by addressing the limitations of traditional copper-based networks. It has enabled the seamless transmission of massive amounts of data over long distances, facilitating global connectivity and supporting bandwidth-hungry applications. OTN's high capacity, scalability, and reliability have made it an essential technology for telecommunications providers, enabling them to meet the ever-increasing demands of the digital age.

2.3 Evolution of Optical Transport Network

The necessity to increase network flexibility and efficiency as well as the desire for high-speed data transfer have propelled the growth of optical transport networks

(OTNs). OTNs have experienced a number of changes throughout time, evolving from conventional SDH/SONET-based networks to contemporary packet-optical transport systems (P-OTS) and networks with software-defined networking (SDN) capabilities[15].

The first-generation OTNs were based on Synchronous Digital Hierarchy (SDH) and Synchronous Optical Networking (SONET) technologies; these networks were intended to support voice and data traffic, and they were distinguished by fixed transport rates and rigid network architectures. However, with the development of the internet and the demand for high-speed data transmission, SDH/SONET-based networks proved insufficient, and second-generation OTNs were created[16].

These networks were more effective than SDH/SONET-based networks and allowed for greater flexibility in network design and management, but they were still constrained in terms of capacity and scalability. The second-generation OTNs were based on. Wavelength Division Multiplexing (WDM) technology, which allowed multiple data signals to be transmitted concurrently over the same optical fiber [17].

The third-generation OTNs, also referred to as P-OTS, were created to address the shortcomings of WDM-based networks. P-OTS networks were created to support both packet-based and circuit-based traffic, allowing for more efficient use of network resources. P-OTS also introduced features like traffic grooming, wavelength switching, and dynamic bandwidth allocation, which improved network efficiency and flexibility[18]. The latest evolution of OTNs is software-defined networking (SDN)-enabled networks. SDN allows for greater network programmability and automation, enabling network operators to easily configure and manage network resources. SDN-enabled OTNs also allow for more efficient use of network resources and support for emerging technologies such as 5G, cloud computing, and the Internet of Things (IoT) [4][15].

2.4 Conventional Optical Network

In optical communication networks, the conventional (fixed) grid Wavelength Division Multiplexing (WDM) system is a frequently used technique. By employing several light wavelengths, it permits the simultaneous transmission of many signals across a single optical cable. This structural analysis will provide readers a thorough grasp of the traditional grid WDM system by highlighting its essential elements, signal multiplexing and demultiplexing methods, and implementation difficulties.

The traditional grid WDM system is made up of a number of essential parts that make signal transmission effective. These comprise optical receivers, optical fibers, optical transmitters, and optical amplifiers. Electrical impulses must be transformed into optical signals at certain wavelengths by optical transmitters. To make up for the signal loss during transmission, optical amplifiers like erbium-doped fiber amplifiers (EDFAs) are employed to enhance the optical signals. The optical signals are sent across great distances with little loss using optical fibers as the medium. After receiving the optical impulses, optical receivers change them back into electrical signals so that they may be processed further [19].

Signal multiplexing and demultiplexing are essential steps in the traditional grid WDM system for combining and separating multiple signals, respectively. Signals of various wavelengths are multiplexed onto a single optical cable using passive optical components known as multiplexers. Dense Wavelength Division Multiplexing (DWDM), the most popular multiplexing method, enables the transmission of several channels over a single fiber. Demultiplexers, which divide the combined signals into their individual wavelengths, are used to execute demultiplexing. By allowing many signals to be sent simultaneously over a single fiber, this approach greatly expands the network's capacity[20][21].

The typical grid WDM system has many benefits, however there are still some difficulties with deployment. Crosstalk, which happens when signals at different wavelengths interfere with one another and degrade transmissions, is a serious problem. This may be reduced by utilizing cutting-edge data processing methods and premium optical components. The fixed grid's limited capacity to scale presents another difficulty since it necessitates careful wavelength allocation and cooperation amongst network operators. Fiber nonlinearities, dispersion, and polarization mode dispersion can also have an impact on the system's performance, lowering signal quality and reducing transmission range. Continuous research and development efforts are needed to address these issues and enhance system performance and dependability [22].

2.5 Elastic Optical Network

Unlike conventional fixed-grid optical networks, elastic optical networks (EONs) allow for dynamic allocation of spectrum resources, enabling higher data rates and improved network scalability[23]. EONs use wavelength-division multiplexing (WDM) technology, which allows for the simultaneous transmission of numerous signals over a range of light wavelengths. EONs use variable channel widths, commonly referred to as spectrum slices or super-channels, in contrast to typical WDM systems, which have fixed channel spacing. Since the channel width may be changed in accordance with the unique data rate needs of each connection, this flexibility enables greater usage of the spectrum that is now accessible[24]. EONs' main benefit is their improved capacity for spectrum resource allocation. EONs may assign precisely the necessary amount of spectrum for each connection while eliminating waste and optimizing network capacity by dynamically modifying the channel width. This adaptability is especially useful in conditions with fluctuating traffic demands and various service requirements. To allow effective spectrum management and control, EONs also combine cutting-edge technology like flexible-grid ROADMs (Reconfigurable Optical Add-Drop Multiplexers) and software-defined networking (SDN). With the help of these technologies, optical connections may be dynamically provisioned, rerouted, and optimized, resulting in effective resource management and network flexibility[25].

2.6 Types of Elastic Optical Networks

There are several different types of Elastic Optical Networks (EONs) that have been proposed and studied. Here are three prominent types:

2.6.1 Gridless Elastic Optical Networks:

Griddles Elastic Optical Networks are a type of EON that enables flexible and fine-grained allocation of spectrum resources without being restricted by fixed grid spacing. In grid less networks, the spectrum is divided into smaller frequency slots, referred to as super channels or subcarriers, which can be dynamically assigned to accommodate varying data rates and modulation formats. This flexibility enhances the network's capacity and spectral efficiency by enabling effective utilization of the available spectrum. The performance of grid less EONs has been extensively studied, with studies concentrating on developing cutting-edge modulation schemes, routing algorithms, and resource allocation techniques.

2.6.2 Spectrum-Sliced Elastic Optical Networks:

Elastic optical networks (EONs) that use the idea of spectrum slicing are also referred to as Flex grid Networks. These networks split the optical spectrum into discrete, adjacent frequency slices, each able to support a certain data rate. Slice width, the size of these slices, can be dynamically changed to correspond to the necessary data rate and modulation type. Compared to conventional fixed-grid networks, spectrum-sliced EONs provide more flexibility in spectrum distribution since they allow for finer granularity and more effective exploitation of the available spectrum. The development of spectrum allocation algorithms, slice width modification methods, and resource management strategies for the best performance have been the main topics of this research.

2.6.3 Space Division Multiplexing (SDM) Elastic Optical Networks:

Elastic optical networks (EONs) that use spatial division multiplexing (SDM) make use of both wavelength and spatial dimensions to boost capacity. Multiple independent data channels are carried in different spatial routes by SDM EONs using multicore fibers or few-mode fibers. Data transmission and aggregation in parallel is made possible by the independent access to and switching of these geographical pathways. By using the fiber's spatial resources, SDM EONs offer increased capacity and greater spectrum efficiency. Research in this field has concentrated on creating effective SDM designs, creating crosstalk reduction strategies, and examining the performance trade-offs and constraints of SDM EONs.

2.7 Benefits of Elastic Optical Networks

The cost of network upgrades is greatly reduced by elastic optical networks (EONs). For traditional optical networks to meet rising bandwidth demands, costly and time-consuming improvements are needed. However, by utilizing the idea of spectrum slicing, EONs offer a versatile and economical alternative. EONs enable more effective use of the network resources by breaking down the available optical spectrum into smaller subcarriers. Due to the lack of expensive hardware changes, network operators may now dynamically assign bandwidth based on demand. In comparison to conventional optical networks, EONs can save the cost of network upgrades by up to 50%, according to a research by Zhang et al. (2017).

Modern networking must focus on maximizing energy efficiency, and EONs do this exceptionally well. The energy consumption of optical networks may be optimized by EONs by utilizing cutting-edge modulation schemes and flexible spectrum distribution. Traditional networks frequently run at a constant data rate, consuming energy inefficiently during times of low demand. EONs, on the other hand, dynamically modify the data rate according to demand, enabling more effective power use. EONs are a sustainable option for future networking infrastructure because, according to a research by Chen et al. (2018), they can save up to 40% more energy than traditional networks.

In today's diversified network traffic scenario, EONs have the benefit of meeting heterogeneous data rate needs, which is essential. Networks must accommodate a broad variety of data rates due to the expansion of bandwidth-intensive applications like video streaming, cloud computing, and Internet of Things (IoT) devices. This problem is solved by EONs, which enable adjustable subcarrier allocation with various modulation schemes and data speeds. As a result, the network resources are used effectively, and the unique data rate needs of each user are satisfied. EONs can provide a range of data throughput requirements while retaining high spectral efficiency and low latency, according to a research by Wang et al. (2019).

Reducing carbon dioxide (CO2) emissions is an important issue for the environment, and EONs support sustainability by reducing the carbon footprint of optical networks. Fixed data rates are a common feature of traditional networks, which leads to wasteful energy use and elevated CO2 emissions. EONs, on the other hand, minimize power needs by dynamically altering the data rate in response to demand, which optimizes energy use. There are less CO2 emissions as a result of this energy-efficient operation. According to a research by Chen et al. (2020), EONs can reduce CO2 emissions by up to 30% when compared to traditional networks, making them an eco-friendly option for network operators.

2.8 Scenarios to Use EONs

1. High-Capacity Data Centers:

To fulfill the rising demand for high-capacity and scalable interconnection, EONs may be installed within data center settings. EONs can effectively support the expansion of data traffic inside and between data centers by offering flexible spectrum resource distribution. The performance and scalability of data center networks are enhanced by the elastic nature of EONs, which enables dynamic bandwidth allocation and supports a variety of traffic patterns.

2. Metro and Long-Haul Networks:

EONs provide important advantages in metro and long-haul networks by facilitating effective use of the optical spectrum. EONs' flexible spectrum allotment enables more effective response to shifting traffic conditions and a range of service needs. Comparing this to conventional fixed-grid networks yields improvements in capacity, spectral efficiency, and cost-effectiveness.

3. Next-Generation Access Networks:

The growing demand for high-speed internet services may be satisfied by deploying EONs in access networks. EONs may accommodate varied data speeds and enable effective usage of fiber infrastructure by utilizing variable spectrum allocation. As a result, service providers may support different access methods and offer high-bandwidth services to consumers in residential, commercial, and mobile settings.

4. Smart Grid and Utility Networks:

EONs can be used in utility networks and smart grids to support the reliable and efficient transmission of data for monitoring, controlling, and managing purposes. By offering flexible bandwidth allocation and accommodating diverse data rates, EONs enable the integration of different smart grid applications and facilitate real-time monitoring of power grids, improving grid reliability and energy management.

5. Mobile Backhaul Networks:

EONs provide benefits for mobile backhaul networks, which need to have flexible and high-capacity connection to handle the rising data needs of mobile networks. EONs are able to effectively manage the changing traffic patterns and offer scalable backhaul solutions because they have the capacity to dynamically assign spectrum resources. This makes it possible for improved mobile network performance and helps with the switch to 5G and beyond.

6. Content Delivery Networks (CDNs):

In order to keep up with the rising demand for online multimedia services, CDNs rely on effective content distribution and delivery. EONs may be implemented in CDNs to enable dynamic and flexible bandwidth allocation, allowing for effective content delivery among servers that are spread out geographically. This enables enhanced user experience, decreased latency, and efficient content delivery.

7. Research and Education Networks:

Research and education networks, which need high-capacity connection to enable data-intensive scientific research, cooperation, and remote learning, offer a substantial amount of potential for EONs. Advanced research and educational applications may be supported by EONs' efficient and scalable network architecture by providing flexibility in spectrum allocation and supporting varied data rates.

2.9 Challenges of Elastic Optical Networks

2.9.1 Technical Challenges:

- **Spectrum Management:** To meet shifting traffic demands and maintain high spectral efficiency, the available spectrum resources must be efficiently allocated and managed.
- **Flexibility and Scalability:** ensuring the network's capability to grow in response to rising capacity demands and react dynamically to changing traffic patterns.
- **Signal Processing:** flex-grid technology is one example of an advanced signal processing approach that is being used to provide fine-grained wavelength granularity and enhance spectral efficiency.
- **Optical Reach and Transmission:** to maintain signal quality and reach required transmission lengths, one must overcome physical restrictions such signal deterioration, chromatic dispersion, and optical impairments.

2.9.2 Economic and Business Challenges:

- **Cost and ROI:** EON deployment's financial feasibility and return on investment (ROI) are evaluated, taking equipment, upgrade, maintenance, and possible income streams into account.

- **Standards and Regulations:** navigating changing legal frameworks, industry standards, and recommendations in relation to EON installations to guarantee compliance and interoperability.
- **Service Provisioning:** Creating pricing and service models that take into account consumer needs, bandwidth-on-demand, and service-level agreements (SLAs) in order to be compatible with the flexibility and capabilities of EONs.

2.10 Realizing Technologies of Elastic Optical Networks

2.10.1 Components of EONs & their function

The key components of EONs include:

Transponders:

Transponders are optical devices that transform electrical impulses into optical signals and vice versa. Transponders are essential for sending and receiving data across the optical network in EONs. They are in charge of modifying the optical signals' wavelength, modulation format, and power level as well as modulating and demodulating the signals.

Reconfigurable Optical Add-Drop Multiplexers (ROADMs):

In EONs, ROADMs are devices that add, drop, or pass through particular light signal wavelengths at various network nodes. They provide flexible routing and management of optical channels, enabling dynamic bandwidth allocation in response to traffic needs. In EONs, ROADMs facilitate effective resource usage and wavelength routing.

Optical Amplifiers:

To make up for signal loss that happens during transmission, optical amplifiers are utilized to amplify the optical signals in EONs. They increase the optical strength of the signals, enabling them to travel farther without suffering much. In EONs, optical amplifiers support signal quality maintenance and long-distance transmission.

Software-Defined Networking (SDN) Controllers:

In EONs, the network infrastructure is managed and controlled by SDN controllers, which are software components. They offer a central control plane that makes it possible to dynamically deploy, configure, and manage network resources. SDN controllers make network operations programmable and automated, enabling effective resource management and traffic engineering in EONs.

Network management systems (NMS):

NMS software controls, configures, and oversees the general performance of EONs. It offers network managers a graphical user interface (GUI) or command-line interface (CLI) via which they may keep track of network performance, set up network components, and resolve problems. NMS software aids in ensuring the efficient operation and upkeep of EONs.

Optical Line Systems:

The physical elements that make up the backbone of EONs, such as fiber optic cables, connectors, and other parts, are known as optical line systems. The physical foundation for sending and receiving optical signals over a network is provided by these technologies.

Tools for Network Planning and Optimization:

These programs help with the creation, organization, and optimization of EONs. They aid network administrators in traffic pattern analysis, resource allocation optimization, and capacity planning. The effectiveness and performance of EONs are improved with the use of these instruments.

2.10.2 Modulation Techniques of Elastic Optical Networks

The most common modulation techniques that are used in elastic optical networks have been described below:

OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a popular modulation method in elastic optical networks (EONs) because it makes good use of the spectrum that is accessible[26]. The data stream is split up into a number of orthogonal subcarriers, each of which carries a low-rate data signal in OFDM. Due to the tight spacing of these subcarriers in the frequency domain, the available bandwidth may be used effectively[27]. High-speed optical transmission is a good fit for OFDM because it offers resilience against channel imperfections such inter-symbol interference and inter-carrier interference. Additionally, it allows for adaptive modulation and variable subcarrier distribution depending on the various connections' differing bandwidth needs in EONs[28].

NWDM

Nyquist Wavelength Division Multiplexing (WDM) is another kind of modulation used in EONs to attain excellent spectral efficiency. Nyquist pulses, which are used in Nyquist WDM and are intended to reduce inter-symbol interference, are used. The subcarriers can be positioned closer together without interfering if the pulses are precisely shaped and their spectral properties are optimized. As a result, the number of channels within the available spectrum may be increased, enhancing EONs' spectral efficiency. Numerous studies have demonstrated the efficacy of Nyquist WDM modulation methods, such as Nyquist single-carrier transmission and Nyquist pulse-shaping, in obtaining high data rates and spectrum efficiency in optical communication systems[33].

TFP

Time Frequency Packing (TFP) is a modulation method created especially for elastic optical networks to maximize spectrum use[31]. TFP uses the time and frequency domains to compress the representation of data signals [37]. For the best possible distribution of the available spectrum resources, time-frequency packing methods are used[34]. Multiple data signals are bundled together in the time-frequency plane (TFP), which provides great spectral efficiency and variable bandwidth allocation to meet different data rate needs[35]. It has been suggested and researched whether TFP modulation schemes, such as time-frequency packing OFDM and time-frequency packing Nyquist, are beneficial in attaining efficient usage of optical spectrum resources in EONs[36], [37].

Based on the articles[38][39], here is a table (i.e.,Table 1) to show the advantage and disadvantages of the three modulation techniques:

Modulation Technique	Description	Advantages	Disadvantages
OFDM (Orthogonal Frequency Division Multiplexing)	A modulation technique that divides the available spectrum into multiple orthogonal subcarriers for simultaneous data transmission.	- High spectral efficiency - Resilient to multipath fading - Mitigates inter-symbol interference (ISI) - Suitable for high-speed data transmission	- Complex implementation - Susceptible to frequency and phase offsets - Requires precise synchronization between transmitter and receiver
Nyquist WDM (Wavelength Division Multiplexing)	A modulation technique that uses advanced pulse shaping techniques to achieve high spectral efficiency.	- Efficient utilization of the optical spectrum - Enhanced spectral efficiency compared to traditional WDM - Mitigates inter-symbol interference (ISI)	- Requires precise synchronization between transmitter and receiver - Sensitive to chromatic dispersion
TFP (Time Frequency Packing)	A modulation technique that combines orthogonal frequency division multiplexing (OFDM) and time division multiplexing (TDM) principles.	- High spectral efficiency - Improved resilience to multipath fading - Supports high data rates - Robust against frequency and phase offsets	- Increased complexity compared to individual modulation schemes - Requires precise synchronization between transmitter and receiver

Table 1: Advantage and disadvantages of OFDM, NWDM and TFP

2.10.3 Realizing Algorithms of Elastic Optical Networks

I. Spectrum Defragmentation Algorithm (SDA)

Spectrum Defragmentation Algorithms are essential for Elastic Optical Networks' (EONs') resource usage optimization. These algorithms are designed to reduce the spectrum fragmentation brought on by changing traffic needs. The First-Fit Spectrum Assignment (FFSA) method, which distributes the available spectrum to incoming requests based on the first-fit principle, is one frequently used algorithm. The Best-Fit

Spectrum Assignment (BFSA) method, which distributes the spectrum to requests based on the best-fit principle, is another well-known technique. Numerous studies and evaluations of these algorithms have been published in the scientific literature, indicating their efficacy in lowering spectrum fragmentation and enhancing network performance[40].

II. Routing and Spectrum Allocation (RSA)

Routing and Spectrum Allocation (RSA) Algorithms are made to jointly optimize the EON's spectrum allocation and routing processes. For each connection request, these algorithms find the most effective path and spectrum assignment by taking into account both the traffic needs and the physical layer limits. The Distance-Adaptive RSA (DA-RSA) technique, which considers the distance between nodes and modifies spectrum allocation correspondingly, is one frequently researched RSA algorithm. The Traffic Grooming RSA (TG-RSA) technique, which grooms numerous traffic needs into a single wavelength, is another famous algorithm that optimizes the allocation of spectrum resources. These RSA techniques let EONs use their resources more effectively and increase network efficiency[42].

III. Traffic Engineering Algorithms (TEA)

The primary goals of traffic engineering algorithms in EONs are resource optimization and dynamic network adaptation to shifting traffic patterns. These algorithms are designed to reduce congestion and balance network load. The Load Balancing Routing and Spectrum Assignment (LB-RSA) method, which divides traffic among several channels and optimizes spectrum assignment to prevent congestion, is an example of a traffic engineering algorithm. Some methods, like the Traffic Prediction-based RSA (TP-RSA) algorithm, proactively distribute spectrum resources based on anticipated future needs by using traffic prediction techniques. These traffic engineering methods aid in improving network performance and resource usage in EONs[48].

IV. Energy-Efficient Algorithms (EEA)

Energy-Efficient Algorithms is a major issue in contemporary networks, particularly EONs. Energy-efficient algorithms seek to lower network component power consumption while preserving passable network performance. The Energy-Aware Routing and Spectrum Allocation (EA-RSA) algorithm is one illustration of an algorithm that takes energy use and spectrum allocation into account when deciding how to route data. The Sleep-Awake RSA (SA-RSA) technique is a different approach that uses network devices' sleep mode to conserve energy when there is less traffic. The sustainability and economic viability of EONs are enhanced by these energy-efficient algorithms[54].

2.11 Architecture of Elastic Optical Networks

Elastic Optical Networks' (EONs') architecture is created to offer scalability and flexibility in the distribution of optical spectrum resources.

The physical layer, the spectrum layer, and the service layer are the three layers that make up an EON. According to [48] the physical layer includes the physical infrastructure, which includes optical fiber cable, Sliceable Bandwidth variable Transponder (SBVT), Reconfigurable Optical Add Drop Multiplexer (ROADM), and Fiber-Optic Cables.

The spectrum layer is in charge of breaking down the available spectrum into more manageable frequency slots or subcarriers, which may then be dynamically assigned to support various transmission speeds and modulation styles.

The service layer offers the essential administration and control features, including service provisioning, spectrum allocation, and routing.

The following figure (i.e., Figure 1) represents the most common type of EON architecture:

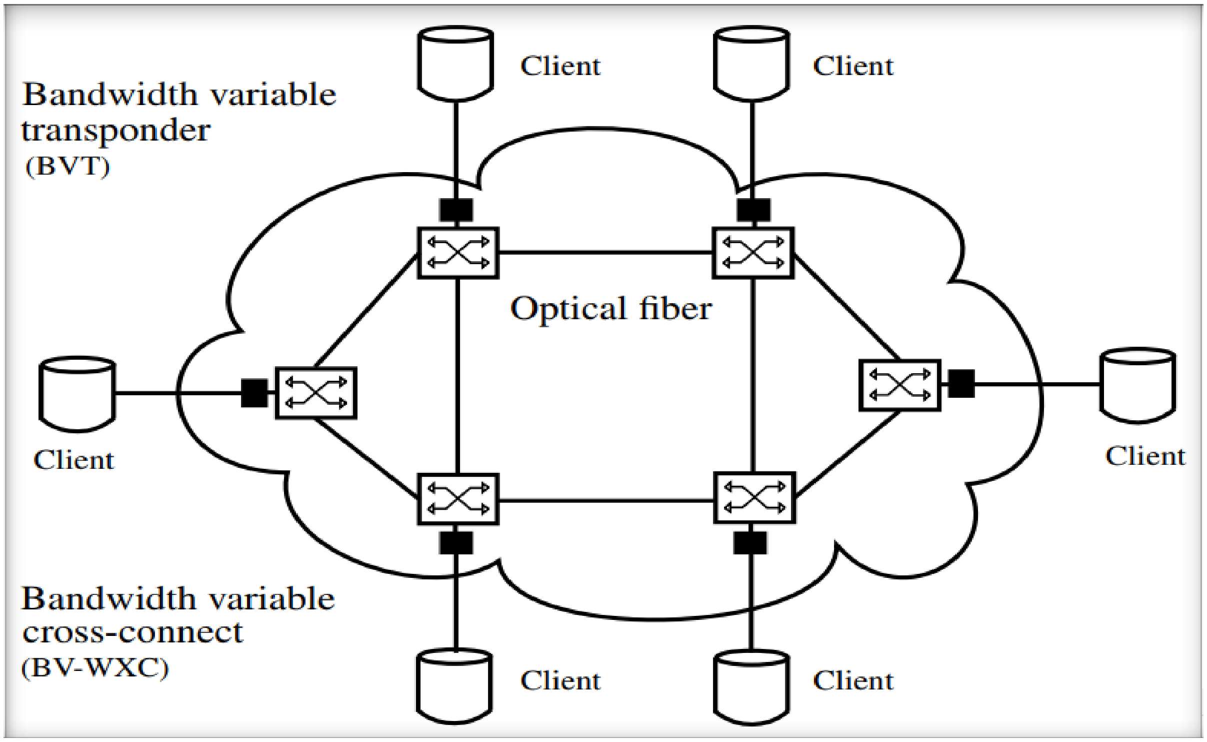


Figure 1: Architecture of Elastic Optical Network [59]

CHAPTER 3

3. Techno-Economic Analysis and Modeling

3.1 Introduction to Techno-Economic Analysis (TEA)

Techno-economic Analysis (TEA) is a thorough evaluation technique used to judge a technology or process's economic viability and feasibility. It analyzes the costs, advantages, and risks related to deploying a given technology by combining technical and economic data. TEA is frequently used to direct decision-making processes and improve resource allocation in a variety of industries, including the energy, industrial, and environmental sectors[48].

Identification of the technology or process being evaluated, gathering pertinent technical and economic data, and conducting a thorough analysis are some of the main elements in TEA. The technical analysis is concerned with comprehending the technical features of the technology, such as its performance, scalability, and efficiency. On the other side, the economic analysis looks at the monetary factors, such as capital and operational expenses, income sources, and return on investment. TEA offers insights into the economic viability, possible dangers, and prospects for advancement of a technology or process by combining these two aspects[49].

3.2 Techno-Economic Assessment Models

TEA models are effective instruments for assessing the commercial viability and economic viability of technology initiatives or processes. The costs, advantages, and dangers related to deploying a specific technology are evaluated using these models, which combine technical and economic data. To make educated judgments about investments, policy, and project planning, TEA models are often used in a variety of industries, including the energy, industrial, and environmental sectors. TEA models offer useful insights into the financial performance and potential profitability of a technology by taking into account elements including capital expenditures, operational expenses, energy consumption, and revenue generation.

TEA models often require a thorough examination of a technology's complete life cycle, from development and use through decommissioning and disposal. This comprehensive method enables decision-makers to comprehend a technology's long-term economic repercussions and spot significant cost-saving possibilities. Sensitivity analysis is frequently used in TEA models to determine how unknown parameters and outside variables affect the economic results. These models may also be used to compare various technological possibilities, enabling stakeholders to pick the best economically and environmentally sound solution[50].

The trustworthiness of the results produced by TEA models depends on the use of precise and current data. Therefore, gathering data and validating it are essential elements in creating a strong TEA model. Various sources, including as industry reports, governmental databases, and experimental investigations, can provide the data utilized in TEA models. When choosing data, it is crucial to take the geographical and chronological contexts into account in order to guarantee its applicability and correctness. Furthermore, as these elements have a considerable impact on a technology's economic viability, TEA models should be regularly updated to reflect changes in technological costs, market dynamics, and regulatory frameworks.

When assessing the findings of TEA models, it is important to take into account their numerous limitations. These models frequently make use of simplifications and assumptions, which might inject biases and uncertainties into the study. The quality and availability of data, as well as the presumptions used throughout the modeling process, have a significant impact on the accuracy of TEA models. Additionally, TEA models could not account for all of a technology's externalities, such as social costs or environmental effects. TEA models continue to be useful instruments for decision-making despite these drawbacks, offering a systematic and quantitative way to evaluate the economic viability of technology initiatives.

The Techno-Economic Results from the Advanced Communications Technologies and Services (TERA) model offers a thorough examination of the financial effects and advantages brought about by advanced communication technologies. To evaluate the potential improvements in productivity, innovation, and market growth, renowned specialists in the industry developed the TERA model, which combines cutting-edge technology developments with rigorous economic research. The TERA model provides useful insights into the financial effects of implementing modern communication technologies by taking into account elements including network infrastructure, spectrum allocation, and user demand. Its conclusions are an essential resource for scholars, industry stakeholders, and policymakers who want to comprehend the revolutionary potential of these technologies in advancing social development and economic growth.

3.3 Techno-Economic Result from ACTS (TERA) Model

3.3.1 TERA Framework

The Techno-Economic Results from ACTS (TERA) Framework is a thorough technique made to assess the techno-economic features of cutting-edge communications technologies and services. TERA, which was created as a component of the ACTS initiative, offers a methodical way to evaluate the feasibility and possible effects of new technologies on the telecom sector. By emphasizing its essential elements, input parameters, output metrics, and pertinent references, this brief seeks to give a general overview of the TERA Framework.

The techno-economic modeling framework used in different TEA projects is shown in Figure 2.[62]:

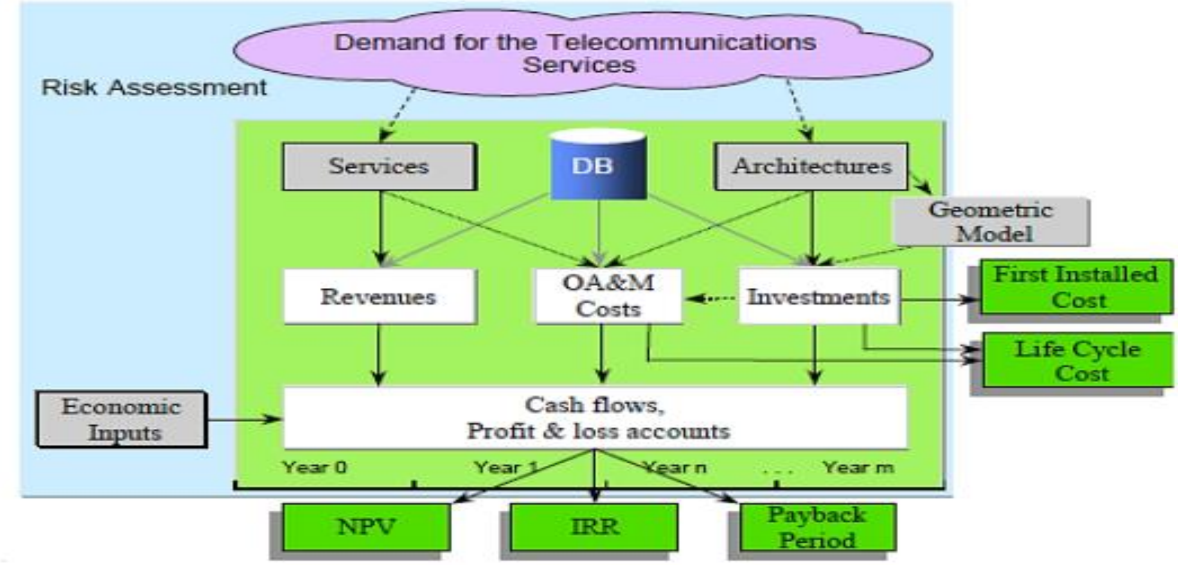


Figure 2: TERA Framework [62].

3.4. Cost Modeling

One of the key criteria for determining the viability of an elastic optical network deployment is the component cost. Capital expenditures (CAPEX) and operational expenditures (OPEX) are the two categories into which the costs of constructing and running an optical transport network may be divided. The cost calculations are done using data on the needed service configuration for each year as well as component pricing information. Calculations for CAPEX and OPEX represent the expenses related to installing and running the new system, respectively.

3.4.1. Capital Expenditure (CAPEX)

The ROADM, Multiplexer (OMU), Demultiplexer (ODU), Line, and Client Boards, as well as Licensed System Software, are investments in hardware and software that make up the CAPEX in this study. The required quantity of hardware and software licenses are acquired for each deployment option based on the component dimensioning results, and the investment costs are then determined.

CAPEX can be analytically described in accordance with Eq. (3.4.1)

$$CAPEX = C_{SW} + \sum_{S=1}^{10} (C_{ROADM} + C_{MUX} + C_{DEMUX} + C_{LB} + C_{CB})_S \dots\dots\dots\dots (3.4.1)$$

Where, $\boldsymbol{C_{SW}}$, $\boldsymbol{C_{ROADM}}$, $\boldsymbol{C_{MUX}}$, $\boldsymbol{C_{DEMUX}}$, $\boldsymbol{C_{LB}}$, $\boldsymbol{C_{CB}}$ is cost of software, ROADM, Multiplexer, DE multiplexer, Line Board and Client Boards respectively and S stands for Station numbers starts from 1 to 10.

3.4.2. Operational Expenditure (OPEX)

Operational expenditures (OPEX) are the continuing costs a business must pay to maintain its functional capabilities and sustain its regular operations.

In this study the operational expenditure consist of cost of upgrading, energy and board maintenance.

Their value can be calculated by the following equations:

a. Cost of upgrading

$$C_{UP} = \sum_{i}^{T} N_j^i * C_j^i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.4.2.a)$$

Where:

C_{UP} is total cost of upgrading

N_j^i is number of required components type j in period i

C_j^i is cost of component type j in period i.

b. Energy Expenses:

$$P_T = \sum_i^T (N_{NE} * P_{NE(kwh)}) \ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots (3.4.2.b1)$$

Where:

P_T is total power consumption,

N_{NE} is number of network elements

$P_{NE(kwh)}$ is power consumption value of each network element in kilo watt hour.

T is stands to represent time value of the study period.

$$C_E = P_T * C_{kwh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.4.2.b2)$$

Where:

C_E is total cost of energy

P_T is total power consumption

C_{kwh} is cost of power per kilo watt hour.

c. Board Maintenance Costs:

$$C_M = \sum_i^T (N_{BOARDS} * C_{M_{BOARD}}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.4.2.c)$$

Where:

C_M is total cost of maintenance

N_{BOARDS} is total number of faulty boards

$C_{M_{BOARD}}$ is cost of maintenance per each board.

$$\therefore OPEX = C_{UP} + C_E + C_M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.,\ldots. (3.4.2.d)$$

Where:

$OPEX$ is operational expenditures

C_{UP} is total cost of upgrading

C_E is total cost of energy

C_M is total cost of maintenance

3.4.3. Total Cost of Ownership (TCO)

The formula for determining total cost of ownership (TCO), which is the sum of operational and capital expenses (CapEx and OpEx), is given in equation 3.4.3.

$$TCO = CAPEX + OPEX \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.4.3)$$

3.5. Revenue Modeling

When determining the yearly revenue value, several variables are taken into account, including the demand for various data rates (1G, 10G, 40G, and 100G) services, the distance in kilometers, and the duration in months. These elements have a role in deciding the revenue made over the course of a year.

The amount of annual revenue can be calculated by the following formula, equation 3.5:

$$\boldsymbol{AR} = \mathbf{12}\sum_{\boldsymbol{S_T}}(\boldsymbol{C_S} * \boldsymbol{D_S})_{\boldsymbol{S_T}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(3.5).$$

Where:

AR = Annual Revenue

S_T = Service types i.e., 1G, 10G, 40G, & 100G

C_S = Cost of each service type per kilometer per month

And is equal to $C_S = \frac{S_T}{Km}/Month$

D_S = total distance value of each services

3.6. Techno-Economic Evaluation Metrics

One of the most crucial findings in a techno-economic study is whether a project will be lucrative or not. The net present value, internal rate of return, and payback period are some of the popular metrics used to assess a project's profitability. The discounted cash flow (DCF) analysis and cash flow (CF) analysis, both of which are shown below, were methods used in this techno-economic study.

3.6.1. Cash Flow (CF)

The net amount of cash collected and spent throughout the research period is known as cash flow. The CF model is constructed using the results from the cash and revenue model as shown in Equation 3.6.1.[53]:

$$CF = \sum_{i}^{T} (R_T - C_T)_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots. (3.6.1)$$

Where

CF = Cash Flow

R_T = Total Revenue

C_T = Total Cost

T = The number of time (study) period

3.6.2. Discounted Cash Flow (DCF)

The term "discounted cash flow" (DCF) refers to a method of valuation that calculates an investment's value based on anticipated future cash flows. By using predictions of how much money an investment will make in the future, DCF analysis aims to evaluate the value of a particular investment now[53].

DCF modeled mathematically as shown in Eq. (3.6.2)[53]:

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_i}{(1+r)^i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.6.2)$$

Where:

DCF is discount cash flow,

CF_1, CF_2, CF_i is cash flow of year 1, 2 up to the study period i,

r is rate of discount.

3.6.3. NPV, IRR, PI and PBP

- **Net present value (NPV)** is a financial statistic that determines the present value of anticipated future cash flows and compares it to the needed rate of return to determine the profitability of an investment.

NPV can be mathematically represented in Eq. (3.6.3.a)[51]:

$$NPV = \sum_{i=0}^{T} \left(\frac{CF_i}{(1+r)^i} \right) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.6.3.a)$$

- **Internal rate of return (IRR)** is a statistic used in financial analysis to calculate the profitability of possible investments. In a discounted cash flow analysis, IRR acts as a discount rate to bring all cash flows' net present values (NPV) to zero.

  The internal rate of return can be computed using the following Eq. (3.6.3.b):

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \dots \dots \dots . \dots \dots \dots \dots . . \dots \dots . . (3.6.3.b)$$

Where:

C_t = Net cash inflow during the study period t

C_0 = Total initial investment costs

IRR = The internal rate of return

t = The number of time (study) period

- **Profitability index (PI)**

The profitability index (PI), also known as the value investment ratio (VIR) or profit investment ratio (PIR), is an indicator that shows how the benefits and expenses of a proposed project are related.

The profitability index is determined by dividing the project's original investment by the present value of predicted future cash flows.

The profitability index can be computed using the following Eq. (3.6.3.c):

$$PI = \frac{PV\ of\ future\ cash\ flows}{Initial\ investment} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6.3.c)$$

- **Payback period (PBP)** is

  The duration needed to recoup an investment's cost is referred to as the payback period. Simply described, it is the period of time it takes for an investment to break even.

  The payback period can be computed using the following Eq. (3.6.3.d)[51]:

$$PBP = LP + \frac{Abs(CCF)}{CF} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6.3.d)$$

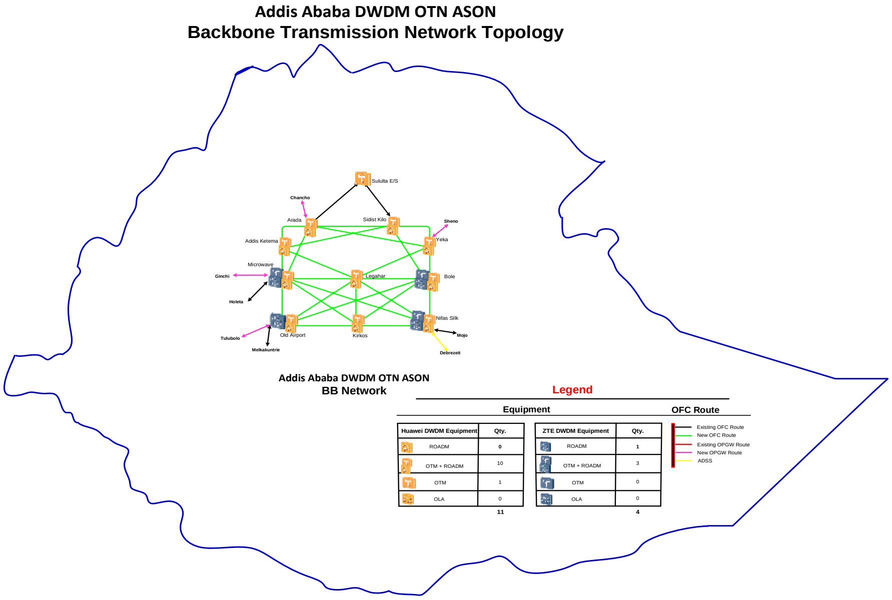
CHAPTER 4

4. Deployment Options and Dimensioning

4.1 Deployment Options of EON

The choice of network architecture is a key factor in optical networking since it affects network performance, reliability, scalability, failure resilience, and bandwidth capacity. The purpose of this comparative analysis is to assess the appropriateness of several EON topologies, including star-based, ring-based, and mesh-based, for connecting ten of Addis Ababa's optical backbone nodes (i.e. Bole, Microwave, Legahar, Kirkos, Nifas Silk, Arada, Addis Ketema, Yeka, Sidist Kilo & Old airport) in Ethio telecom. The assessment has taken into account the aforementioned restrictions to identify the best form of EON for the case at hand.

The existing Addis Ababa back bone optical network topology is depicted by the following figure (i.e., figure 3)



Huawei DWDM Equipment	Qty.
ROADM	**0**
OTM + ROADM	10
OTM	1
OLA	0
	11

ZTE DWDM Equipment	Qty.
ROADM	**1**
OTM + ROADM	3
OTM	0
OLA	0
	4

Figure 3: Existing Addis Ababa Back Bone Infrastructure

4.1.1 Star-Based EON:

In a star-based EON, each optical node has a direct connection to a hub or switch in the center. This architecture has several benefits, including easier resource allocation, easier scaling, and simpler network administration. However, if the central hub fails or gets backed up, it might become a single point of failure and reduce the network's overall resilience. In star-based EONs, bandwidth capacity may be a possible bottleneck since the central hub must manage the combined traffic from all linked nodes.

4.1.2 Ring-Based EON

A complete loop of optical nodes that are individually coupled to their neighboring nodes is a characteristic of ring-based EON structure. This architecture has built-in fault tolerance since traffic may be diverted both clockwise and counterclockwise in the case of a link or node failure. Given that each node has a dedicated connection to its neighbors, the ring-based EON also has a higher bandwidth capacity than star-based networks. As adding or deleting nodes might disturb the entire ring structure, scalability can be difficult in large-scale installations.

4.1.3 Mesh-Based EON:

Of the three topologies under consideration, mesh-based EONs provide the greatest degree of adaptability and failure resistance. Each node in a mesh-based EON is interconnected with several additional nodes, resulting in a redundant and fault-tolerant network. Traffic can be dynamically routed over several pathways to avoid congestion or outages, allowing for effective traffic engineering. Due to the many connections that each node may have, mesh-based EONs often have large bandwidth capacities. A mesh-based EON can be difficult to manage and provision connections in, especially for large-scale implementations.

It is advised that a mesh-based Elastic Optical Network (EON) is the most ideal topology for connecting the ten optical nodes based on the examination of network performance, reliability, scalability, resiliency to failure, and bandwidth capacity. Superior resilience against failures, effective bandwidth utilization, and the ability to dynamically route data over numerous channels are all features of the mesh-based architecture. Even while administration and provisioning may be more complicated, the advantages of improved network performance and scalability exceed the difficulties. This recommendation is consistent with other research that has emphasized the reliability and capacity benefits of mesh-based EON [35].

On the next page there is a table (i.e., table 2) to summarize the characteristics of the three deployment options:

Parameters	Deployment Options		
	Star-EON	Ring-EON	Mesh-EON
NW Performance	Offers good performance	Provides moderate performance	Offers excellent performance
Reliability	Provides good reliability as failures in one node do not affect other nodes, but the central hub becomes a single point of failure.	Offers high reliability as traffic can be rerouted in case of link or node failures, ensuring continuous connectivity.	Provides the highest reliability as multiple paths are available, allowing traffic to be dynamically rerouted in case of failures.
Scalability	Offers good scalability as additional satellite nodes can be easily connected to the central hub	Provides moderate scalability as adding more nodes to the ring requires reconfiguration of the entire ring.	Offers excellent scalability as new nodes can be added and connected to the existing mesh without disrupting the network.
Resiliency to failure	Offers limited resiliency as failures in the central hub can disrupt connectivity to all satellite nodes.	Provides high resiliency as traffic can be rerouted in case of failures, ensuring continuous connectivity.	Offers the highest resiliency as failures in one part of the network can be bypassed by using alternative paths.
Bandwidth capacity	Offers good bandwidth capacity, depending on the capacity of the central hub and the number of satellite nodes.	Provides moderate bandwidth capacity, shared among all nodes in the ring.	Offers excellent bandwidth capacity, as traffic can be dynamically routed through multiple paths, avoiding congestion.
Management	Offers centralized management, making it easier to monitor and control the network from the central hub.	Requires distributed management, as each node in the ring needs to be monitored and managed individually.	Requires complex management due to the large number of interconnected nodes, requiring advanced monitoring and control systems.

Table 2: Characteristics of the three types of EON in various parameters

4.2 Dimensioning

The proposed formulas determine the total number of components needed for the implementation of an elastic optical network while accounting for the current network topology, the quantity of add-and-drop channels, services (such as 1G, 10G, 40G, and 100Gs), and the fiber links that connect the individual nodes. The formulas provide an accurate assessment of the component quantities required by taking into account the particular network topology and connectivity between nodes, ensuring effective resource allocation and cost optimization during the deployment process.

4.2.1 Dimensioning of ROADM Boards

The total number of ROADM is found by the following formula:-

$$TN_{ROADM} = \sum_{S=1}^{10} {}^{N_{FL}}/_{(NP_{ROADM})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.2.1)$$

Where

TN_{ROADM} is the total number of ROADM boards

N_{FL} is number of available Fiber Links at station S.

NP_{ROADM} is the port number of ROADM at station S.

4.2.2 Dimensioning of Multiplexer (MUX)

The total number of Multiplexer can be found by the following formula:-

$$TN_{MUX} = \sum_{s=1}^{10} (NE)_S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.2.2)$$

Where

TN_{MUX} is the total number of multiplexer.

NE is number of available network elements at each station.

S it stands for station which holds backbone optical network element in Addis Ababa.

4.2.3 Dimensioning of Demultiplexer (DEMUX)

The total number of Demultiplexer can be found by the following formula:-

$$TN_{DEMUX} = \sum_{s=1}^{10} (NE)_S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.2.3)$$

Where

TN_{DEMUX} is the total number of multiplexer.

NE is number of available network elements at each station.

S it stands for station which holds backbone optical network element in Addis Ababa.

4.2.4 Dimensioning of Line Boards

The total number of Line boards is found by the following formula:-

$$TN_{LB} = \sum_{s=1}^{10} \left({}^{N_{OC}}/_{PN_{LB}}\right)_S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.2.4)$$

Where

$\mathrm{TN_{LB}}$ is the total number of optical line boards.

$\mathrm{N_{OC}}$ is number of add/drop optical channels at each station

$\mathrm{PN_{LB}}$ is the port number of the optical line board

S it stands for station which holds backbone optical transport network in Addis Ababa.

4.2.5 Dimensioning of Client Boards

The total number of Client boards is found by the following formula, equation 4.2.5.

$$TN_{CB} = \sum_{S=1}^{10} \left({}^{N_{Traffic}}/{}_{PN_{CB}}\right)_S \text{ ……………………………. (4.2.5)}$$

Where

$\mathrm{TN_{CB}}$ is the total number of client boards.

$\mathrm{N_{Traffic_S}}$ is number of traffics/services per station.

$\mathrm{PN_{CB_S}}$ is the port number of the client board.

S it stands for station which holds backbone optical transport network in Addis Ababa.

CHAPTER 5

5. Implemented TEA Model and Input Values

5.1 Implemented TEA Model

The original TERA (techno-economic analysis) model has been modified for this study to take into account the particular evaluation criteria emphasizing both technical and economic benefits. It enables a thorough evaluation of the techno-economic viability of the proposed elastic optical network deployment by customizing the model to the study's requirements. Key elements including performance measures, cost analyses, revenue estimates, and financial indicators are incorporated into the redesigned model. These improvements make the updated TERA model an effective tool for assessing the feasibility and potential benefits of setting up an elastic optical network. For this thesis, a modified TEA model (Figure 4) has been constructed based on input/output parameters from the TERA and a modified model.

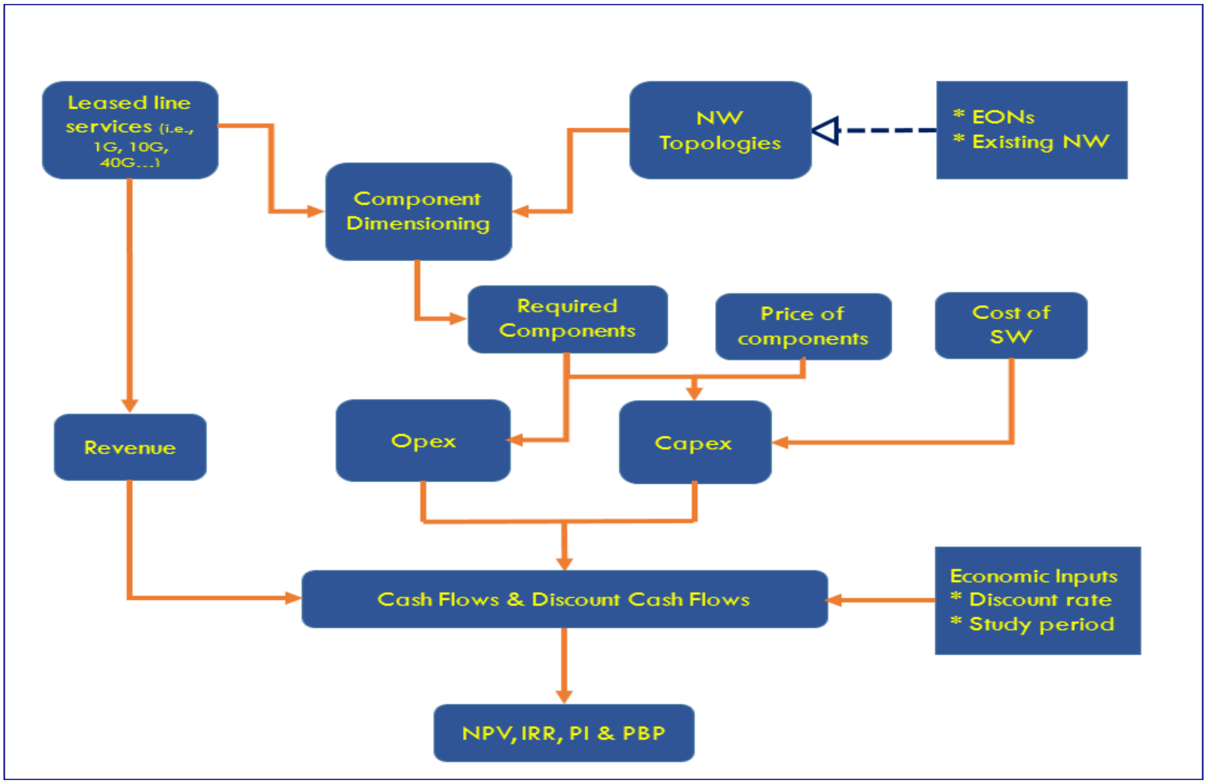


Figure 4: Modified and Implemented TEA Model

5.2 Model Description

A thorough techno-economic analysis model is used in the evaluation of an elastic optical network deployment. Revenue, capital expenditures (capex), operational expenditures (opex), discount rate, and study duration are just a few of the many input factors that this model takes into account. The income value is calculated for this study based on the service/demand needs, especially taking into account various data rates like 1G, 10G, 40G, and 100G. On the other hand, the network topology/deployment choice and the expenses related to both hardware and software components have an impact on the capex value.

The opex value also accounts for the expenses of maintenance, energy use, and upgrading, as well as the trend shown over the previous five years. The techno-economic analysis model offers a thorough evaluation of the technical and financial viability of setting up an elastic optical network by taking these input characteristics into account.

5.3 Input Values

5.3.1 Services

Based on the past five years traffic data which have been taken from Ethio Telecom the future service/demand value has been estimated and forecasted for the next seven years using regression method. And the following figure (figure 5) depicted us the future service/demand value in different data rates (i.e. 1G, 10G, 40G, & 100G services).

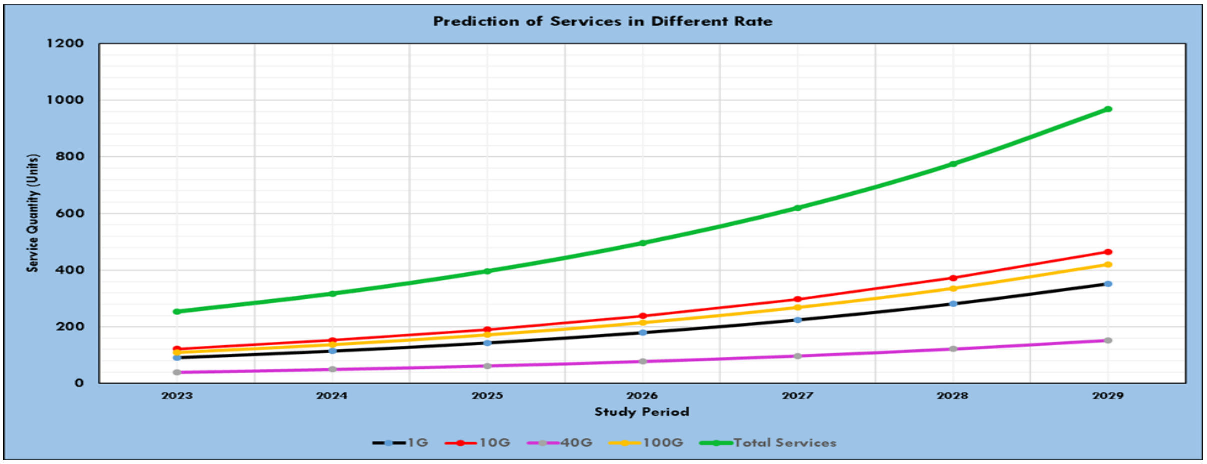


Figure 5: Estimated and Forecasted Service Quantities

5.3.2 Revenue

Based on the above service/demand value (i.e., figure 5) and by using revenue modeling in chapter 3, equation 3.5, the value of the next seven years revenue is depicted in table 3.

Years of the study	**Estimated and Forecasted Revenue Values($)**				
	1G($)	10G($)	40G($)	100G($)	**Total($)**
2023	$ 144,000.00	$ 467,280.00	$ 544,992.00	$ 462,384.00	$ 1,618,656.00
2024	$ 165,600.00	$ 514,008.00	$ 583,141.44	$ 476,255.52	$ 1,739,004.96
2025	$ 190,440.00	$ 565,408.80	$ 623,961.34	$ 490,543.19	$ 1,870,353.33
2026	$ 219,006.00	$ 621,949.68	$ 667,638.63	$ 505,259.48	$ 2,013,853.80
2027	$ 251,856.90	$ 684,144.65	$ 714,373.34	$ 520,417.27	$ 2,170,792.15
2028	$ 289,635.44	$ 752,559.11	$ 764,379.47	$ 536,029.78	$ 2,342,603.80
2029	$ 333,080.75	$ 827,815.02	$ 817,886.04	$ 552,110.68	$ 2,530,892.49

Table 3: Estimated and Forecasted Revenues ($)

5.3.3 CAPEX

The value of Capex mainly depends on the type of network topology (or deployment options) and the value of service or demand.

And using all the dimensioning equations in chapter 4, the value of capex has been depicted in the following figure (Figure 6).

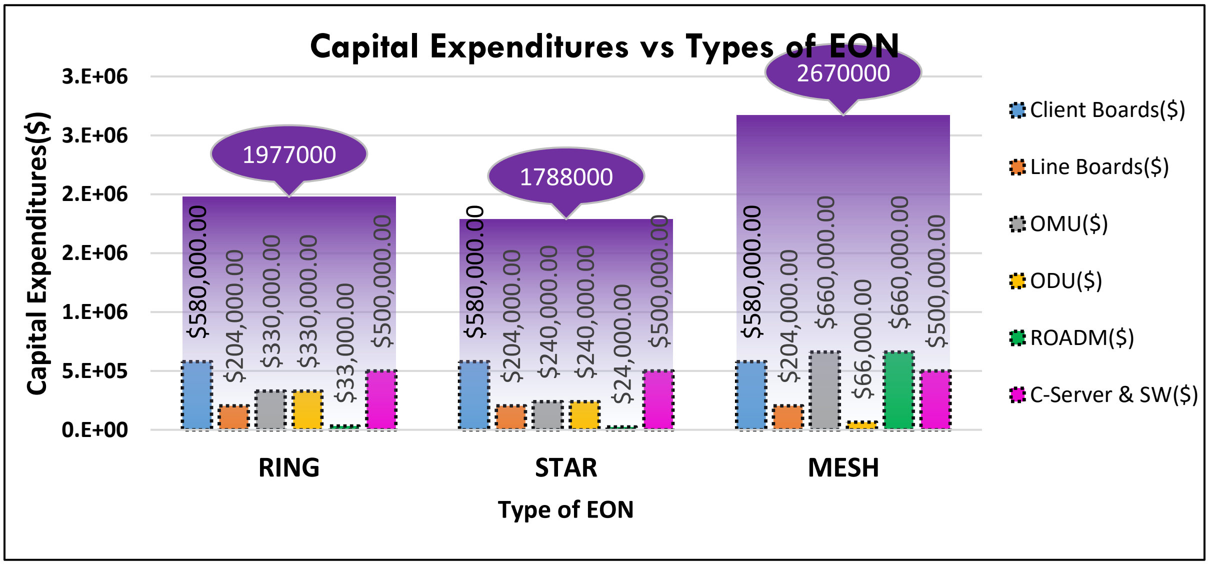


Figure 6: Required Capital Expenditures for each deployment type

5.3.4 OPEX

Table 4 Shows operational expenditure (Opex) values derived from considering the past five years' Opex values, various network types, and utilizing operational expenditure equations from Chapter 4.

Year of study	Opex Type	Network Types			
		Existing-OTN	Star-EON	Ring-EON	Mesh-EON
Year-1	Spare Part($)	$ 300000.00	$ 120000.00	$ 90000.00	$ 150000.00
	Energy($)	$ 46,486.95	$ 9,956.01	$ 8,200.88	$ 24,923.82
	Maintenance($)	$ 678,030.30	$ 372,916.67	$ 325,454.54	$ 339,015.15
	Total Year-1 Opex($)	$ 1,024,517.25	$ 502,872.68	$ 423,655.42	$ 513,938.97
Year-2	Spare Part($)	$ 324,000.00	$ 123,600.00	$ 90,900.00	$ 159,000.00
	Energy($)	$ 52,065.39	$ 11,150.73	$ 9,184.98	$ 27,914.67
	Maintenance($)	$ 745,833.33	$ 384,104.16	$ 328,709.09	$ 355,965.91
	Total Year-2 Opex($)	$ 1,121,898.72	$ 518,854.90	$ 428,794.07	$ 542,880.58
Year-3	Spare Part($)	$ 349,920.00	$ 127,308.00	$ 91,809.00	$ 168,540.00
	Energy($)	$ 58,313.23	$ 12,488.82	$ 10,287.18	$ 31,264.43
	Maintenance($)	$ 820,416.66	$ 395,627.29	$ 331,996.18	$ 373,764.20
	Total Year-3 Opex($)	$ 1,228,649.90	$ 535,424.11	$ 434,092.36	$ 573,568.64
Year-4	Spare Part($)	$ 377,913.60	$ 131,127.24	$ 92,727.09	$ 178,652.40
	Energy($)	$ 65,310.82	$ 13,987.48	$ 11,521.64	$ 35,016.17
	Maintenance($)	$ 902,458.33	$ 407,496.11	$ 335,316.14	$ 392,452.41
	Total Year-4 Opex($)	$ 1,345,682.75	$ 552,610.83	$ 439,564.87	$ 606,120.98
Year-5	Spare Part($)	$ 408,146.69	$ 135,061.06	$ 93,654.36	$ 189,371.54
	Energy($)	$ 73,148.12	$ 15,665.98	$ 12,904.24	$ 39,218.11
	Maintenance($)	$ 992,704.16	$ 419,720.99	$ 338,669.30	$ 412,075.03
	Total Year-5 Opex($)	$ 1,473,998.97	$ 570,448.03	$ 445,227.90	$ 640,664.68
Year-6	Spare Part($)	$ 440,798.42	$ 139,112.89	$ 94,590.90	$ 200,733.84
	Energy($)	$ 81,925.90	$ 17,545.90	$ 14,452.75	$ 43,924.28
	Maintenance($)	$ 1,091,974.58	$ 432,312.62	$ 342,056.00	$ 432,678.79
	Total Year-6 Opex($)	$ 1,614,698.90	$ 588,971.41	$ 451,099.65	$ 677,336.90
Year-7	Spare Part($)	$ 476,062.30	$ 143,286.28	$ 95,536.81	$ 212,777.87
	Energy($)	$ 91,757.00	$ 19,651.40	$ 16,187.08	$ 49,195.19
	Maintenance($)	$ 1,201,172.04	$ 445,282.00	$ 345,476.56	$ 454,312.72
	Total Year-7 Opex($)	$ 1,768,991.34	$ 608,219.68	$ 457,200.45	$ 716,285.78

Table 4: Values of Opex in different network type with in the study period

5.3.5 Discount Rate

An average discount rate of 12% has been chosen for this study because of the wide range of commercial possibilities offered to Ethio Telecom. It is possible to conduct a thorough study of the potential return on investment and long-term economic advantages associated with the project using this discount rate as a baseline for assessing the profitability and financial viability of the deployment of an elastic optical network.

5.3.6 Study Period

Seven years have been chosen as the study period and the average duration for this analysis since the backbone network has a longer technology change time than the access network. This additional time period enables a thorough assessment of the elastic optical network deployment, taking into account elements like technological advancements, scalability needs, and economic viability over a sufficient amount of time to capture the network's long-term performance and potential benefits.

CHAPTER 6

6. Result and Analysis

6.1 Technical Analysis

In this study the technical analysis mainly focus on bandwidth utilization, deployment options, component dimensioning and traffic forecasting.

6.1.1 The Preferable Deployment Option

In chapter four of the research, deployment options for elastic optical networks are thoroughly examined while taking into account both the characteristics of the new system and the optical fiber infrastructure that already exists at ethio telecom. Elastic Optical Networks with a focus on star-based, ring-based, and mesh-based deployment are covered in great detail and also this study confirmed that all the deployment options are very possible in the case of ethio telecom.

But based on technical parameters (i.e., NW Performance, Reliability Scalability, Resiliency to failure, Bandwidth capacity & Management) the most preferable deployment option is Mesh-based Elastic Optical Network has been confirmed.

6.1.2 Required Components per NW Types

By considering future service demand and the past five years trend analysis, to give complete service and achieve expected revenue values the required components amount per each deployment option have been listed out in table 5 of the next page.

Item list	Total required quantity of components based on network type/deployment options		
	Star-EON	Ring-EON	Mesh-EON
Client Boards	395	395	395
Line Boards	170	170	170
Multiplexer	16	22	48
Demultiplexer	16	22	48
ROADM	16	22	48
Server PC with SW	2	2	2

Table 5: Required components in different NW Type

6.2 Techno-Economic Analysis

In this sub section we will see the result of cash flows (CF), discount cash flows (DCF), net present value (NPV), internal rate of return (IRR), payback period (PBP), and return on investment (ROI) of each network type.

6.2.1 Cash Flow Analysis (CF) for S-EON

Here by considering values of capital and operational expenditures, revenues, discount rate and study period, the value of cash flows of each network type have been shown by the following figures.

Here is the cash flow value of Star type EON (i.e., figure 7).

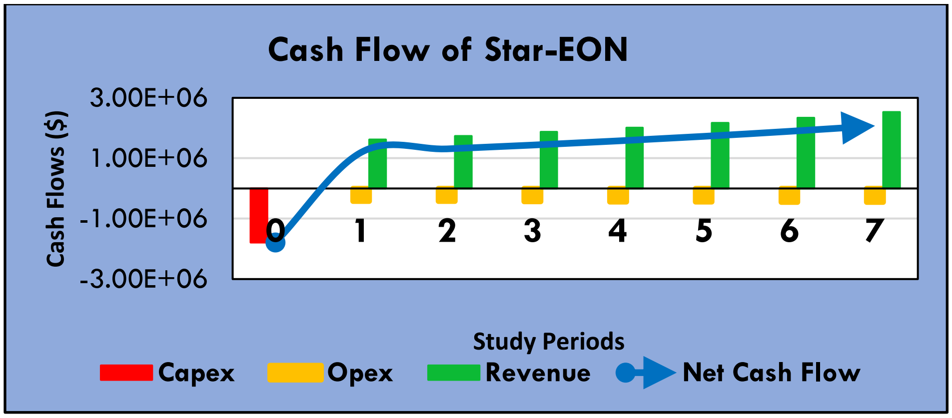


Figure 7: Cash Flow Value of Star based EON

6.2.2 Cash Flow Analysis (CF) for R-EON

Here is the cash flow value of Ring type EON (i.e., figure 8).

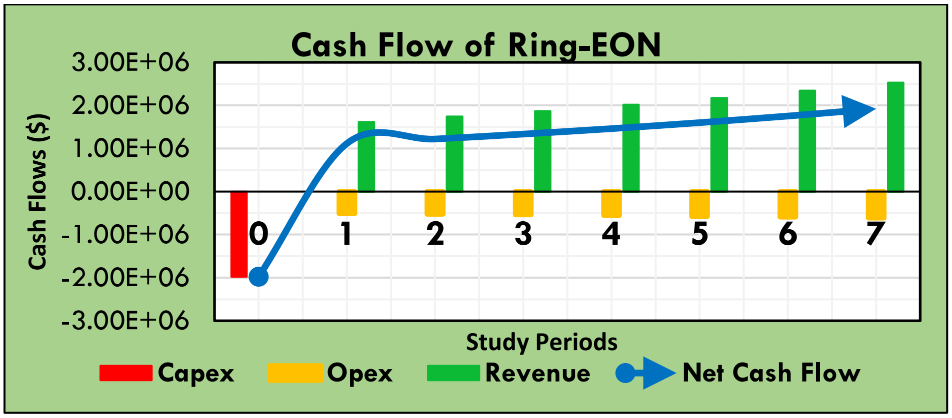


Figure 8: Cash Flow Value of Ring type EON

6.2.3 Cash Flow Analysis (CF) for M-EON

Here is the cash flow value of Mesh type EON (i.e., figure 9).

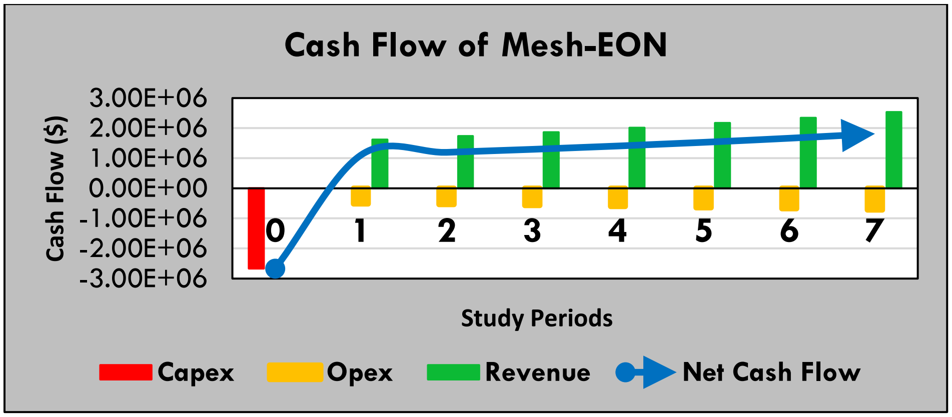


Figure 9: Cash Flow Value of Mesh type EON

6.2.4 Cash Flow Analysis (CF) value of Existing System

Here is the cash flow value of Existing system (i.e., figure 10).

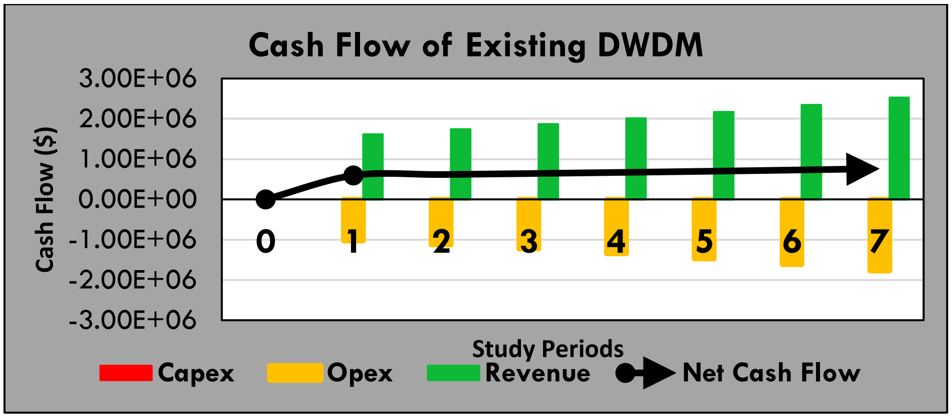


Figure 10: Cash flow value of Existing System

6.2.5 Net Present Value (NPV)

The net present value (NPV) is a financial metric that measures the profitability of an investment by calculating the present value of expected cash flows and subtracting the initial investment cost. In the case of the techno-economic analysis of Elastic Optical Network (EON) deployments in star, ring, and mesh topologies, assuming different cost of capital rates (12%, 14%, 16%, and 18%), the calculated NPV values are have been described by the figure 11.

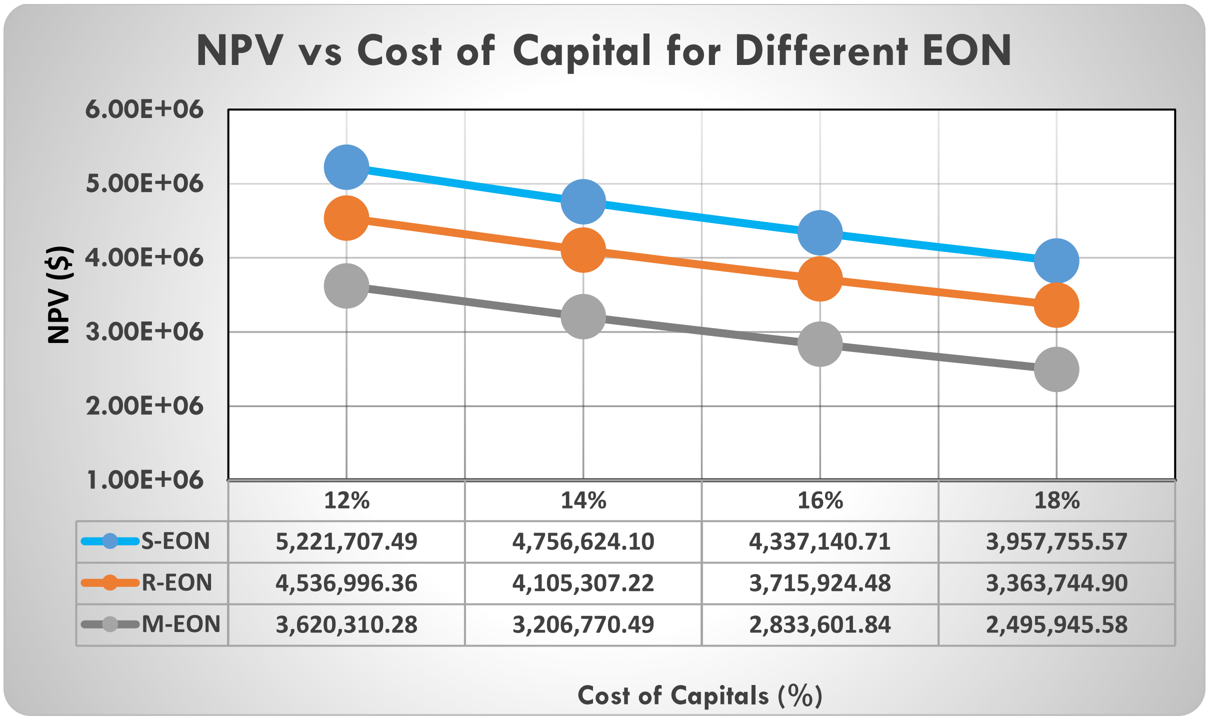


Figure 11: Net Present Value of all EON Architecture

6.2.6 Internal Rate of Return (IRR)

The discount rate at which the net present value of cash inflows equals zero, or the rate of return at which the investment breaks even, is found using the IRR measure. More favorable investments with larger prospective returns typically have higher IRR levels. The projected IRR values for the EON installations in star, ring, and mesh topologies change depending on the estimated cost of capital rates. The IRR values for all three topologies have been depicted in figure 12.

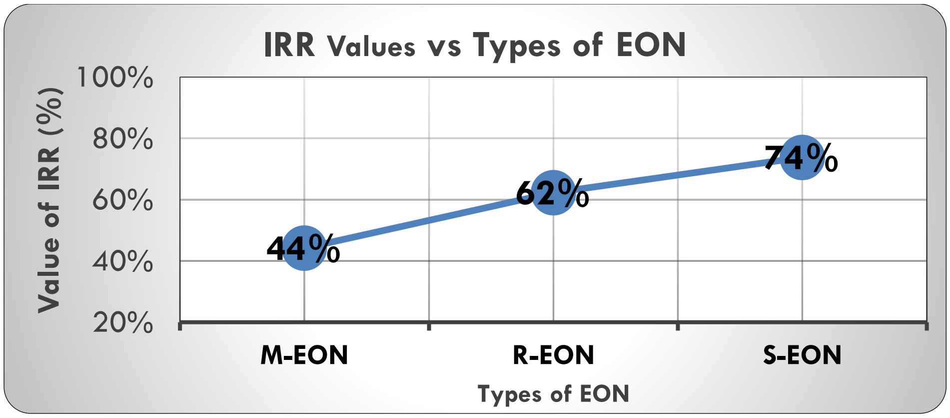


Figure 12: IRR Values of all EON Architectures

6.2.7 Pay Back Period (PBP)

A financial indicator called the payback period shows how long it takes for an investment to recoup its initial cost or investment expenditure. The predicted payback period for each topology in the techno-economic study of Elastic Optical Network (EON) deployments in star, ring, and mesh topologies is as follows:

In assessing the viability and profitability of an investment, the payback period is a key indicator. A quicker return on investment is a good thing, hence a shorter payback period is a good thing. The payback durations of 15.8 months, 19.6 months, and 23.9 months, respectively, for the EON installations in star, ring, and mesh topologies point to the possible financial feasibility of these network designs.

The payback period values of all the three architectures depicted by figure 13.

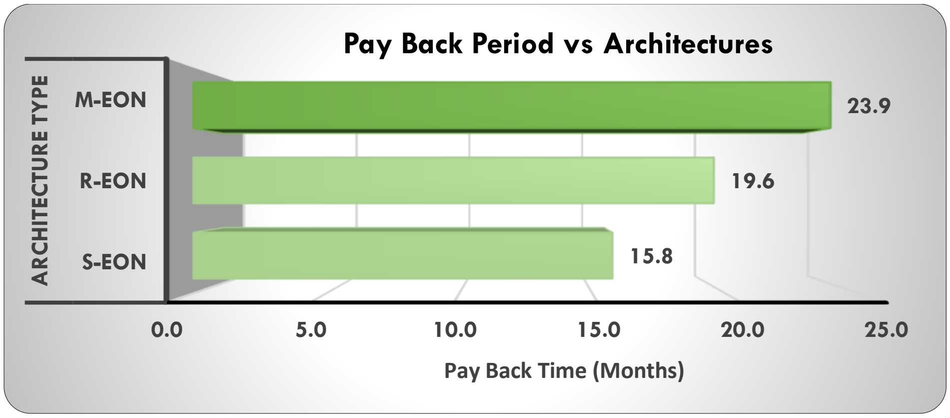


Figure 13: Pay Back Period Value of all EON Architecture

6.2.8 Profitability Index (PI)

The following figure (i.e., figure 16) illustrates the value of return on investment (ROI) for three different network architectures. The ROI values are calculated based on a 12% cost of capital, providing insights into the financial viability of each architecture.

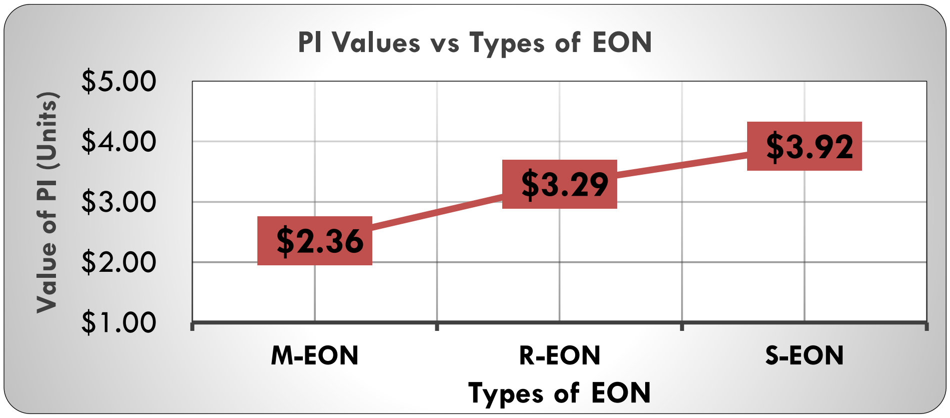


Figure 14: Profitability Index Value of all EON Architecture

CHAPTER 7

7. Conclusion and Future Work

7.1 Conclusion

In conclusion, a thorough techno-economic study of the implementation of elastic optical networks (EONs) has been done in this thesis. According to the conclusions reached after thorough investigation and assessment, the use of EON technology is very lucrative economically. According to the report, EONs have a lot to offer in terms of better spectrum usage, flexibility in meeting changing bandwidth requirements, and effective resource distribution. These elements help network operators generate more income, save money, and improve their overall profitability. The results of this thesis provide solid evidence in favor of the technical and financial viability of implementing EONs in contemporary telecommunications networks.

7.2 Future Work

The deployment of several elastic optical network types for Addis Abeba backbone networks, as well as their technical and financial advantages, are the main topics of this research study.

In order to improve benefits like dynamic resource allocation, network virtualization, service orchestration, automation, network intelligence, and interoperability, there are also additional techno-economic study possibilities for integrating Software Defined Networks (SDN) with Elastic Optical Networks.

References

[1] M. Jinno and S. Member, “Elastic Optical Networking : Roles and Benefits in Beyond 100-Gb / s Era,” vol. 8724, no. 26220905, 2016, doi: 10.1109/JLT.2016.2642480.

[2] G. A. Beletsioti, S. Mavridopoulos, and G. A. Tziroglou, “Power-aware Algorithms for Energy-efficient Elastic Optical Backbone and Metro Networks,” no. Icete, pp. 63–70, 2019, doi: 10.5220/0007925000630070.

[3] Y. Yin, L. Liu, R. Proietti, and S. J. B. Yoo, “Software Defined Elastic Optical Networks for Cloud Computing,” pp. 12–18, 2016.

[4] D. Simeonidou, N. Amaya, and G. Zervas, “Infrastructure and Architectures on Demand for Flexible and Elastic Optical Networks,” no. c, pp. 3–5, 2012.

[5] M. Jinno, H. Takara, Y. Sone, K. Yonenaga, and A. Hirano, “Elastic optical path network architecture: Framework for spectrally-efficient and scalable future optical networks,” *IEICE Trans. Commun.*, vol. E95-B, no. 3, pp. 706–713, 2012, doi: 10.1587/transcom.E95.B.706.

[6] K. U. N. Wang, *Migration Towards Next Generation Optical Access and Transport Networks*. 2017.

[7] L. Velasco, O. G. De Dios, V. López, and G. Junyent, “Finding an Objective Cost for Sliceable Flexgrid Transponders,” pp. 2011–2013, 2013.

[8] C. Boworntummarat, “Light-Tree Based Protection Strategies for Multicast Traffic in Transport WDM Mesh Networks with Multi-Fiber Systems,” vol. 00, no. c, pp. 1–3, 2004.

[9] D. Sharma and D. (Col) S. Kumar, “An Overview of Elastic Optical Networks

and its Enabling Technologies," *Int. J. Eng. Technol.*, vol. 9, no. 3, pp. 1643–1649, 2017, doi: 10.21817/ijet/2017/v9i3/170903022.

[10] B. Kozicki, H. Takara, Y. Sone, A. Watanabe, and M. Jinno, "Distance-adaptive spectrum allocation in elastic optical path network (SLICE) with bit per symbol adjustment," *Opt. InfoBase Conf. Pap.*, pp. 6–8, 2010, doi: 10.1364/ofc.2010.omu3.

[11] G. Zhang, M. De Leenheer, A. Morea, and B. Mukherjee, "A survey on OFDM-based elastic core optical networking," *IEEE Commun. Surv. Tutorials*, vol. 15, no. 1, pp. 65–87, 2013, doi: 10.1109/SURV.2012.010912.00123.

[12] T. Miyamura and A. Misawa, "Improving efficiency of network resources in elastic optical transport network by using in-network cache functions," *Opt. Switch. Netw.*, vol. 42, no. May, p. 100629, 2021, doi: 10.1016/j.osn.2021.100629.

[13] C. Bhar, E. Agrell, K. Keykhosravi, M. Karlsson, and P. A. Andrekson, "Channel allocation in elastic optical networks using traveling salesman problem algorithms," *J. Opt. Commun. Netw.*, vol. 11, no. 10, pp. C58–C66, 2019, doi: 10.1364/JOCN.11.000C58.

[14] A. Lord, C. Matrakidis, A. Tomaszewski, A. Lord, and E. Riccardi, "Lessons and conclusions from elastic optical networks," pp. 1–96, 2015.

[15] X. Cao, N. Yoshikane, I. Popescu, T. Tsuritani, and I. Morita, "Software-Defined Optical Networks and Network Abstraction With Functional Service Design [Invited]," vol. 9, no. 4, pp. 65–75, 2017.

[16] Y. Ji, J. Zhang, Y. Xiao, and Z. Liu, "5G flexible optical transport networks with large- capacity , low-latency and high-efficiency," no. 1, pp. 1–14.

[17] J. Liu *et al.*, "EXPERIMENTAL VALIDATION OF IP OVER OPTICAL

TRANSPORT NETWORK BASED ON HIERARCHICAL CONTROLLED SOFTWARE DEFINED NETWORKS ARCHITECTURE," pp. 14–16, 2015.

[18] J. Pedro, J. Santos, P. Monteiro, and J. Pires, "Optimization Framework for Supporting 40 Gb / s and 100 Gb / s Services over Optical Transport Networks," pp. 3–6, 2010.

[19] M. I. Mousa, G. Cansevera, and T. H. Abd, "Design and Implementation DWDM Toward Terabit for Long-Haul Transmission System," *HORA 2020 - 2nd Int. Congr. Human-Computer Interact. Optim. Robot. Appl. Proc.*, no. June, pp. 8–13, 2020, doi: 10.1109/HORA49412.2020.9152885.

[20] B. C. Chatterjee, N. Sarma, P. P. Sahu, and E. Oki, "Limitations of conventional WDM optical networks and elastic optical networks for possible solutions," *Lect. Notes Electr. Eng.*, vol. 410, pp. 101–115, 2017, doi: 10.1007/978-3-319-46203-5_8.

[21] T. Liu, H. Mei, Q. Sun, and H. Zhou, "Application of Neural Network in Fault Location of Optical Transport Network," pp. 1–6, 2019.

[22] J. Comellas and G. Junyent, "Improving Link Spectrum Utilization in Flexgrid Optical Networks," vol. 7, no. 7, pp. 618–627, 2015.

[23] M. Filer *et al.*, "Elastic Optical Networking in the Microsoft Cloud [Invited]," vol. 8, no. 7, pp. 45–54, 2016.

[24] H. Ivanov, E. Leitgeb, M. Sobieraj, and M. Stasiak, "Simulation studies of elastic optical networks based on 3-stage Clos switching fabric," vol. 36, no. January, 2020, doi: 10.1016/j.osn.2020.100555.

[25] Y. Wang, C. Li, Q. Hu, J. Flor, and M. Jalalitabar, "Routing and Spectrum

Allocation in Spectrum-Sliced Elastic Optical Path Networks : A Primal-Dual Framework," pp. 1–13, 2021.

[26] S. Akhtar and A. M. Hafiz, "No Title," pp. 45–48, 2012.

[27] H. Yeh and A. F. Tehrani, "Space-Time Code Orthogonal Frequency Division Multiplexing in Power Line Communications," pp. 0–5, 2017.

[28] C. Yeh, C. Chow, and C. Hsu, "40-Gb / s Time-Division-Multiplexed Passive Optical Networks Using Downstream OOK and Upstream OFDM Modulations," vol. 22, no. 2, pp. 118–120, 2010.

[29] M. Xiang, S. Fu, H. Tang, M. Tang, P. Shum, and D. Liu, "Linewidth-Tolerant Joint Digital Signal Processing for 16QAM Nyquist WDM Superchannel," vol. 27, no. 2, pp. 129–132, 2015.

[30] R. Zhou *et al.*, "Injection Locked Wavelength De-Multiplexer for Optical Comb-Based Nyquist WDM System," vol. 27, no. 24, pp. 2595–2598, 2015.

[31] D. Vcsel, "Time-Frequency Packing applied to Cost-Effective IM / DD Transmission based on," vol. 8724, no. c, 2017, doi: 10.1109/JLT.2017.2743529.

[32] M. Jana, L. Lampe, and J. Mitra, "Design of Time-Frequency Packed WDM Superchannel Transmission Systems," vol. 8724, no. c, pp. 1–13, 2020, doi: 10.1109/JLT.2020.3019257.

[33] M. Jana, L. Lampe, and J. Mitra, "Interference Cancellation for Time-Frequency Packed Super-Nyquist WDM Systems," vol. 1, no. 1, pp. 1–4, 2018, doi: 10.1109/LPT.2018.2877751.

[34] M. Jana, L. Lampe, J. Mitra, W. Jin, and K. Law, "Probabilistic Shaping in Time-Frequency-Packed Terabit Superchannel Transmission," vol. 32, no. 17, pp.

1065–1068, 2020.

[35] M. Jana, “Precoded Time-Frequency-Packed Multicarrier Faster-than-Nyquist Transmission,” *2019 IEEE 20th Int. Work. Signal Process. Adv. Wirel. Commun.*, pp. 1–5, 2019.

[36] G. Meloni, “Field Trial Transmission of Time Frequency Packed DP-QPSK Superchannel with Spectral Efficiency of 6 . 2 bit / s / Hz,” vol. xx, no. xx, pp. 1–8, 2016, doi: 10.1109/JPHOT.2016.2539549.

[37] M. Secondini *et al.*, “Optical Time – Frequency Packing : Principles , Design , Implementation , and Experimental Demonstration,” vol. 33, no. 17, pp. 3558–3570, 2015.

[38] W. M. Jang and S. Sikander, “Cooperative Cognitive Systems with Orthogonal Frequency Division Multiplexing and Frequency Hopping,” vol. 1, pp. 2–4.

[39] G. Meloni *et al.*, “Experimental Comparison of Transmission Performance for Nyquist WDM and Time – Frequency Packing,” vol. 33, no. 24, pp. 5261–5268, 2015.

[40] F. Lezama, G. Castañón, A. M. Sarmiento, and I. B. Martins, “Routing and Spectrum Allocation in Flexgrid Optical Networks Using Differential Evolution Optimization,” pp. 3–6, 2014.

[41] A. Ferreira and M. M. Alves, “YBS Heuristic for Routing and Spectrum Allocation in Flexible Optical Networks,” pp. 6–11.

[42] G. Savva and K. Manousakis, “Eavesdropping-Aware Routing and Spectrum / Code Allocation in OFDM- Based EONs Using Spread Spectrum Techniques,” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 11, no. 7, pp. 409–421, 2019, doi:

10.1364/JOCN.11.000409.

[43] J. Zhang, C. Yu, L. Luo, X. Liu, and J. Shen, “Maximum-Spectrum-Completeness based Routing and Spectrum Assignment Algorithms for Elastic Optical Networks,” no. Wocc, 2019.

[44] H. Chai, S. Yin, H. Liu, B. Guo, X. Li, and S. Huang, “Algorithm Research of Routing and Spectrum Allocation based on OSNR impairment model in Elastic Optical Network,” pp. 16–18, 2017.

[45] X. Chen, J. Li, P. Zhu, R. Tang, Z. Chen, and Y. He, “Fragmentation-Aware Routing and Spectrum Allocation Scheme Based on Distribution of Traffic Bandwidth in Elastic Optical Networks,” vol. 7, no. 11, pp. 1064–1074, 2015.

[46] L. Ruan and Y. Zheng, “Dynamic Survivable Multipath Routing and Spectrum Allocation in OFDM- Based Flexible Optical Networks,” vol. 6, no. 1, 2014.

[47] R. J. Durán *et al.*, “Performance Comparison of Methods to Solve the Routing and Spectrum Allocation Problem,” pp. 3–6, 2012.

[48] T. A. Produced, D. O. E. Advanced, and M. Office, “TËÇHÑØ-ËÇØÑØMÏÇ ÅÑÅLŸSÏS.”

[49] S. Henry, “Overview of Techno-Economic Analysis Process NETL Role with FECM Programs,” 2022.

[50] J. C. F. Ii, “Techno-Economic Analysis (TEA),” 2015.

[51] B. G. Moges, “Techno-Economic Analysis of Cloud RAN Deployment Scenarios : in the Context of Ethio Telecom Techno-Economic Analysis of Cloud RAN Deployment Scenarios : in the Context of Ethio Telecom,” 2022.

[52] “No Title,” 2021.

[53] L. Information and S. B. Berhe, “Addis Ababa Institute of Technology School of Electrical and Computer Engineering Telecommunication Engineering Graduate Program Addis Ababa Institute of Technology School of Electrical and Computer Engineering Telecommunication Engineering Graduate Progr,” no. December, 2021, doi: 10.13140/RG.2.2.25802.11205.

Appendix

Techno-Economic Analysis of Elastic Optical Network Deployment, in case of Ethio Telecom

Biniyam Kiflemariam
School of Electrical and Computer Engineering
Addis Ababa Institute of Technology
Addis Ababa University
Addis Ababa, Ethiopia
biniyam.kiflemariam@gmail.com

Yalemzewd Negash (PhD)
School of Electrical and Computer Engineering
Addis Ababa Institute of Technology
Addis Ababa University
Addis Ababa, Ethiopia
yalemzewdn@yahoo.com

***Abstract*— This thesis offers a thorough techno-economic analysis of elastic optical networks' (EONs) implementation. In order to make efficient bandwidth utilization, to fulfil the rising need for high-capacity, flexible communication networks, and to reduce operational costs, EONs have emerged as a possible alternative. This study intends to examine the technical and financial elements of EON deployment, assessing its viability, affordability, and possible advantages.**

To create a complete techno-economic model, a number of input factors are taken into account, including traffic demand, network architecture, transmission methods, spectrum allocation, equipment costs, operating expenses, revenue models, discount rate, and economic indicators. The techno-economic study examines the effects of many parameters on the effectiveness and financial sustainability of EON deployment using the proposed model. The paper also discusses the difficulties and constraints of EON implementation, including system adaptability, upgradeability, and compatibility with changing network requirements. The research's findings help decision-makers make well-informed decisions about network infrastructure expenditures by advancing our knowledge of the techno-economic elements of EON deployment. In order to satisfy the rising demand for high-capacity communication networks, network operators, service providers, and regulators should follow the study's findings in determining if EON deployment is feasible, allocating resources most efficiently, and maximizing economic advantages.

***Keywords*— Elastic optical networks, Techno-economic analysis, Deployment feasibility, Cost optimization, Revenue generation, Capital expenditure, Operational expenditure, Return on investment.**

I. INTRODUCTION

A possible approach to meet the rising demand for bandwidth in contemporary communication networks is elastic optical networks (EONs). These networks make efficient use of the available resources thanks to the flexible and dynamic distribution of optical spectrum. EONs may greatly increase bandwidth usage by tailoring the transmission capacity to each connection's unique needs, which improves user experience and network performance. The efficient and capacity of data transmission are directly impacted by the bandwidth usage of modern communication networks. EONs provide a flexible method for allocating bandwidth, enabling the effective use of resources. EONs can maximize the use of the optical spectrum by dynamically modifying the spectrum distribution based on traffic needs.

Recent research have suggested sophisticated algorithms and methods to improve EON bandwidth consumption. For example, the application of machine learning algorithms for resource allocation and traffic prediction has demonstrated promising outcomes in increasing bandwidth utilization [1]. Additionally, dynamic and effective bandwidth provisioning is made possible by EONs' use of software-defined networking (SDN) concepts [2]. These improvements in bandwidth consumption help to improve EONs' overall performance. Utilizing energy is another essential component of contemporary communication networks, since rising energy Consumption creates serious problems for sustainability and operating expenses.

EONs have an advantage over conventional networks in terms of potential energy savings. The development of EON energy-efficient techniques has been the subject of recent study. For instance, the introduction of energy-aware routing algorithms takes into account both network element energy usage and traffic needs, resulting in optimal energy use [3]. A further factor in lowering energy usage in EONs is the adoption of energy-efficient components such low-power transceivers and amplifiers [4]. These improvements in energy efficiency help communication networks remain sustainable in the long run by lowering operational expenses as well. Network operators and service providers are very concerned about the expense of updating network infrastructures. EONs take use of the adaptability and scalability of optical spectrum allocation to offer a cost-effective solution. In order to meet the rising bandwidth needs, recent research have offered cost-effective ways for improving network infrastructures. A good example is the effective use of the current fiber infrastructure made possible by the deployment of flexible grid technology [5], which eliminates the need for expensive infrastructure expansions. Furthermore, by utilizing reconfigurable optical add-drop multiplexers (ROADMs), it is possible to dynamically provide network resources, avoiding the need for manual intervention and lowering operational expenses [6]. EONs are a desirable option for network operators because to developments in low-cost network infrastructure improvements.

The urgent need to reduce carbon dioxide (CO2) emissions is reflected in the fact that communication networks are responsible for a sizeable amount of these emissions.

EONs have potential advantages over conventional networks in terms of lowering CO2 emissions. Creating green business strategies for EONs has been the subject of recent study. For instance, the use of energy-efficient parts and technologies, such as low-power transceivers and improved modulation formats, lowers the amount of energy used by EONs and, as a result, lowers their CO2 emissions [7]. Further reducing the carbon footprint of EONs is possible through the network infrastructure's incorporation of renewable energy sources like solar and wind [8].

The overall sustainability of communication networks is improved by these developments in CO2 emission reduction.

II. RELEVANT WORK

The inability of current optical communication networks, in particular Dense Wavelength Division Multiplexing (DWDM), to effectively handle diverse and fluctuating traffic needs is discussed in [7].

EONs provide an adaptable and flexible infrastructure to manage the rapidly growing data traffic more effectively and economically.

The elastic optical network (EON), which is intended to meet the rising need for line rates over 100 Gb/s in metro/core optical networks, is the main topic of[8]. The EON provides several advantages, including increased spectrum efficiency thanks to rate-adaptive super channels and distance-adaptive modulation. Additionally, it permits cost- and energy-effective traffic grooming in the optical domain [9].

According to [1] a promising approach that offers higher effectiveness, adaptability, and scalability is elastic optical networks. In comparison to DWDM-based networks, elastic optical networks considerably increase network usage efficiency by using narrow slots and spectrum allocation depending on client bandwidth requirements. These networks are a possible substitute for WDM-based networks to meet future needs for high-speed optical connections since they also allow for the adjustment of transmission characteristics including optical data rate, modulation format, and wavelength spacing.

The information-centric elastic optical transport network (i-CEON), a unique network design that intends to improve content delivery effectiveness, is introduced in the study of [10]. Establishing optical transport network topologies appropriate for content delivery becomes essential as video traffic grows in volume. The authors expand the idea of information-centric networking to include elastic optical networks in order to solve this.

The paper [11] offers a thorough analysis of elastic optical network technologies based on OFDM. Broadband wireless and wireline communication systems frequently use the modulation technique known as orthogonal frequency-division multiplexing (OFDM). High spectrum efficiency, robustness against interference, and flexibility to changing channel circumstances are benefits of using multiple spectral-overlapped subcarriers, which also enable high-speed data transfer. A possible method for extremely high-speed optical communication is optical OFDM (O-OFDM). A flexible and elastic optical network architecture that can handle a range of services and keep up with the quick increase in internet traffic may be built by utilizing O-OFDM [11].

According to [12] EONs enable operators to effectively address the various demands of their clients by providing flexibility and flexible data rates. Although Wavelength Switched Optical Networks (WSONs) currently have a reliable control plane, EONs need further development before they can use conventional WSON control plane solutions. Because of this, current research has concentrated on creating control plane designs expressly for EONs, frequently suggesting enhancements to current systems.

EONs boost spectrum utilization by balancing data rates with available bandwidth and enhancing spectral efficiency with multi-carrier and high-order modulation techniques, according to the paper [13]. The architecture and important technologies for the physical layers of EONs are the main topics of the essay. It specifically suggests using bandwidth-variable optical transponders based on optical combs and optical switching nodes that permit software specification. Experimental demonstrations are made of a number of crucial technologies for the physical layer of elastic optical networks, such as bandwidth-variable add/drop, sub band switching, spectrum conversion, defragmentation, and multicasting for optical super-channels[14].

III. METHODOLOGY

- Literature Review:

Literature, including books, journals, online sources, and other references, will be used.

- Data Collection:

Data of Optical Channels Configuration and each service type data has been gathered.

- Model Development:

By using the TERA model, the cost modelling has been done for the two architectures (i.e. fixed grid DWDM and EON).

- Model Evaluation:

By using economic indicators (i.e., NPV, IRR, PBP), comparison has be done.

- Finally, the better technical architecture/technology has been recommended.

IV. MODELING

a) Cost Modeling

One of the key criteria for determining the viability of an elastic optical network deployment is the component cost. Capital expenditures (CAPEX) and operational expenditures (OPEX) are the two categories into which the costs of constructing and running an optical transport network may be divided. The cost calculations are done using data on the needed service configuration for each year as well as component pricing information. Calculations for CAPEX and OPEX represent the expenses related to installing and running the new system, respectively.

- Capital Expenditure (CAPEX)

The ROADM, Multiplexer (OMU), Demultiplexer (ODU), Line, and Client Boards, as well as Licensed System Software, are investments in hardware and software that make up the CAPEX in this study. The required quantity of hardware and software licenses are acquired for each deployment option based on the component dimensioning results, and the investment costs are then determined.

CAPEX can be analytically described in accordance with the following equation (Eq. 1).

$$CAPEX = C_{SW} + \sum_{S=1}^{10} (C_{ROADM} + C_{MUX} + C_{DEMUX} + C_{LB} + C_{CB})_s \ldots (1)$$

Where:

$\boldsymbol{C_{SW}}$, $\boldsymbol{C_{ROADM}}$, $\boldsymbol{C_{MUX}}$, $\boldsymbol{C_{DEMUX}}$, $\boldsymbol{C_{LB}}$, $\boldsymbol{C_{CB}}$ is cost of software, ROADM, Multiplexer (OMU), Demultiplexer (ODU), Line Board and Client Boards respectively and S stands for Station numbers starts from 1 to 10.

- Operational Expenditure (OPEX)

Operational expenditures (OPEX) are the continuing costs a business must pay to maintain its functional capabilities and sustain its regular operations.

In this study the operational expenditure consist of cost of upgrading, energy and board maintenance.

Their value can be calculated by the following equations:

d. Cost of upgrading

$$C_{UP} = \sum_{i}^{T} N_j^i * C_j^i \ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots.\ldots\ldots..(2)$$

Where:

C_{UP} is total cost of upgrading

N_j^i is number of required components type j in period i.

C_j^i is cost of component type j in period i.

e. Energy Expenses:

$$P_T = \sum_{i}^{T} (N_{NE} * P_{NE(kwh)}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where:

P_T is total power consumption,

N_{NE} is number of network elements

$P_{NE(kwh)}$ is power consumption value of each network element in kilo watt hour.

T is stands to represent time value of the study period.

$$C_E = P_T * C_{kwh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where:

C_E is total cost of energy

P_T is total power consumption

C_{kwh} is cost of power per kilo watt hour.

f. Board Maintenance Costs:

$$C_M = \sum_{i}^{T} (N_{BOARDS} * C_{M_{BOARD}}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5)$$

Where:
C_M is total cost of maintenance
N_{BOARDS} is total number of faulty boards.
$C_{M_{BOARD}}$ is cost of maintenance per each board.

$$\therefore OPEX = C_{UP} + C_E + C_M \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Where:
$OPEX$ is operational expenditures
C_{UP} is total cost of upgrading
C_E is total cost of energy
C_M is total cost of maintenance

- Total Cost of Ownership (TCO).

The formula for determining total cost of ownership (TCO), which is the sum of operational and capital expenses (CapEx and OpEx), is given in equation 7.

$$TCO = CAPEX + OPEX \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$

b) Revenue Modeling

When determining the yearly revenue value, several variables are taken into account, including the demand for various data rates (1G, 10G, 40G, and 100G) services, the distance in kilometers, and the duration in months. These elements have a role in deciding the revenue made over the course of a year.

The amount of annual revenue can be calculated by the following formula, equation 8:

$$\boldsymbol{AR = 12 \sum_{S_T} (C_S * D_S)_{S_T}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (8).$$

Where:

$\boldsymbol{AR}$ = Annual Revenue

$\boldsymbol{S_T}$ = Service types i.e., 1G, 10G, 40G, & 100G

$\boldsymbol{C_S}$ = Cost of each service type per kilometer per month

And is equal to $\boldsymbol{C_S = \frac{S_T}{Km} / Month}$

$\boldsymbol{D_S}$ = total distance value of each services

c) Implemented TEA Model

The original TERA (techno-economic analysis) model has been modified for this study to take into account the particular evaluation criteria emphasizing both technical and economic benefits. It enables a thorough evaluation of the techno-economic viability of the proposed elastic optical network deployment by customizing the model to the study's requirements. Key elements including performance measures, cost analyses, revenue estimates, and financial indicators are incorporated into the redesigned model. These improvements make the updated TERA model an effective tool for assessing the feasibility and potential benefits of setting up an elastic optical network.

For this thesis, a modified TEA model (Figure 3) has been constructed based on input/output parameters from the TERA and a modified model.

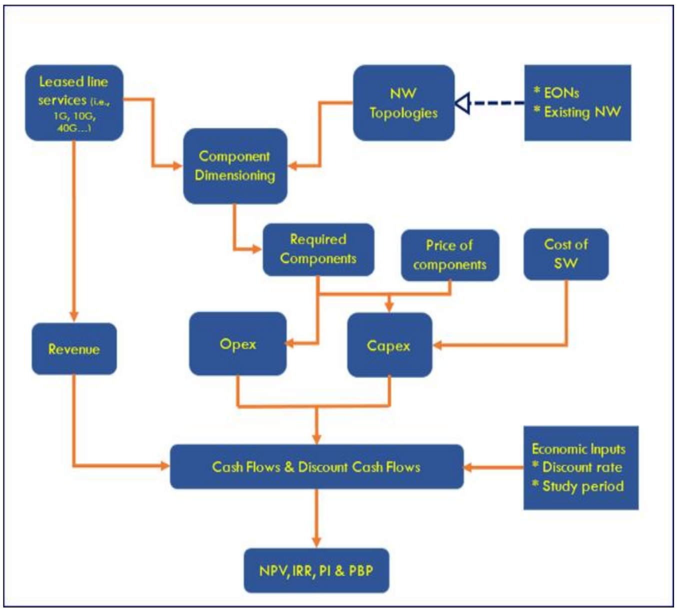


Figure 1: Implemented Techno Economical Analysis

V. RESULT AND ANALYSIS

- Technical Analysis

Required Components per NW Types

By considering future service demand and the past five years trend analysis, to give complete service and achieve expected revenue values the required components amount per each deployment option have been listed out in figure 2.

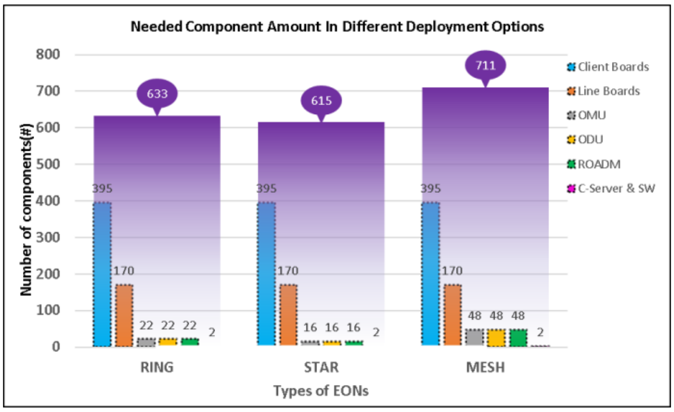


Figure 2: Required component type & amount in d/t NWs

- Economic Analysis

Capital Expenditure (CapEx)

Based on the deployment scenarios, the required components amount and the overall capital expenditure (CapEx) values are different.
So that the CapEx values of all the three deployment scenarios have been depicted in figure 3. As you have seen from the figure 1 the meshed based elastic optical network the highest capex value where us star based elastic optical network requires the lowest capex value of the system.

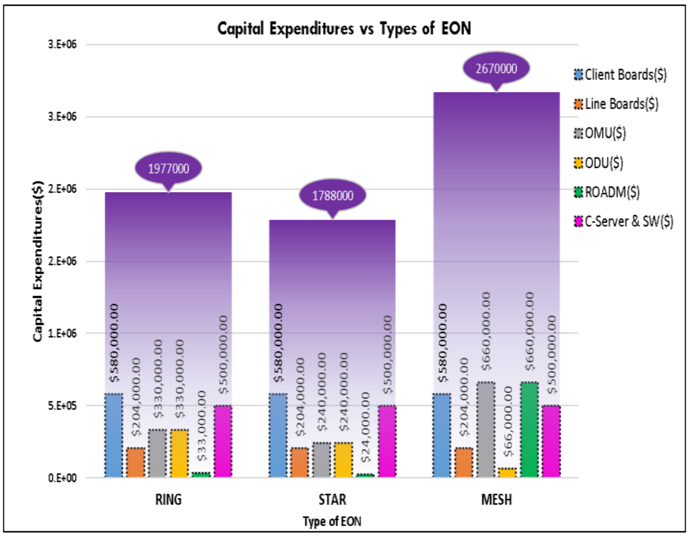


Figure 3: Capex values of d/t EONs

- Techno-Economic Analysis

a) Cash flow (CF) of Mesh-EON

By considering values of capital and operational expenditures, revenues, discount rate and study period, the value of cash flows of Mesh type EON has been shown by the following figure (i.e., figure 4).

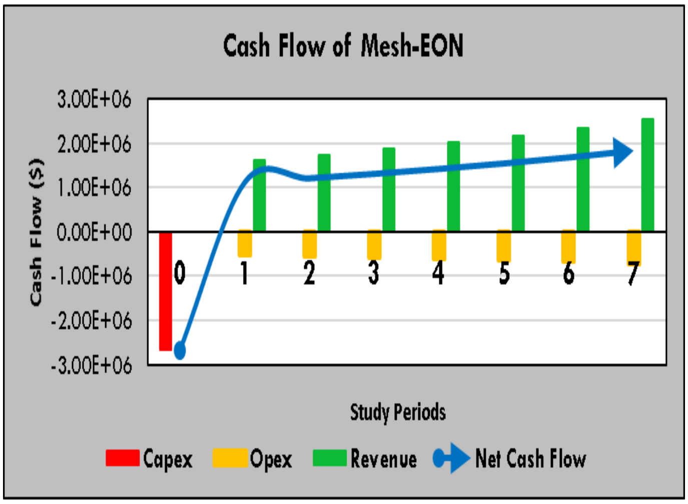
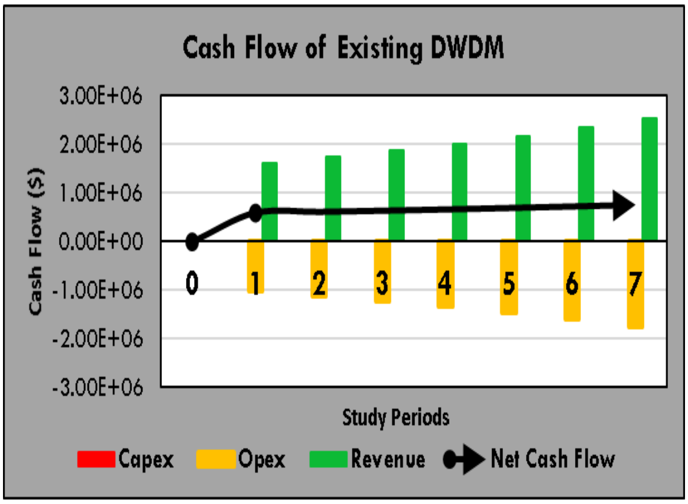


Figure 4: Cash Flow value of Meshed based EON

b) Cash flow (CF) values of existing system

Here also the cash flow value of the existing is depicted by figure 5.



*

Figure 5: Cash Flow value of Existing DWDM NW

c) Net Present Values of d/t EONs

In the case of the techno-economic analysis of Elastic Optical Network (EON) deployments in star, ring, and mesh topologies, assuming different cost of capital rates (10%, 12%, 14%, and 16%) the calculated NPV values are have been described by the figure 6.

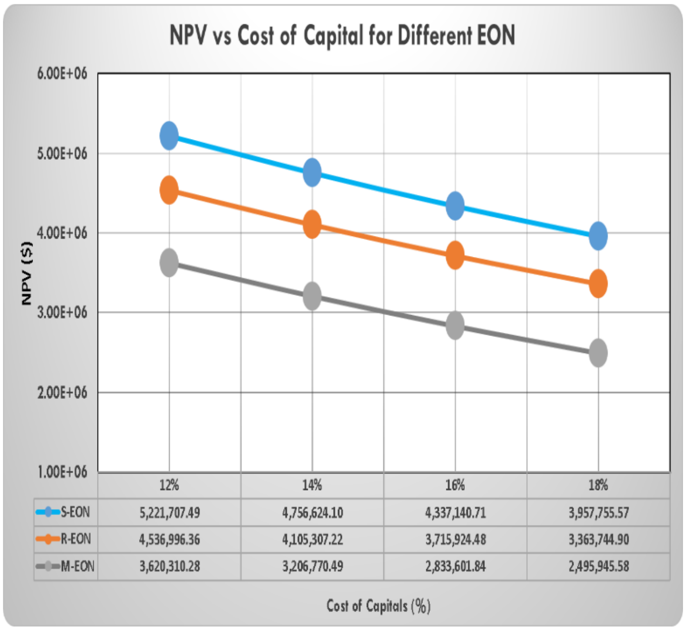


Figure 6: Net Present Value of d/t EONs

d) Internal Rate of Return (IRR)

The projected IRR values for the EON installations in star, ring, and mesh topologies change depending on the estimated cost of capital rates. The IRR values for all three topologies have been depicted in figure 7.

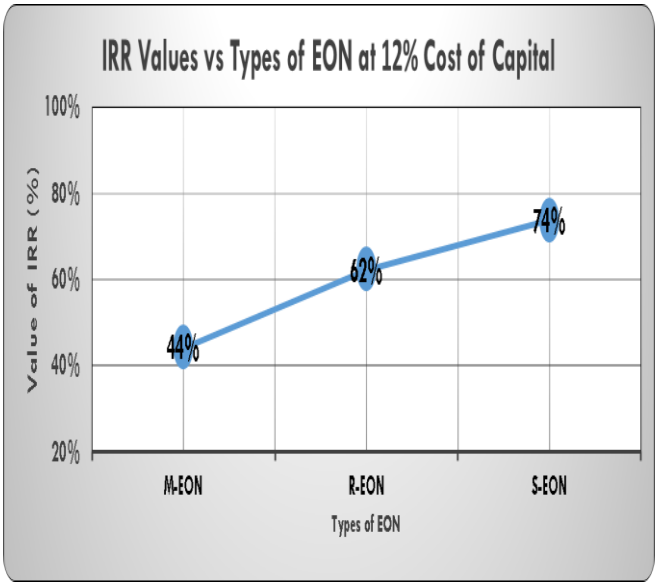


Figure 7: Internal Rate of Return of d/t EON

e) Pay Back Period (PBP) values

All possibilities have a payback period of between 15.8 and 23.9 months. The return on investment for each scenario is less than it was throughout the research period.

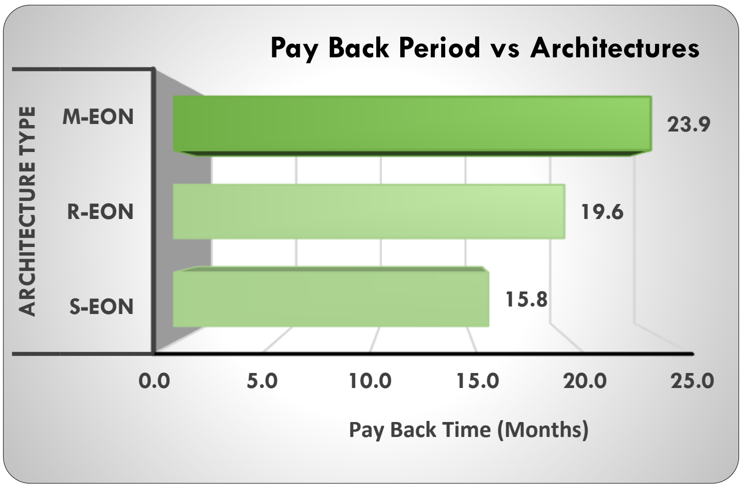


Figure 8: Pay Back Period values of d/t EONs

VI. CONCLUSIONS

In conclusion, a thorough techno-economic study of the implementation of elastic optical networks (EONs) has been done in this thesis. According to the conclusions reached after thorough investigation and assessment, the use of EON technology is very lucrative economically. According to the report, EONs have a lot to offer in terms of better spectrum usage, flexibility in meeting changing bandwidth requirements, and effective resource distribution. These elements help network operators generate more income, save money, and improve their overall profitability. The results of this thesis provide solid evidence in favor of the technical and financial viability of implementing EONs in contemporary telecommunications networks.

VII. FUTURE WORK

The deployment of several elastic optical network types for Addis Abeba backbone networks, as well as their technical and financial advantages, are the main topics of this research study.

In order to improve benefits like dynamic resource allocation, network virtualization, service orchestration, automation, network intelligence, and interoperability, there are also additional techno-economic study possibilities for integrating Software Defined Networks (SDN) with Elastic Optical Networks.

REFERENCES

[1] M. Jinno and S. Member, “Elastic Optical Networking : Roles and Benefits in Beyond 100-Gb / s Era,” vol. 8724, no. 26220905, 2016, doi: 10.1109/JLT.2016.2642480.

[2] G. A. Beletsioti, S. Mavridopoulos, and G. A. Tziroglou, “Power-aware Algorithms for Energy-efficient Elastic Optical Backbone and Metro Networks,” no. Icete, pp. 63–70, 2019, doi: 10.5220/0007925000630070.

[3] Y. Yin, L. Liu, R. Proietti, and S. J. B. Yoo, “Software Defined Elastic Optical Networks for Cloud Computing,” pp. 12–18, 2016.

[4] D. Simeonidou, N. Amaya, and G. Zervas, “Infrastructure and Architectures on Demand for Flexible and Elastic Optical Networks,” no. c, pp. 3–5, 2012.

[5] M. Jinno, H. Takara, Y. Sone, K. Yonenaga, and A. Hirano, “Elastic optical path network architecture: Framework for spectrally-efficient and scalable future optical networks,” IEICE Trans. Commun., vol. E95-B, no. 3, pp. 706–713, 2012, doi: 10.1587/transcom.E95.B.706.

[6] K. U. N. Wang, Migration Towards Next Generation Optical Access and Transport Networks. 2017.

[7] L. Velasco, O. G. De Dios, V. López, and G. Junyent, “Finding an Objective Cost for Sliceable Flexgrid Transponders,” pp. 2011–2013, 2013.

[8] C. Boworntummarat, “Light-Tree Based Protection Strategies for Multicast Traffic in Transport WDM Mesh Networks with Multi-Fiber Systems,” vol. 00, no. c, pp. 1–3, 2004.

[9] D. Sharma and D. (Col) S. Kumar, “An Overview of Elastic Optical Networks and its Enabling Technologies,” Int. J. Eng. Technol., vol. 9, no. 3, pp. 1643–1649, 2017, doi: 10.21817/ijet/2017/v9i3/170903022.

[10] B. Kozicki, H. Takara, Y. Sone, A. Watanabe, and M. Jinno, “Distance-adaptive spectrum allocation in elastic optical path network (SLICE) with bit per symbol adjustment,” Opt. InfoBase Conf. Pap., pp. 6–8, 2010, doi: 10.1364/ofc.2010.omu3.

[11] G. Zhang, M. De Leenheer, A. Morea, and B. Mukherjee, “A survey on OFDM-based elastic core optical networking,” IEEE Commun. Surv. Tutorials, vol. 15, no. 1, pp. 65–87, 2013, doi: 10.1109/SURV.2012.010912.00123.

[12] T. Miyamura and A. Misawa, “Improving efficiency of network resources in elastic optical transport network by using in-network cache functions,” Opt. Switch. Netw., vol. 42, no. May, p. 100629, 2021, doi: 10.1016/j.osn.2021.100629.

[13] C. Bhar, E. Agrell, K. Keykhosravi, M. Karlsson, and P. A. Andrekson, “Channel allocation in elastic optical networks using traveling salesman problem algorithms,” J. Opt. Commun. Netw., vol. 11, no. 10, pp. C58–C66, 2019, doi: 10.1364/JOCN.11.000C58.

[14] A. Lord, C. Matrakidis, A. Tomaszewski, A. Lord, and E. Riccardi, “Lessons and conclusions from elastic optical networks,” pp. 1–96, 2015.