Addis Ababa University
College of Technology and Built Environment
School of Electrical and Computer Engineering
Telecommunication Network Engineering Graduate Program

Optimizing Energy Consumption in WDM Optical Networks through a Combined Sleep Mode and Traffic Grooming Approach: A Case Study in Ethio Telecom Optical Backbone Network

by:

Danayit Girma

Advisor:
Dr. Yalemzewd Negash

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master's Science in Telecommunication Network Engineering

June, 2025
Addis Ababa, Ethiopia

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Approval by Board of Examiners	Signature	Date
Advisor's Name:		
Dr. Yalemzewd Negash	____________	____________
Examiners' Name:		
Dr.-Ing. Dereje Hailemariam	____________	____________
Dr. Tsegamlak Terefe	____________	____________

Declaration

I declare that this thesis is entirely my own work and does not include any content from other educational institutions without proper acknowledgment. To the best of my knowledge, it does not contain previously published material by another person without recognition.

Name of the Student	Signature	Date
Danayit Girma	____________	____________

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

Name of the Advisor	Signature	Date
Dr. Yalemzewd Negash	____________	____________

Addis Ababa, Ethiopia

ABSTRACT

In recent years, the advancement of technologies and the increase in traffic demand have led to rise in necessity of deploying capable and power intensive telecom networks. To support this demand, optical backbone networks have been deployed with high resource provisions. The aggressively increasing traffic demand and the need for the networks to handle it, have posed a significant challenge for telecommunication sector. This research focuses on optimizing energy utilization in optical transport network through combined traffic grooming and sleep mode approach.

This case study is on Ethio Telecom's optical transport network. Traffic grooming is responsible in aggregating sub rate traffic into higher traffic line so that it will let the line idle to be in sleep mode. This combined approach is formed through mathematical model that account for latency and blocking probability resulted from the implementation the combined method. The multi-objective optimization problem is developed expressing the conflicting nature of power with latency and blocking probability through weights.

The model results in optimization in energy utilization and other optical resources, such as line cards, wavelength, and etc. The combined framework achieves an average energy reduction of 50 % across network nodes compared to the baseline configuration. The energy savings at the nodal level vary and are analyzed under different weightings of power, latency, and blocking probability. The savings are translated in monetary terms by quantifying the reductions in energy bills and idle-card for future scalability. The proposed method achieved optimization in energy utilization while maintaining QoS.

Key Words: Traffic Grooming, Sleep Mode, Optimization, Energy, Resources

Acknowledgments

First and foremost, I want to express my gratitude to God for the strength and encouragement He offered me throughout the challenges of completing this dissertation. I am deeply grateful for His endless love, mercy, and grace.

I gratefully acknowledge Dr. Yalemzewd for being a supportive advisor throughout this research. His guidance, support, and invaluable insights were instrumental in shaping the outcome of this study.

I wish to express my sincere gratitude to my evaluators Dr.-Ing Dereje H. Woldegebreal, Dr.Tsegamlak Terefe and Dr.Bethelhem Seifu for their continuous support and guidance throughout this journey. Their constructive feedback, encouragement, and valuable insights have greatly contributed to the development and completion of this research.

I would also like to extend my heartfelt thanks to the employees of Ethio Telecom for their cooperation and support in providing essential information. Their willingness to share their expertise played a significant role in the success of this project.

In addition, I am thankful to the School of Electrical and Computer Engineering for providing me with the opportunity to conduct this research.

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List of Abbreviations

ATM	Asynchronous Transfer Mode
BW	Bandwidth
CAPEX	Capital Expenditure
CWDM	course wavelength division multiplexing
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
ETB	Ethipian Birr
ETC	Ethio Telecom
FEC	Forward Error Correction
GA	Genetic Algorithm
GMP	Generic Mapping Procedure
GMPLS	Generalized Multi-Protocol Label Switching
HD	High Definition
ICT	Information and Communication Technology
ILP	Integer Linear Programming
IP	Internet Protocol
ISP	Internet Service Provider
MCF	Minimum Cost Flow
MILP	Mixed Integer Linear Programming
MLR	Mixed Line Rate
MOOP	Multi Objective Optimization Problem
MPLS	Multiprotocol Label Switching
NSGA	Non-dominated Sorting Genetic Algorithm
NSGA	Non-dominated Sorting Genetic Algorithm
OCh	Optical Channel
OPEX	Operating Expenditure
O-E-O	Optical–Electrical–Optical
ODU	Optical Channel Data Unit
OLA	Optical Line Amplifier
OLA	Optical Line Amplifier
OMS	Optical Multiplex Section
OPU	Optical Channel Payload Unit
OTM	Optical Transport Module
OTN	Optical Transport Network

OTU	Optical transport Unit
OSPF-TE	Open Shortest Path First – Traffic Engineering
OTS	Optical Transmission Section
OXC	Optical Cross Connect
PATE-a	Power Aware Traffic Engineering with attenuation
QoS	Quality of Service
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RSVP-TE	Resource Reservation Protocol – Traffic Engineering
SDH	Synchronous Digital Hierarchy
SDN	Software-Defined Networking
SARIMA	Seasonal Auto-Regressive Integrated Moving Average
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing
TM	Traffic Matrix
WCSS	Within-Cluster Sum of Squares
WCSS	Within Cluster Sum of Squares
WDM	Wavelength Division Multiplexing

Chapter 1: **Introduction**

1.1 Motivation

Information and Communication Technology (ICT) devices and services have taken a central part in our lives and have fundamentally transformed the way we work, communicate, travel, and play in the last few decades [1]. Moreover, quick and global development of network technologies such as the Internet of things, 5G, or cloud computing causes instant growth of endpoint devices. To overcome the possible capacity crunch problem in the internet, network operators build and incessantly improve backbone networks utilizing various optical technologies. However, constantly growing network traffic presents new challenges to the network operators by resulting significant energy consumption to facilitate the data transmission. Meanwhile, to improve the performance of optical Wavelength Division Multiplexing (WDM) networks, various techniques have been used [2].

But still Experiencing a surge in traffic, which is expected to affect the internet in the near future, will reflect on the energy needs of telecom networks, possibly posing a serious environmental problem, and unacceptably raising the energy bill for network operators. Therefore, reducing energy consumption is becoming the most important challenge for the future advancements in telecom [3].

WDM optical networks are crucial for global telecommunications but often waste resources due to over provisioning, redundant links and poor resource utilization methods. Legacy network designs usually keep transponders, amplifiers, and routers running all the time, regardless of traffic levels. Additionally, inefficient traffic grooming where low-rate traffic streams are sent separately across wavelengths results in underused bandwidth, limiting the network's ability to grow as demand increases. Traffic Grooming is resource conservation method which aggregate subrate traffics into high traffic line to let the unused link idel. On the other side, sleep mode is used to power down those unused resources so that better energy utilization is acheived.

While traffic grooming methods and sleep mode strategies have been studied separately, their combined use has not been explored enough. Using sleep modes alone degrades service quality during busy traffic times, and managing power without proper traffic grooming does not solve energy waste [4]. This gap is important for telecom providers who need to balance cost and Quality of Service (Qos) as demand grows to accommodate advance technologies.

This research addresses these challenges by proposing a combined method that merges traffic grooming with sleep mode. By optimizing how energy-efficient hardware is controlled and how wavelength is allocated, the framework aims to achieve the following:

- Better use of resources by grouping traffic streams into full wavelengths,
- Energy savings by turning off idle components when not needed
- Maintenance of Qos through flexible resource allocation based on current traffic.

The findings from this study will help develop energy-aware optical networks, giving carriers a cost-effective way to meet growing demand without significantly increasing infrastructure or energy costs.

1.2 Statement of Problem

Optical WDM backbone networks experience considerable energy and resource consumption beyond what is required. This is mainly due to the following reasons.

- WDM boosts internet backbone capacity by transmitting multiple light signals simultaneously, but this high capacity requires substantial processing power in network devices, leading to high energy consumption.
- Redundant active devices in WDM networks while ensuring uptime, waste resources, and energy. Idle devices constantly consume power without contributing to actual network traffic.
- Over provisioning bandwidth offers a safety net for unpredictable traffic spikes and potential errors, but comes at the cost of wasted resources and high energy consumption. It's a trade-off between smooth operation and efficiency.

Saving resources in networks often comes at the cost of slower speeds and reduced responsiveness. This inherent trade-off creates a challenge where prioritizing resource conservation can potentially limit network capabilities. Research articles suggested that minimizing the number of active devices in the network is not feasible since it needs an overall change in the entire network architecture. It is also impossible to shutdown or avoid all redundant links that are installed. Therefore, operational methods are expected to do better in dynamically allocating and managing resources. In this research, we will try to combine the two methods together to conserve resource, especially energy, while maintaining the existing performance.

1.3 Objectives

1.3.1 General Objective

The general objective of this thesis is to optimize the utilization of energy in WDM optical transport networks using the combined sleep mode and traffic grooming approach.

1.3.2 Specific Objectives

- Investigation about the energy consumption and conservation methods in the optical backbone network.
- Understanding the power consumption models of optical network devices.
- Assessing the architecture of the Ethio-telecom's optical backbone network.
- Understanding the traffic pattern of the Ethio Telecom network.
- Evaluating resource consumption, mainly the energy consumption of the Ethio-telecom backbone network.
- Proposing a combined method of traffic grooming and sleep mode.
- Evaluating the effectivity of traffic grooming and sleep mode on Ethio-telecom's network efficiency.

1.4 Literature Reviews

In this section, reviews of the literature on research papers related to energy conservation are presented. Some of the papers are about traffic grooming, and the other about the implementation of sleep mode.

1.4.1 Sleep Mode Operation for Energy Consumption Minimization in Optical Networks: A Case Study of Ethio Telecom Backbone Optical Transport Network

The motivation of this research [5] was the reality that current optical networks prioritize reliability and maximum traffic capacity, neglecting energy efficiency. And this leads to unused, power-intensive devices even when traffic demand is low. To address this, the author proposed a "sleep mode" approach called Power Aware Traffic Engineering with attenuation (PATE-A). The researcher uses an Integer Linear Programming (ILP) model to account for physical impairments such as signal loss alongside normal traffic and link constraints. Inputs such as the network topologies, traffic patterns, and Open Shortest Path First–Traffic Engineering (OSPF-TE) or Resource Reservation Protocol – Traffic Engineering messages feed into PATE-a, which is solved by the open-source GLPK optimizer. The optimized model is then tested in the TOTEM simulator within a Generalized Multi-Protocol Label Switching (GMPLS) control plane, comparing traditional Minimum Cost Flow (MCF) routing (which ignores energy) against the new energy-aware heuristic. Results showed the PATE-a model reduces power consumption by 30 % while keeping link loads acceptable, demonstrating that energy-aware routing can significantly reduce waste in optical networks. The complexity of the model, which pose implementation challenge in the scalability of networks can be state as limitation.

1.4.2 Energy-Aware Routing and Grooming for IP Transport over WDM Mixed Line Rate Networks

This research [6] focused on reducing energy consumption in Portugal's 12-node optical backbone network by using energy-aware routing and traffic grooming. Motivated by the rapid growth of traffic and energy usage, the study compared two types of networks: IP over WDM (IPoWDM) and IP over OTN over WDM (IPoOTNoWDM). Both network architectures are studied with and without traffic grooming. Using a Mixed-Integer Linear Programming Model (MILP) and IBM CPLEX software, the researchers optimized traffic flow by grouping low-speed traffic into high-speed channels. This allowed some devices to be shut down. Two routing strategies were tested; one for minimizing energy only and the other one is balancing energy with shorter path lengths. The results showed that IPoWDM with energy-aware routing achieved the highest energy savings around 29%. However, the study did not confirm if devices were actually switched off and did not account for factors like Qos, cost, and reliability, which were recommended for future research.

1.4.3 Traffic Grooming of Scheduled Demands for Minimizing Energy Consumption

The motivation of this paper [7] is the need to reduce the increase in energy consumption in optical WDM networks driven by the high traffic demands associated with advanced technologies. It addresses the problem of energy-efficient resource allocation for scheduled and periodic traffic demands, where demands repeat predictably over time. The objective is to minimize total network power consumption and cost of the transceiver through optimized routing and scheduling. The methodology combines comprehensive ILP formulations for both fixed and sliding window models with a novel Genetic Algorithm (GA). This efficiently searches for optimal solutions by jointly determining routing, demand start times, and resource sharing. Experimental results show that GA achieves energy savings of over 40% in small networks and remains computationally feasible for larger networks. Whereas, ILP solutions fail to converge, with execution times ranging from a few seconds to several minutes as network size increases. For example, in a six-node network with 21 traffic demands, the GA reduces energy consumption by approximately 15–40% compared to traditional routing. The limitations of the approach include the increased computational complexity as the network size increases and the limitation in highly dynamic traffic scenarios.

1.4.4 Power consumption modeling in optical multilayer networks

The paper [8] is motivated by the need to improve the understanding and management of power consumption in optical multilayer networks. The drive was environmental sustainability, economic savings, and the increasing deployment of large-scale ICT infrastructure. The core problem it addresses is the lack of standardized, accurate, and accessible power consumption data for various network components. This in turn hinders comprehensive energy efficiency assessments and design optimization. To address this, the authors set objectives to compile and update reliable reference power values for equipment such as IP/MPLS routers, optical transponders, amplifiers, and other key components. It is develop to develop a simplified yet accurate analytical power consumption model that can estimate total network power usage. Their methodology includes processing publicly available product data, designing an analytical model based on average hop count, traffic demands, and network topology. Then validating it through case studies involving different network scenarios, including optical bypass strategies. The paper discusses both proportional power models, which assume power scales linearly with load, and mentions ON/OFF models, which consider equipment being fully powered or off depending on utilization. The results demonstrate that the analytical model can approximate the results of detailed simulation with over 90 % accuracy and reveal that employing optical bypass can potentially halve the power consumption compared to traditional approaches. Limitation of the study involve the use of average power values that may not reflect all real world constraints. Despite the limitation, the work provides a valuable foundation for energy-efficient design and policy considerations in optical network planning.

1.5 Methodology

To achieve the stated objectives, this thesis employs the following methodology.

- Review of research papers on resource consumption and conservation methods in optical networks.
- Data collection on Ethio Telecom network architecture, devices, traffic flow, and power consumption. Data collection is done using the service provider's network management system.
- Formulating the statement of the problem.
- Processing of the collected data to feed the model to be developed.
- Modeling a multi-objective optimization model that encompasses power, latency, and blocking probability.
- Solving the multi-objective problem using libraries of python.
- Quantitative results are presented using tables and graphs, while qualitative findings are conveyed through conclusions.

1.6 Scope and Limitation

This section presents the scope of the study and the specific aspects and boundaries that this research will cover. In addition, it outlines the limitations of the research.

1.6.1 Scope of the Study

This research focuses on the optical transport network of Ethio-telecom, which is of the largest service providers in Ethiopia. This research tried to formulate a mathematical model for networks that incorporates technology in general. But the data about network architecture, devices, traffic and power are collected and specific to Ethio-telecom. The network considered in this research is the backbone transport network, which does not include the IP network.

1.6.2 Limitations

The limitations of this research are listed below.

- The research relies on traffic data collected for 30 days, and no further predictions have been made.
- The research is done on the optical transport network of Ethio-Telecom which exclude the IP network.
- Fixed grooming sites are utilized; consequently, scalability and dynamicity of traffic grooming are limited.

1.7 Contribution

This thesis presents a synergetic method that uses traffic grooming and sleep mode together to save energy in WDM optical networks. The research formed a mathematical model showing the effect of power consumption, delay, and blocking probability on each other. From this model, the research build an optimization problem that lets the service provider choose to focus more on saving energy, reducing delay, or lowering blocking probability by changing the configuration of weights assigned to each. To test the method power consumption of active devices with active wavelength is calculated and presented in comparison with baseline. The combined method achieved about a 50% cut in energy use between different nodes and traffic loads.

In addition to the main energy-saving purpose, the research explains the real-world benefits and costs. Energy savings are converted into ETB amounts by looking at estimated electricity bills and fewer new line cards needed. By changing the weights between energy, latency, and blocking, this research presented different levels of energy conservation and active devices. Finally,This research shows that the approach works well for networks of different sizes and traffic patterns, offering a simple guide for building energy aware optical networks.

1.8 Organization of Thesis

The rest of the thesis work is organized as follows. Chapter one gives background information on optical networking basics, building blocks of optical network systems, components in an optical network system and their features, some operational issues in optical networking and about traffic grooming and sleep mode. Chapter three is all about the existing network of ETC. It covers analysis of the ETC traffic, power consumption, optical components and network architectures. Chapter four discuss the problem formulation of the research. It start with the concepts and algorithms used to select the traffic grooming sites and then it covers the mathematical model of the research. Chapter five covers the results obtained in the research both the selection of the grooming site and the application of the combined method into the selected sites.

Chapter 2: Fundamentals of Optical Networking and Optimization Problem

2.1 Telecom Network

A telecommunications network, often referred to as a telecom network, is a collection of interconnected communication devices and systems that allow the transmission of voice, data and video signals over long distances. These networks facilitate communication between individuals, businesses, and organizations through various means, such as telephone lines, fiber optics, satellites, and wireless technologies. In the telecommunication network, optical network transmission system is one of the most important components. Optical network transmission system and technology has a vital direct impact on the safe operation and innovative development of telecommunications networks. Consequently, it is very important and necessary to analyze and discuss the application of this technology in telecommunications networks [9].

2.2 Optical Network

An optical network is a type of telecommunication network that uses optical fibers to transmit data as light signals. Optical networks are known for their high bandwidth capacity, fast data transmission speeds, and low signal loss over long distances. These networks rely on optical components such as lasers, modulators, and detectors to convert electronic signals into light signals for transmission and vice versa. Optical networks are commonly used in long-haul communication systems, data centers, and high-speed internet connections due to their efficiency and reliability in transmitting large volumes of data quickly and securely. By leveraging the properties of light for data transmission, optical networks play a crucial role in supporting the growing demand for high-speed and high-capacity communication services in today's digital age. To full fill this demand, an increase in the capacity of point-to-point links is required in optical transport network. OTN is a technology used to implement the Internet backbone network. This is the core long haul fiber optical network that connects the world together. OTN uses special polarization and modulation techniques to transmit data rates of 40-Gbps and 100-Gbps [10]. For clear economic reasons, the increase in capacity has to be realized by better exploiting the potential of the existing infrastructure of OTN. An optical backbone network is structured using interconnected nodes and WDM links in a suitable configuration [11]. WDM represents an efficient and cost-effective means of providing high capacity point-to-point transmission on the already installed fiber plant [12].

In an optical WDM backbone network, different data signals are assigned to specific wavelengths of light, allowing them to travel independently without interference. This enables the network to carry a large amount of data traffic efficiently and cost-effectively over long distances. WDM technology increases the capacity of optical fiber networks by enabling the transmission of multiple channels of data at different wavelengths, effectively multiplying the bandwidth of the fiber. Optical WDM backbone networks are commonly used by telecommunications carriers and internet service providers to support the growing demand for high-speed data transmission and to connect various locations within a network infrastructure.

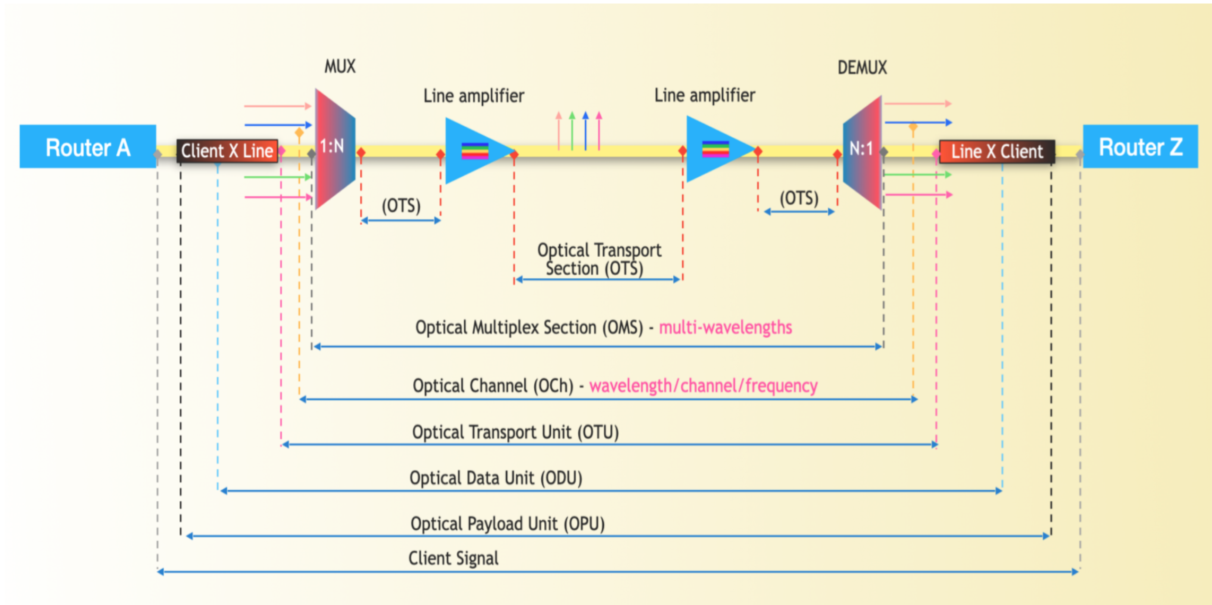

Figure 2.1: Layer-wise flow of a client signal through OTN [13]).

An optical backbone network is a high-capacity telecommunication infrastructure that forms the core backbone of a communication network. Using optical fiber technology, it can transmit large amounts of data over long distances at high speeds. Optical fibers are thin, flexible, transparent threads made of glass or plastic that can transmit data using light pulses. In an optical backbone network, these fibers serve as the transmission medium, allowing for efficient and rapid data transfer. The network typically consists of a series of nodes, such as routers or switches, interconnected by optical fibers. These nodes help route the data to its intended destination. Optical backbone networks play a crucial role in enabling the transmission of vast amounts of information, such as internet traffic, between different regions or cities, forming the backbone of modern communication infrastructures.

2.2.1 IP-over OTN-over WDM

Fiber optic and are promising technologies that are expected to satisfy the drastically increasing bandwidth requirements of the Internet. WDM is an approach that can exploit the huge optoelectronic bandwidth mismatch by requiring that each end-user's equipment operate only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber [14].

In the IP/WDM architecture, core routers are connected directly over point-to-point WDM links, whereas in the IP/OTN architecture, they are connected through a reconfigurable optical backbone consisting of electro-optical cross-connects (OXCs) interconnected in a mesh WDM network. Over the past decade, multilayer network design has received significant attention in the scientific literature. However, the explicit modeling of IP/MPLS over OTN over Dense Wavelength Division Multiplexing (DWDM) in which the OTN layer is specifically considered has not been addressed before. This multilayer network architecture has been identified as promising that bridges integration and interaction between the IP and optical layers [15]. The purposes of the three layers are presented as follows.

- IP/MPLS Layer: The routing and packet-switching domain where traffic originates and terminates.

- OTN Layer: A digital-wrapper layer that transparently encapsulates client signals, provides grooming/multiplexing, and creates reconfigurable lightpaths via OXCs.
- WDM Layer: The physical fiber infrastructure carrying multiple wavelength channels, with Reconfigurable Optical Add-Drop Multiplexer (ROADMs) and Erbium Doped Fiber Amplifier (EDFAs), over which the OTN lightpaths are instantiated.

2.2.2 Optical Devices

Transponders

An optical transponder consists of a transmitter and a responder, which is similar to a transceiver that includes a transmitter and a receiver. The optical transponder extends the transmission distance by converting the wavelengths and amplifying the signal. It automatically receives, amplifies, and then retransmits a signal on a different wavelength without changing the data/signal content. That is to say, an optical signal received by the transponder is converted to an electrical data stream which it then processes and regenerates. The transponder then converts the signal of standard optical wavelengths to an optical Coarse Wavelength Division Multiplexing (CWDM) or DWDM signal. This process is commonly referred to as OEO (optical to electrical to optical) conversion.

Optical Cross-Connect

The OXC is the main network element of the optical path layer. Its function is the routing of high speed WDM data fluxes and the add/dropping of single channels from/to the Digital Cross-Connect (DXC) interface. If the optical path layer has to be modular, scalable, and transparent, the OXC has to fulfil some structural requirements [16].

Reconfigurable Optical Add-Drop Multiplexer

ROADM is an element in DWDM ring and mesh networks. ROADM can provide flexibility and re-configurability for an OTN. Such capabilities enable network operators to quickly and flexibly respond to network changes, such as establishing new lightpaths or releasing existing lightpaths [17]. The device has an important role in extending and modifying existing WDM networks, as it enables adding new wavelengths and changing the path of existing wavelengths within the network.

Optical Line Amplifiers

An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier may be thought of as a laser without an optical cavity, or one in which feedback from the cavity is suppressed. Optical amplifiers are important in optical communication and laser physics. They are used as optical repeaters in the long distance fiber-optic cables which carry much of the world's telecommunication links.

Multiplexers and De-Multiplexers

A WDM multiplexer and a WDM de-multiplexer are required for the combination and separation of optical signals. Optical Mux is a module at the transmitter end that brings several data signals together for transporting over a single fiber, while demux is a module at the receiver end that separates the signals that come together and passes each channel to an optical receiver. WDM mux and demux modules are made into multiple WDM channels into one or two fibers.

Regenerators

Optical regenerators that enable signal re-amplification combined with re-shaping (2R), and even re-timing (3R) are used to limit signal degradation by noise sources in optical communication systems.

2.3 Resource Utilization of Optical WDM Network

Optical network resources include bandwidth, energy, wavelength, and etc. In WDM backbone networks, bandwidth refers to data capacity, energy refers to efficient power use, and wavelengths are specific light frequencies for transmitting data. These resources are crucial for fast, scalable data transmission, optimized energy consumption, and reliable signal integrity in the network, supporting diverse services efficiently.

Data traffic has experienced exponential growth in recent years, driven by factors such as the increase in Internet users, the proliferation of connected devices, and the growing popularity of data-intensive applications and services. This surge in data traffic places a higher demand on optical backbone networks, leading to increased resource consumption. As data traffic grows, network operators need to expand the capacity of their optical backbone networks to accommodate increasing data volumes. This expansion involves deploying additional network infrastructure, such as fiber optic cables, optical transceivers, amplifiers, switching and routing equipment.Those are active devices and consume energy. Transceivers convert electrical signals into optical signals and vice versa, consuming power in the process. Optical amplifiers are used to boost the strength of signals for long-distance transmission, and they also require power. Switching and routing equipment, such as routers and switches, facilitate the movement of data across the network, but they consume energy to operate. Other devices like Multiplexers, de-multiplexers and ROADMs also consume energy which lead in to high energy consumption in backbone networks.

On the other side, optical backbone networks are typically over provisioned for various reasons, primarily to guarantee dependable and effective network operation. Factors such as uncertainty in traffic growth, the necessity for resilience and redundancy, scalability requirements, and Qos all contribute to this over provisioning. However, this excess provisioning results in significant resource consumption despite minimal resource utilization.

In addition, optical backbone networks often incorporate redundancy measures to ensure high availability and fault tolerance. Redundant equipment and backup power systems consume additional energy to maintain continuous operation in case of failures or outages. Despite, this research will focus on conserving resources inthe operating links of ethio telecom backbone network rather than the redundant links.

2.4 Resource Conservation Methods in Optical Backbone Network

Resource consumption in optical backbone networks is a critical consideration due to the increasing demand for data transmission and the need for sustainable infrastructure. Vendors, Internet Service Providers (ISPs), and other stakeholders in optical backbone networks are actively involved in the implementation of a range of measures to facilitate resource conservation. Resource conservation in WDM backbone networks is crucial for optimizing network efficiency, reducing costs, and ensuring sustainable operations.

Strategies such as traffic grooming, dynamic bandwidth allocation, and streamlined network design can be regarded as effective approaches for conserving bandwidth and capacity. There are various approaches available for energy conservation, such as activating sleep mode, designing energy-efficient networks, using energy-efficient network devices, implementing dynamic Power Management, and integrating renewable energy sources.

However, implementing methods and measures for resource conservation in optical backbone networks involves trade-offs with network performance. The compromises include complexity, quality of service, flexibility, and cost. However, Achieving and synergizing energy conservation and performance in optical backbone networks is of utmost importance for sustainable and efficient network operations.

To achieve this, a holistic approach is required. This includes optimizing network design, leveraging energy-efficient components, implementing intelligent power management strategies such as dynamic power scaling, and considering the activation of sleep mode for idle network components. By carefully balancing energy-saving measures with network performance requir-ements, operators can minimize energy consumption without compromising the reliability or quality of service. This synergy is crucial in addressing the growing energy demands of data traffic while reducing the environmental impact. Not only helps to reduce operational costs and carbon emissions, it also enhances network resilience and future scalability. By prioritizing both resource conservation and performance, operators can create a greener and more efficient optical backbone network infrastructure that meets the needs of today's digital society while contributing positively to environmental sustainability.

2.5 Traffic Grooming

Traffic grooming is a network optimization technique used in telecommunications to improve the efficiency of data transmission by consolidating and rearranging traffic streams. As WDM networks provide very high speed for a huge amount of data transfer, traffic grooming is even more important for these networks [18]. It involves aggregating multiple low-capacity traffic streams into higher-capacity connections, reducing the overall number of connections and improving network utilization. By grooming traffic, network operators can minimize bandwidth wastage, enhance network performance, and reduce operational costs. Moreover, careful aggregation of low speed traffic streams onto lightpaths can decrease the cost of the transceivers used in the network [19].

This process helps in optimizing the use of network resources and improving the overall quality of service for end-users. Traffic grooming is particularly beneficial in scenarios where there are multiple sources of traffic with varying bandwidth requirements, allowing for more efficient utilization of network capacity.

2.5.1 Client Signal to Line Signal Mapping

An OTN is composed of a set of optical network elements connected by optical fiber links. It provides the functionality of transporting, multiplexing, routing, management, supervision, and survivability of optical channels carrying client signals. A client signal is the original data stream (e.g. SONET/SDH, Ethernet, Fiber Channel, ATM, IP) that enters the OTN for transport. This client signal should be mapped and encapsulated in OTU containers and form line signal to be transported through the WDM link. The process of OTN and traffic grooming is explained through the following steps.

- Optical Payload Unit (OPUk) Formation (Client to OPUk): The incoming client bit-stream is first aligned and framed into an Optical Payload Unit (OPUk) by inserting pointer-justification and adaptation overhead. This provides rate matching and performance monitoring at the payload layer [20].

- Optical Data Unit (ODUk) Wrapping (OPUk to ODUk): The OPUk frame is then encapsulated into an ODUk. This is done by adding path layer overhead identifiers, path monitoring bytes, and protection switching information for end-to-end transparency and survivability. This is where O-E-O conversion occurs and then traffic grooming. Multiple client signals aggregated together in ODU containers so that it can be transported in OTU which are embedded in wavelength [20].

- Optical Transport Unit (OTUk) Framing (ODUk→OTUk): Finally, Forward Error Correction (FEC) parity bytes and framing alignment signals are appended to form the OTUk, which is serialized at a fixed line-rate (e.g., 10.709b Gb/s for OTU2, 111.8 Gb/s for OTU4) for optical transmission [21].

- Optical Channel (OCh): The OTUk serialized bit stream is mapped onto an OCh, i.e. a single WDM wavelength, by an optical transponder that converts the electrical OTUk signal into the optical domain and vice-versa at the receive end.

- Optical Multiplex Section (OMS): Multiple OCh wavelengths are combined via a WDM multiplexer into the OMS, carrying them together over a fiber span between ROADMs.

- Optical Transmission Section (OTS): One or more OMS signals traverse the transmission section potentially across multiple fiber spans and amplifiers before reaching the next ROADM or terminal node.

The capacity of each container in the OTN is shown in the following figure.

OTN Containers in TDM Frames

Traffic grooming is an important and practical approach for designing WDM networks, which refers to the technique of efficiently multiplexing a set of low-speed connection requests onto high-capacity optical circuits and intelligently switching them at intermediate nodes. For example, Time Division Multiplexing (TDM) divides the bandwidth's time domain into repeated time slots of fixed bandwidth. Therefore, with TDM, multiple signals can share a given wavelength if they are non-overlapping in time. The resulting multi-wavelength optical time division multiplexed network is referred to as WDM–TDM network. In a grooming node, incoming sub-wavelength demands are mapped via a TDM

Container	Bit Rate (Gbps)	Mapping/Multiplexing	Description
OPUk	Variable	Client signal (e.g., Ethernet, SDH) → OPUk	Encapsulates client signals with payload-specific overhead.
ODU0	1.244	OPU0 → ODU0	Carries sub-1G signals (e.g., 1GbE).
ODU1	2.498	OPU1 → ODU1	Carries 2.5G signals (e.g., STM-16).
ODU2	10.037	OPU2 → ODU2	Carries 10G signals (e.g., 10GbE, STM-64).
ODU2e	10.399	OPU2e → ODU2e	Enhanced ODU2 for 10GbE with GFP mapping.
ODU3	40.319	OPU3 → ODU3	Carries 40G signals (e.g., 40GbE, STM-256).
ODU4	104.794	OPU4 → ODU4	Carries 100G signals (e.g., 100GbE).
ODUflex	Configurable	OPU flex → ODU flex	Flexible container for variable client rates (1.25G increments).
OTU1	2.666	ODU1 + OTU1 overhead → OTU1	Adds FEC and section monitoring for ODU1.
OTU2	10.709	ODU2 + OTU2 overhead → OTU2	Adds FEC and section monitoring for ODU2.
OTU3	43.018	ODU3 + OTU3 overhead → OTU3	Adds FEC and section monitoring for ODU3.
OTU4	111.809	ODU4 + OTU4 overhead → OTU4	Adds FEC and section monitoring for ODU4.
OTUCn	n × 105.25	Multiple ODU4/ODUf lex → OTUCn	Scalable OTU for 200G, 400G, etc. (e.g., OTUC2 = 211.6 Gbps).
Multiplexing	—	Lower-order ODUs → Higher-order ODU (e.g., ODU0→ODU1→ODU2)	Hierarchical multiplexing (e.g., 8×ODU0 → ODU1, 4×ODU1 → ODU2, 3×ODU2 → ODU3).

Figure 2.2: Client signal to Line signal Mapping

cross-connect into ODUk containers. Each container is a time-slotted frame where individual client streams occupy dedicated time slots in the payload area.[22]. Once the ODUk is wrapped and FEC framed into an OTUk, it's converted to optical and transmitted as one OCh single wavelength on the fiber. All the TDM slots formed at the ODU layer will travel together transparently over that OCh and the optical layer doesn't know or care about individual sub-streams.

2.5.2 Classification of Traffic Grooming

Traffic grooming can be classified along a number of dimensions, including control mode, switching domain, traffic granularity, and service awareness. One basic segregation of grooming is static versus dynamic grooming.

In static grooming, the objective is to provision the network to carry a set of long-term traffic demands while minimizing the overall network cost; the latter is typically taken as the number of electronic ports needed to originate and terminate the set of lightpaths in the logical topology.In terms of grooming traffic, static grooming can be defined as allocation of resources that is planned at some point in time based on predicted demands. The assumption is that demands will remain fairly constant or predictable. In fact, static grooming is usually planned during the design of the network or in response to planned traffic increases. Static groomed networks are easy to control, but if demand for traffic change drastically, there will be inefficiencies in resources used. In static grooming the objective is to provision the network to carry a set of long-term traffic demands while minimizing the overall network cost; the latter is typically taken as the number of electronic ports needed to originate and terminate the set of lightpaths in the logical topology. In dynamic grooming, on the other hand, the goal is to develop online algorithms for efficiently grooming and routing of connections that arrive in real time [23]. This type of grooming requires adjusting resources in real-time or near real-time to account for new traffic demands, traffic failures, or changing conditions in the network. Dynamic grooming can provide better efficiencies and can be more responsive to dynamic changes in traffic or network demands, but requires additional logic/control mechanisms which typically will leverage a Software Defined Network (SDN) or intelligent network management systems.

Another important classification is along the switching domain, where you have electrical grooming vs. optical grooming. Electrical grooming is when you take in incoming optical signals and convert them to the electrical domain first where fine-grained traffic flows are aggregated or switched to other destinations with OTN switches or electrical cross-connects. This allows aggregating traffic flows at sub-wavelength granularity such as aggregating several 2.5 Gb/s or 10 Gb/s flows into a single 100 Gb/s channel. In this case the latency would also be higher and there would also be the additional delay for the conversion of the signal into the electrical domain [24].

In terms of granularity, traffic grooming can be categorized into sub-wavelength, wavelength-level, and fiber-level grooming. Sub-wavelength grooming aggregates multiple low-rate client signals into a single high-capacity wavelength, optimizing bandwidth usage and minimizing idle capacity. Wavelength-level grooming assigns an entire wavelength to a single demand, which is straightforward but often inefficient when demands are small. Fiber-level grooming extends this concept further by managing entire bundles of wavelengths across multiple fibers, commonly used in large-scale backbone networks.

Traffic grooming may also be classified according to traffic structure or service type. For instance, OTU-based grooming in OTN systems involves mapping client signals into standardized OTUk containers, enabling efficient transport and multiplexing at various rates. Alternatively, service-aware grooming considers the nature of the traffic—such as IP, Ethernet, or video—to enforce QoS constraints and tailor grooming strategies accordingly.

Finally, grooming can be considered from a topological perspective, distinguishing between node-level grooming, which is confined to the ingress and egress points of a network path, and path-based grooming, where intermediate nodes participate in grooming operations. This distinction is particularly relevant in meshed or multi-hop topologies where routing flexibility and load balancing are crucial.

This multifaceted classification framework provides the foundation for understanding how different grooming strategies impact network performance, energy efficiency, scalability, and cost making it a critical consideration in the design of modern optical transport systems.

2.5.3 Traffic Grooming Site Selection

Traffic grooming site selection is crucial for optimizing telecommunications networks. By strategically placing grooming sites, network operators can effectively aggregate low-speed connections onto high-capacity fibers, reducing hardware costs and maximizing bandwidth utilization. This leads to improved network performance, enhanced scalability, simplified management, faster service provisioning, and ultimately, a better user experience by minimizing congestion, reducing latency, and improving reliability.

Since grooming requires high-capacity, processing-intensive devices, which can be costly, most carriers do not choose to deploy grooming switches at every network node. The nodes without a grooming switch typically must backhaul their sub-rate traffic to nearby grooming nodes. If too few grooming sites are deployed in a network, there may be excessive back-hauling, leading to circuitous end-to-end paths. Furthermore, the few grooming switches may be quite large and the links feeding into the grooming sites may become congested with traffic. If too many nodes have grooming switches, there are likely to be underutilized switches, resulting in unnecessary cost. From experience with actual metro-core and backbone networks, selecting about 20–40 percent of the nodes to be grooming sites produces designs that are efficient from both a cost and a network-utilization perspective. However, carriers may deploy switches at more nodes to provide greater flexibility, forecast tolerance, and reliability [25].

Selecting the nodes in which to deploy grooming switches is usually performed as part of the initial network design phase, before any traffic is provisioned in the network. The network topology and the traffic forecast are used to assist in select- ing the grooming sites. Several factors should be considered in this process. First, a node that generates a lot of subrate traffic is a natural location at which to put a grooming switch. Otherwise, there will be a large amount of traffic to backhaul to other sites, which may be inefficient. Another important factor is the geographic location of the node. Nodes near the center of the network or nodes that lie along heavily trafficked routes are favored for grooming, as it is likely to be efficient to direct subrate traffic to these sites. Furthermore, higher-degree nodes (i.e., those with several incident links) are also good candidates for grooming. Such junction sites provide a good opportunity to "mix-and-match" the subrate traffic coming from many links so that efficiently packed wavelengths are produced. One strategy for indirectly capturing these various criteria is to first perform a test routing of the forecast subrate traffic using, for example, shortest-path routing. The total subrate traffic tentatively routed on the links incident on a node can then be used as one of the metrics to assist in determining the set of grooming nodes. This is related to the betweenness centrality metric, which measures the fraction of shortest path routes that pass through a particular node [26].

With optical-bypass-enabled networks, another factor that should be considered is the amount of regeneration that is likely to occur at a node. Grooming is normally performed in the electrical domain, so that traffic that is groomed is automatically regenerated as well. By deploying grooming switches at sites where a large amount of regeneration may be required anyway, the overall amount of electronics in the network can be reduced further. One should also consider the proximity of the non-grooming nodes to those that do support grooming. For example, a possible goal for an optical-bypass-enabled network design may be to select the grooming nodes such that the non-grooming nodes are able to backhaul their traffic without requiring any regeneration along the backhaul path. Thus, in deciding whether a node should be a grooming site, one can consider the number of other nodes that can be reached from it via a regeneration-free path (although this is typically not the most critical factor in selecting grooming sites). Another factor that may be considered is redundancy, especially with regard to IP routers. Some carriers choose to designate backbone nodes as IP grooming sites in pairs; i.e., two geographically close nodes are both equipped with core routers. This is in addition to having two core routers in each grooming node for purposes of redundancy and facilitation of maintenance activities. Each node in the network can be ranked with respect to the above criteria. Nodes that are ranked highly in two or more categories or that are ranked very highly in one category are generally good nodes to choose as grooming sites. These criteria are used to generate an initial list of grooming sites. As part of the network design process, a few iterations can be run, where a small number of nodes are added or removed as grooming sites to check their effect on network cost and capacity (using the traffic forecast). The results can be used to fine-tune the final selection of grooming nodes

Hierarchical Grooming

Selecting just a subset of the nodes to be equipped with grooming switches implicitly establishes a grooming hierarchy in the network. Hierarchical grooming has been proposed more formally as an effective grooming architecture in [27] and [28]. In these proposals, a grooming hierarchy is explicitly created, where the network nodes are partitioned into clusters, with one node in each cluster selected as the hub. The bulk of the inter-cluster subrate traffic is first directed to the hub corresponding to the source node's cluster; this traffic is then routed to the hub corresponding to the destination node's cluster and from there to the ultimate destination. Most of the intra-cluster subrate traffic is groomed in the hub as well. Some of the inter-cluster and intra-cluster traffic can be routed more directly if the amount of traffic between nodes is high enough.

2.6 Sleep Mode Activation

Energy consumption of core networks is constantly increasing due to constantly increasing traffic demands and despite the improving energy-efficiency in terms of power required to provide certain capacity (Watt/bps). One of the most promising approaches to reduce energy consumption of IP-over-WDM networks is the application of Sleep Mode to network devices. The main idea of this approach is to dynamically deactivate network resources when they are unused and activate them again when needed [29]. In the context of networking, sleep mode activation can be applied to components such as routers, switches, or network interfaces to conserve energy when they are not actively transmitting data. By activating sleep mode during periods of low activity or idle time, network devices can reduce their power consumption, leading to energy savings and improved overall efficiency. When network traffic increases or a device needs to resume normal operation, it can quickly exit sleep mode and return to full functionality. Sleep mode activation is a key strategy for optimizing energy usage in network infrastructure without compromising performance. However, the application of Sleep Mode has an impact on the life time of devices.

2.7 A Non-Dominated Sorting Genetic Algorithm II

A Non-Dominated Sorting Genetic Algorithm II (NSGA-II) is a widely used multi-objective optimization algorithm that efficiently finds a set of non-dominated solutions to a problem with multiple conflicting objectives, by employing a fast non-dominated sorting procedure and a crowding distance mechanism to maintain diversity among the solutions within the population; it is considered one of the most popular and effective methods for solving multi-objective optimization problems due to its balance between convergence and diversity.

NSGA-II applied to an optical backbone network is a computational method used to optimize the design of the network by simultaneously considering multiple objectives. Those multiple objectives might be minimizing cost while maximizing network capacity, by iteratively generating and refining potential network configurations through genetic operators. Selecting the best solutions based on their non-dominance in the objective space, is ultimately finding a set of optimal network designs that balance different performance criteria.

Why NSGA-II

- Multi-objective optimization: NSGA-II excels at handling multiple conflicting objectives. This is crucial for network design where one might need to minimize cost while maximizing bandwidth, minimizing latency, or balancing traffic load across different network links.

- Genetic operators: The algorithm employs genetic operators like crossover and mutation to generate new network configurations by combining characteristics of existing solutions, exploring a wide range of possibilities in the search space.

- Non-dominated sorting: The core mechanism of NSGA-II is the non-dominated sorting process, which identifies solutions that are not dominated by any other solution in the population. This process ensures that the algorithm finds a diverse set of optimal solutions representing different trade-offs between objectives.

Normalization

Normalization in optimization refers to the process of adjusting variables, constraints, or objective functions to improve the numerical stability and efficiency of solving the problem. Variables or parameters with vastly different magnitudes can cause algorithms to converge slowly or become unstable. Normalization ensures all components contribute equally. One of the main function of normalization is Adjusting multi-objective functions to comparable scales, enabling balanced trade-offs. In this research, the objective functions are power, latency and blocking probability with their own measurement unit. So normalization is needed as to bring the three objective together in single multi objective function. There are different types of normalization such as Min-Max Scaling, Z-Score (Standardization), Mean Normalization, Unit Vector, Decimal Scaling and etc. For this research z-score is used since it has better performance in mitigating outlier in data.

$$z = \frac{x - u}{\sigma} \tag{2.1}$$

Where:

x is Original value

u is mean value

σ is Standard deviation of the dataset

Normalization maps the objective values into the (0, 1) interval in the model. It ensures that no objective dominates others simply because of its scale. The optimizer identifies Pareto-optimal trade-offs within the normalized space. After optimization, the results can always be de-normalized to interpret them in real-world units using the same formula used for the normalization.

2.8 Tools Used

2.8.1 Pycharm

PyCharm, a popular Python Integrated Development Environment (IDE) from JetBrains, provides a robust set of features for developers. With capabilities such as code completion, syntax highlighting, debugging tools, and seamless integration with frameworks like Django and Flask, PyCharm streamlines Python development workflows. It supports cross-platform usage, customization through plugins, and educational tools such as Jupyter Notebooks integration, making it a versatile choice for developers of all levels seeking an efficient coding environment.

2.8.2 Graphiz

Graphviz (short for Graph Visualization Software) is a package of open-source tools initiated by AT and T Labs Research for sketching graphs (as in nodes and edges, not as in bar charts) specified in DOT language scripts having the file name extension ”gv”. It also provides libraries for software applications to use the tools. Graphviz is free software licensed under the Eclipse Public License.

Chapter 3: **Characterization and Visualization of Ethio Telecom's Optical Network**

3.1 Ethio Telecom Backbone Network

Ethio Telecom backbone network has basically two types of topology, semi meshed network in Addis Ababa and ring topology in other cities and rural areas of the country. The OTN of ETC consists of optical network devices for transmission purpose. The transport network of ETC contains devices such as transponders, OXCs, ROADM, OLA, MUX/DEMUX, regenerators, etc. The parts of the ETC networks used in this research are some section of the ring network and the semi-meshed network covering addis ababa city.

3.2 Traffic Review of Semi-Meshed Topology

Based on user behavior, traffic demand profile can be naturally sorted weekly into three categories, i.e., weekday, Saturday, and Sunday. And sometimes traffic during holidays can also be considered for complete traffic profile of nodes in the network. For each category, the traffic pattern is divided into three components which are mainly generated in three time periods, i.e., morning, afternoon, and evening [30].

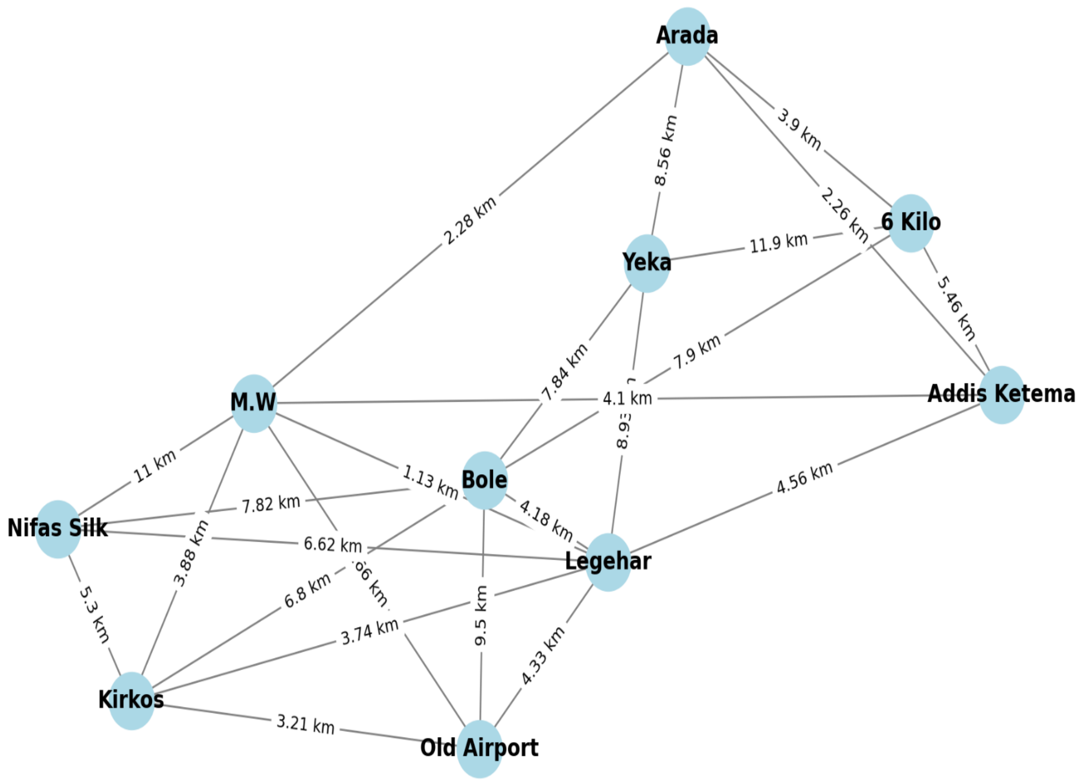

Figure 3.1: A.A Semi-Meshed Topology

Usually, traffic profiles are presented using matrix. A matrix giving the traffic volumes between origin and destination in a network has tremendously potential utility for network capacity planning and management [31]. The traffic of ETC network falls under seasonal traffic type. A seasonal traffic type is a category of network traffic characterized by regular, predictable fluctuations in volume or pattern over defined period of times as it is stated in [32]. In this research, traffic flow over 24 hour, 30 days, during weekdays, weekends and holidays have been assessed. The traffic flow of each node has the same nature. The following traffic figures will demonstrate the traffic nature of nodes. Let us look at traffic flow of a given site for 24 hours.

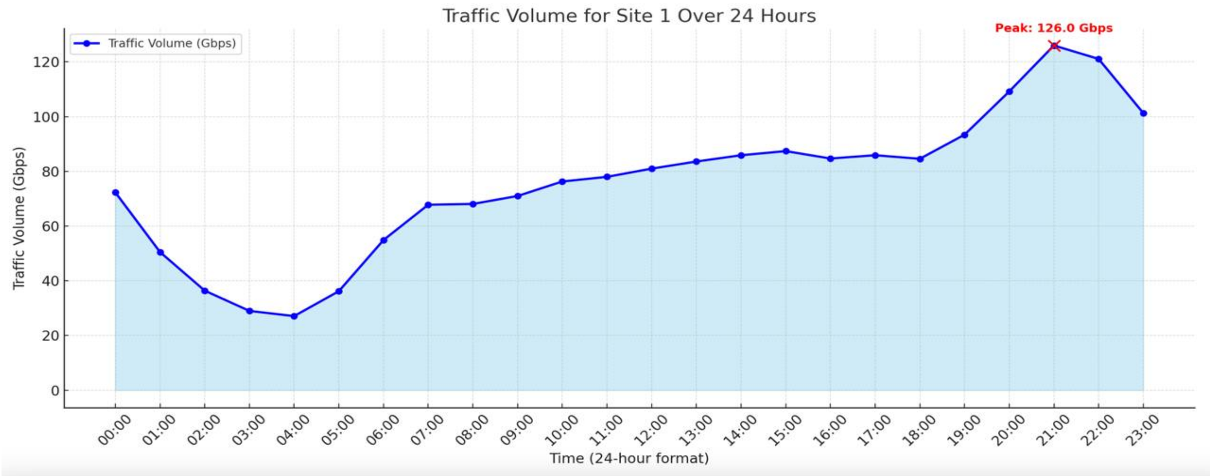

Figure 3.2: Traffic flow of a site 1 over 24 hours

The same traffic pattern is exhibited in the figure below which is averaged traffic over 30 days. Same shape (times of low, moderate, and high load) repeats in the same way every 24 hours of a month, with only a slight difference in magnitude.

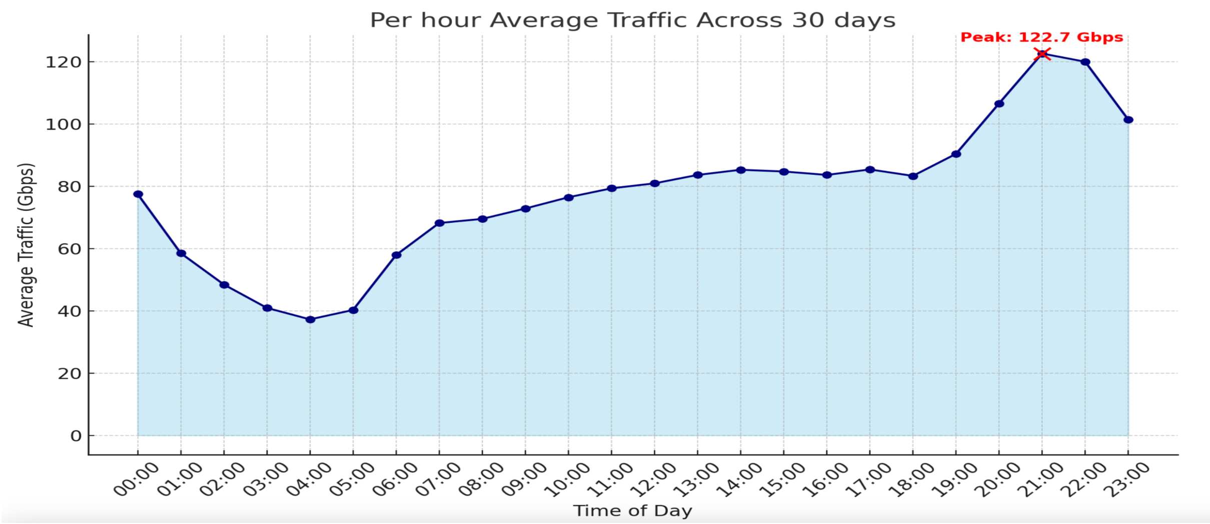

Figure 3.3: Averaged traffic flow of site 1 over 30 days

The traffic flow of the other sites is also shown in the following figure. It shows the same trend.

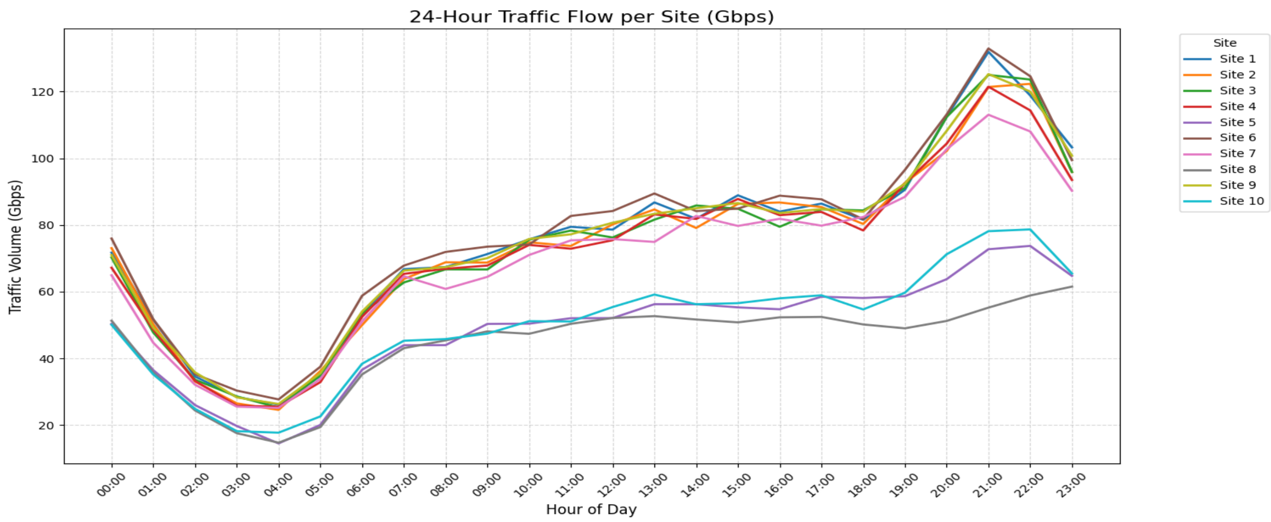

Figure 3.4: A traffic flow of 10 nodes over 24 hours

The following snippet shows the traffic flow comparison between weekdays, weekends and holidays. We can conclude that in the case of ETC, there is same traffic pattern during those times except for some changes in the magnitude of the traffic. There is relatively higher traffic demand during holidays due to the increased number of users on those occasions.

After assessing traffic patterns across various times and occasions, this research focuses on using data from 24-hour traffic flow. This choice is made because the 30-day average traffic tends to smooth out fluctuations, potentially hiding the actual peak traffic periods. However, holiday traffic occurs only occasionally and may not reflect the regular traffic pattern. The above sections demonstrated the traffic trends based on current data, while the following sub-section explains traffic prediction using historical data.

Time (24 hour format)	Monday (Gbps)	Saturday (Gbps)	Sunday (Gbps)	Holiday (Gbps)
00:00	70.93	76.87	80.86	87.90
01:00	53.90	60.60	61.50	67.65
02:00	49.27	49.25	49.54	57.21
03:00	45.75	40.57	39.10	53.15
04:00	43.62	39.30	34.39	52.04
05:00	42.92	42.46	38.65	48.05
06:00	59.70	57.70	60.24	55.03
07:00	64.58	70.48	71.24	66.40
08:00	68.14	70.35	70.98	74.35
09:00	72.78	69.72	73.24	78.64
10:00	76.04	76.18	76.56	83.66
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

Figure 3.5: Traffic flow of a site on different days

Traffic Prediction Using Seasonal Auto-Regression Integrated Moving Average

Seasonal Auto-regressive Integrated Moving Average (SARIMA), is a versatile and widely used time series forecasting model. It's an extension of the non-seasonal ARIMA model, designed to handle data with seasonal patterns.

Components of SARIMA

- Seasonal Component: The "S" in SARIMA represents seasonality, which refers to repeating patterns in the data.
- Auto-regressive (AR) Component: The "AR" in SARIMA signifies the auto0regressive component, which models the relationship between the current data point and its past values.
- Integrated (I) Component: The "I" in SARIMA indicates differencing, which transforms

non-stationary data into stationary data. Stationarity is crucial for time series modelling.

- Moving Average (MA) Component: The "MA" in SARIMA represents the moving average component, which models the dependency between the current data point and past prediction errors.

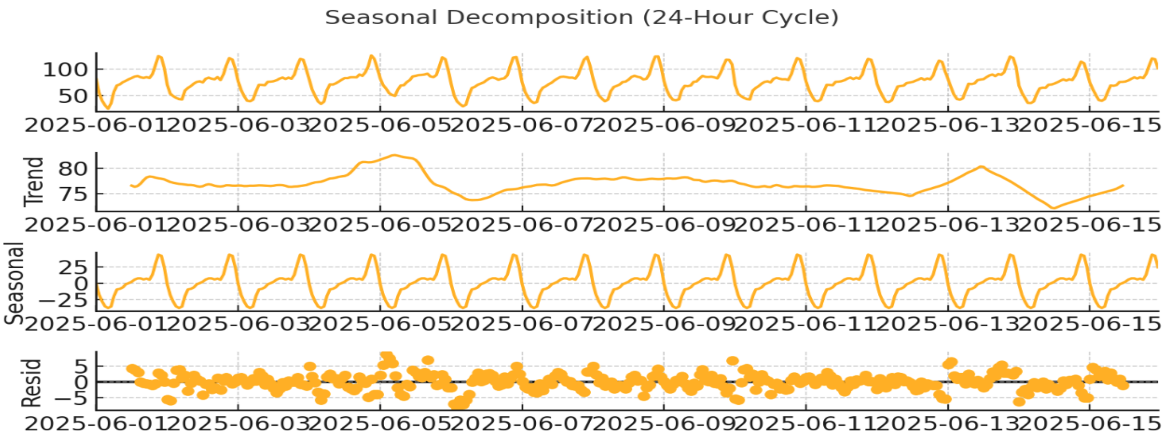

Figure 3.6: Seasonal Decomposition in SARIMA

The first graph shows the raw traffic values, including the up and down swings, which repeat every 24 hours. The trend is a smooth line that averages out the day-to-day noise and shown in the second graph. The seasonal component is the third graph, which is a 24 point pattern that repeats for each day. Residual is what remains after removing both the trend and the repeated daily cycle. Ideally, this looks like random white noise without an obvious pattern; otherwise, there would be spikes to show anomalies of special events or measurement errors.

Auto-correlation Function (ACF) measures and plots the average correlation between data points in time series and previous values of the series measured for different lag lengths.

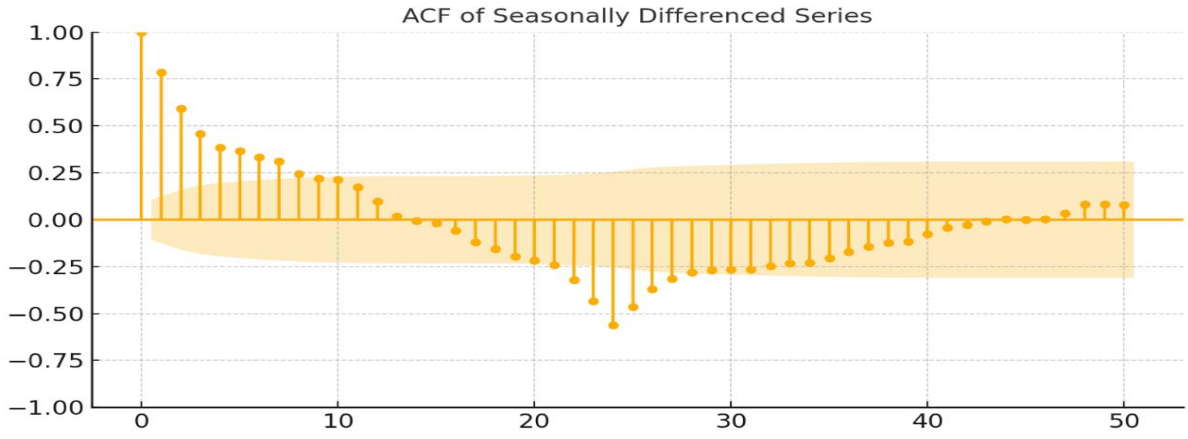

Figure 3.7: Auto-correlation Function in SARIMA

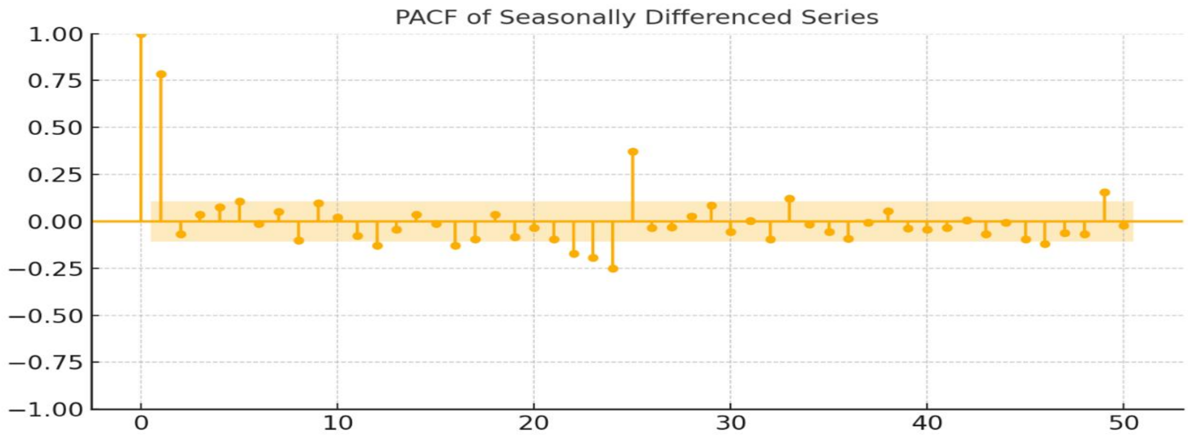

Figure 3.8: Partial Auto-correlation Function

A Partial Auto-correlation Function (PACF) is similar to an ACF except that each partial correlation controls for any correlation between observations of a shorter lag length

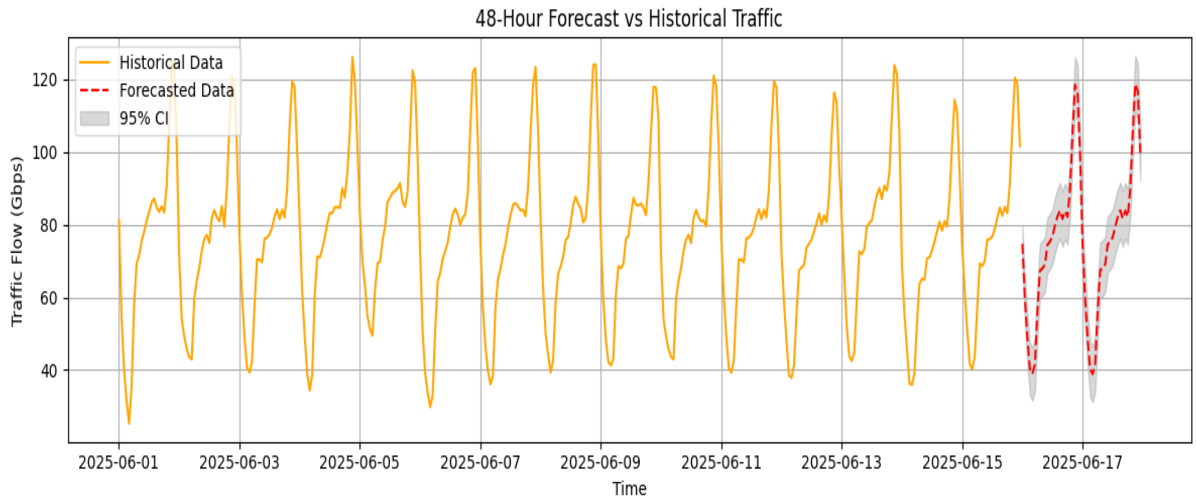

Figure 3.9: Traffic prediction using SARIMA

The figure above clearly shows that ETC traffic is seasonal, and the predicted traffic pattern from the SARIMA model aligns with this trend.

3.3 Traffic Review of Ring Topology

The traffic nature of the ring topology of ETC is more like the same with the traffic nature of semi meshed network of ETC. The difference is that the traffic flow of the ring topology is low when compare with that of the mesh topology. This might be due to the number of the subscribers and the service type requested by the users. The traffic flow of the ring topology consists of two services, voice and data. The traffic volume of this topology have the same characteristic with that of the semi-meshed topology in which it is high during specific (peak hours) times and normal during off-peak hours of a day. The traffic demand of voice is usually expressed in Erlangs which should be converted to bps to be added with data traffic.

Voice traffic

Voice traffic, in the context of telecommunications and networking, refers to the transmission of digital packets that represent audio data, typically for telephone calls or voice communication. It's a real-time and sensitive type of traffic that requires low latency and minimal packet loss to ensure clear and uninterrupted communication.

Erlang: The Erlang unit, named after Danish mathematician Agner Krarup Erlang, is a fundamental measure of telecommunications traffic intensity, particularly in voice networks. It quantifies the volume of voice traffic carried by a system over a specific period, enabling engineers to design networks with optimal capacity and performance. One Erlang represents one continuous hour of voice traffic on a single circuit (e.g., one phone call lasting 60 minutes, or two concurrent calls each lasting 30 minutes). This metric is critical for determining the number of circuits (e.g., phone lines, VoIP channels) required to handle voice traffic while maintaining a target Grade of Service (GoS), which defines the acceptable probability of call blockage or delay. To convert to bps, the concept used is erlang is equal to the continuous usage of circuit switch for one hour which is 60 min. For voice traffic, 64 kbps is allocated.

Data Traffic

This type of network traffic is insensitive traffic to packet loss if we compare with voice and video traffic. It uses retransmission mechanism if any packet loss occurs. Data traffic is used in emails, file transfers, web pages etc. So, guarantee is an important term for such a network traffic. To provide secure and guaranteed transfer, TCP is used with data traffic. The re-transmission mechanism of TCP gives this guarantee and data traffic is sent with a minimum loss.

(Site1, Site3, 6.1)
(Site2, Site3, 2)
(Site3, Site4, 3.6)
(Site4, Site5, 1.9)
(Site5, Site6, 1.9)
(Site6, Site7, 2.3)
(Site7, Site8, 3.5)
(Site8, Site9, 3.5)
(Site9, Site10, 3)
(Site10, Site11, 3)
(Site11, Site12, 4.1)
(Site12, Site13, 3.2)
(Site13, Site14, 3.2)
(Site14, Site15, 3.7)
(Site15, Site16, 3.6)
(Site16, Site17, 3.5)
(Site17, Site18, 2.8)
(Site18, Site19, 2.1)
(Site19, Site20, 2.1)
(Site20, Site21, 2.3)
(Site21, Site22, 1.7)
(Site22, Site23, 1.7)
(Site23, Site24, 1.6)
(Site24, Site25, 1.6)
(Site25, Site26, 3.5)
(Site26, Site27, 3.3)
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Figure 3.10: Traffic flow of ring topology

3.4 Latency

Fiber-optical latency is the time it takes data packets to travel from a device to a server, typically measured in milliseconds.

- For metro networks (20-100km), 0.2–1 ms total latency can be tolerated.

- For regional (Long-Haul) Network, 1–5 ms total latency will be tolerable.

The types of delay that contribute to latency are propagation delay, processing delay, transmission delay, and queuing delay. These are discussed as follows.

Propagation delay

Fiber propagation delay is the time it takes for data to travel through optical fiber. It depends on the distance the signal must cover and the speed of light in the fiber, typically around 200,000 kilometers per second. For a single kilometer distance, the propagation delay in fiber is roughly 5 microseconds, making it suitable for high-speed data transmission.

$$L_{prop} = \frac{D_m}{V}$$

Where:

D_m is distance in meter

V is speed of light in optical fiber.

Processing Delay

In a network based on packet switching, processing delay is the time it takes routers to process the packet header. Processing delay is a key component in network delay.

- OEO Conversion at Grooming Nodes: 50–200 µs overhead at each grooming node handling OEO conversion is added.
- If grooming path traverses ROADMs or protection switches, reserve 10–60 ms per such hop for reconfiguration or protection switching scenarios.

- For services sensitive to per-packet latency (voice, video), allocate 1–5 µs per router hop if using high-performance hardware, but allow 10–100 µs where DPI or encryption is involved.

Queuing Delay

The time a packet is enqueued while the link is busy sending other packets. This is a statistical function and depends on the arrival times of other packets. QoS configurations may prioritize some types of traffic over others. Queuing delay is not considered or included in the mathematical model used in this research.

Transmission Delay

The time required to push all the bits in a packet on the transmission medium in use. Transmission delay is not considered or included in the mathematical model used in this research.

3.5 Blocking Probability

The concepts of blocking probability and end-to-end blocking probability, which are used interchangeably, are equivalent to the so-called burst/packet loss ratio defined as a ratio of the bursts/packets that are lost to the bursts/packets that are sent. The main cause of loss is lack of sufficient network resources as losses due to errors in the physical layer [33]. Blocking probability can be characterized using Erlang B formula. Erlang formulas are mathematical models developed to analyze and optimize telecommunications traffic, particularly in call centers and network design. They were pioneered by Danish mathematician Agner Krarup Erlang in the early 20th century and later expanded by others. Erlang C calculates the probability of a call being delayed (waiting in a queue) in a call center. It's used to determine how many agents are needed to handle the incoming call volume and meet service level targets. Similarly to Erlang C, Erlang A considers abandoned calls (calls that hang up before being answered). It's used to calculate the number of agents needed to handle a mix of answered and abandoned calls, providing a more accurate model when call abandonment is a significant factor. But in this research Erlang B is used to model the blocking probability resulting from the proposed combined model. This research employs the Erlang B model, as it captures the expected traffic blocking associated with the proposed combined approach. The Erlang B formula, also known as the Erlang loss formula, is used to determine the probability of call blocking in a telecommunications system. The following assumptions are used to calculate the blocking probability in WDM network using erlang B formula.

- External calls arrive at each node according to an independent stationary Poisson process with rate .

- Calls that cannot be routed in the network are blocked and lost.

- The capacity of the links is the same for all the links in the network. Each call requires a full wavelength on each link of its path.

- Wavelengths are assigned uniformly randomly from the set of free wavelengths on the associated path [34].

ODUk port in OTN/WDM node is treated as a dedicated 'server' in an M/M/n/0 loss system in which connection requests arrive according to a Poisson process and occupy the port for an exponentially distributed duration [35]. In OTN, each ODUk container (e.g. ODU1, ODU2, ODU4) is a fixed-rate circuits. Once a client signal is mapped into an ODUk, that container remains exclusively for that signal until it tears down. This end-to-end reservation—regardless of whether the payload is Ethernet frames or TDM bytes—means ODUk behaves like a circuit-switched channel.

3.6 Power Analysis

The emerging of various networks such as Internet of Things (IOT) and 5G has resulted in the booming of new network passed applications and services. These have led to a significant rise in bandwidth demands to accommodate the resulting traffic. Optical DWDM coupled with switching paradigms such as optical burst switching (OBS) have been explored as possible transmission and switching network solutions for the huge bandwidth demands. Notably however, is the fact that the native DWDM networks are characterized by inefficiencies as far as key network resources such as spectrum are concerned, since an entire wavelength's capacity is allocated to a single lightpath connection. This result in significant increasing of power consumption [37].

Power consumption in optical networks refers to the electrical energy used by the network's equipment to transmit data over fiber optic cables. This includes the power needed for routers, switches, transponders, optical amplifiers, transponders, regenerators, optical switches, electrical multiplexer or de-multiplexers, and other devices miscellaneous power consuming devices. While optical networks are known for their efficiency in transmitting data, the overall power consumption can be significant, especially in large-scale networks [38]. Since in this research the methods proposed are highly related with the power consumption of optical devices in backbone network, power consumption model of those devices will be discussed next.

The power consumption models used by different authors for optical network segment follow the same pattern as those applied for the general telecommunication network. The power consumption values for components are available from data sheets which state the maximum and/or typical power consumption for each component. For the power consumption of the entire network segment authors use mainly two profile. The first one is the ON-OFF power consumption profile which states that if an optical network component is in operational state it consumes the maximum stated power consumption for that component and when it is not in operation its power consumption is zero. Whereas the second model, proportional power consumption profile, states that the power consumption of an optical network component is proportional to the amount of traffic it carries with a residual/idle constant power consumption that is consumed by the component while it is operating in sleep mode [5].

OTN devices are crucial components in modern optical networks, facilitating the transport, switching, and multiplexing of various data, voice, and video signals across long distances. They act as a ”digital wrapper,” encapsulating client signals within a standardized container for efficient and transparent transmission. Key devices include optical amplifiers, optical switches,WDM Mux/Demux,WDM Transponder or Muxponder and optical cross-connects. Most of the time those devices comes in chassis for which has sub-racks where slots can be deployed to make those devices.

Ethio Telecom has deployed various optical devices across both semi-mesh and ring topologies. The following Huawei product is one of the devices used in the ETC network.

OptiX OSN 8800 T64

The OptiX OSN 8800 T64 is a high-capacity, integrated OTN/WDM transport platform from huawei, designed for national backbone networks, regional/provincial backbones, and metropolitan core sites. It supports a wide range of services, including OTN grooming, ROADM (Reconfigurable Add-Drop Multiplexer), and terabit-bit electrical cross-connection. The T64 designation indicates a maximum capacity of 6.4 Terabits per second. Optix OSN 9800 T32 is another huawei product that Ethio-Telecom uses for long-Haul networks.

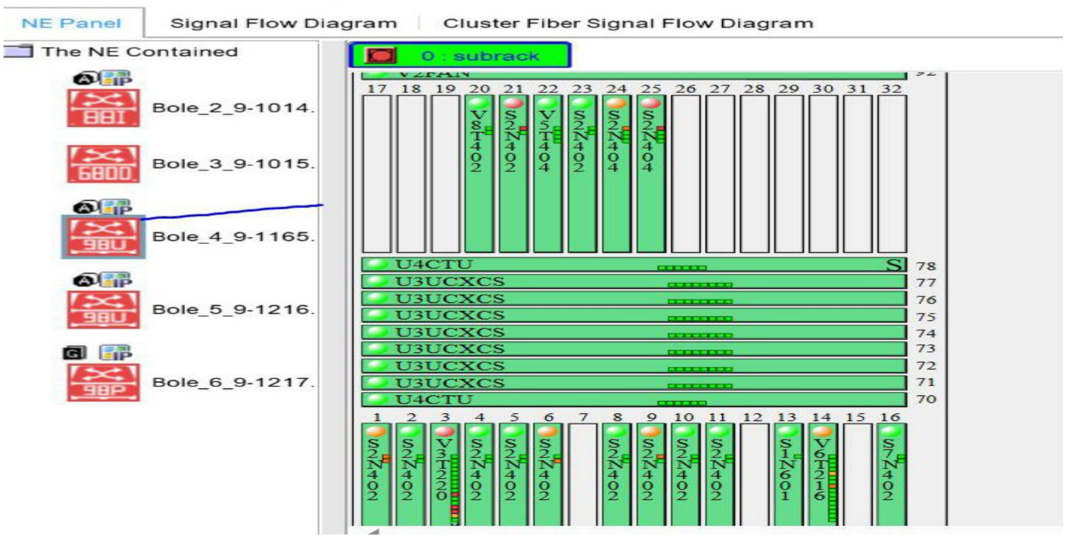

Figure 3.11: Optical Chassis

The figure above represents the optical chassis that has been used in Ethio telecom network. This optical chassis contains sub-racks where transponders, ROADMs, OTM and other installed.

Unit Name	Typical Power (W)	Max Power(W)
OTU subrack 1	1804.6	2827.9
OTU subrack 2	1421.7	2340.9
OTU electrical OXC subrack 1 (general subrack)	2172.7	2822.9
OTU electrical OXC subrack 2 (general subrack)	1839.1	2776.7
OTU electrical (enhanced subrack)	5517.7	6932.4
OTM subrack 1	963.78	1860.3
OTM subrack 2	1470.7	2406.9
OCS subrack (general subrack)	1748	2636
OCS subrack (enhanced subrack)	2135	3076

Table 3.1: Power Consumption of Subracks

The following figure shows the total nominal power consumption of optical devices where all of sub-racks in the chassis is occupied by cards/slots

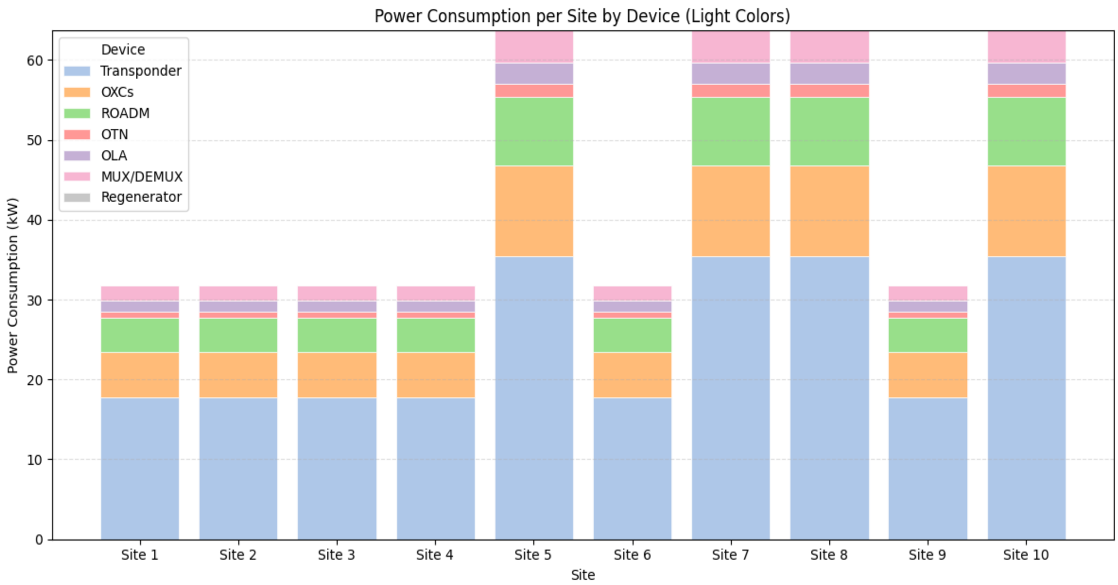

Figure 3.12: Power Consumption of Devices at full load

The figure above shows significant power consumption by the optical devices, which further increases during periods of high traffic load (peak hours). This shows sensitivity of device level power consumption to traffic intensity which needs energy-aware mechanisms.

Chapter 4: **Problem Formulation**

4.1 Grooming Site Selection of Ethio Telecom Network

As networking technology and services have evolved, one characteristic that has persisted is that much of the traffic requires a service rate that is less than that of a full wavelength. For example, while many backbone networks support 40 or 100 Gb/s wavelengths, most client demands require rates of 10 Gb/s or lower. Furthermore, the wavelength line rate is expected to increase to 400 Gb/s and higher, whereas it is forecast that, for the foreseeable future, more than 90 percent of client demands will require rates of 10 Gb/s or below, with almost half of them requiring rates of 2.5 Gb/s or below.

To address the disparity between high-capacity wavelength channels and lower-rate client demands, traffic grooming has emerged as a fundamental technique in optical network design. Instead of dedicating an entire wavelength to each client signal, which would result in under-utilization and higher energy costs, traffic grooming allows multiple services to share the same wavelength in a structured and efficient manner.

4.1.1 Semi-Meshed Network

Traffic grooming site selection of ETC is based on two methods. The first one is for semi meshed network of ETC which contains ten nodes. For this network topology, algorithm will not be used to select the grooming sites since the number of the node is few. Instead grooming sites are selected by assessing parameters like traffic flow, available capacity of the node in terms of bandwidth, device type, grooming granularity of devices, incident links and the presence of international gateway. Based on those parameters site 5,7 and 9 are selected as grooming site. The remaining seven site will backhaul their traffic to those grooming nodes.

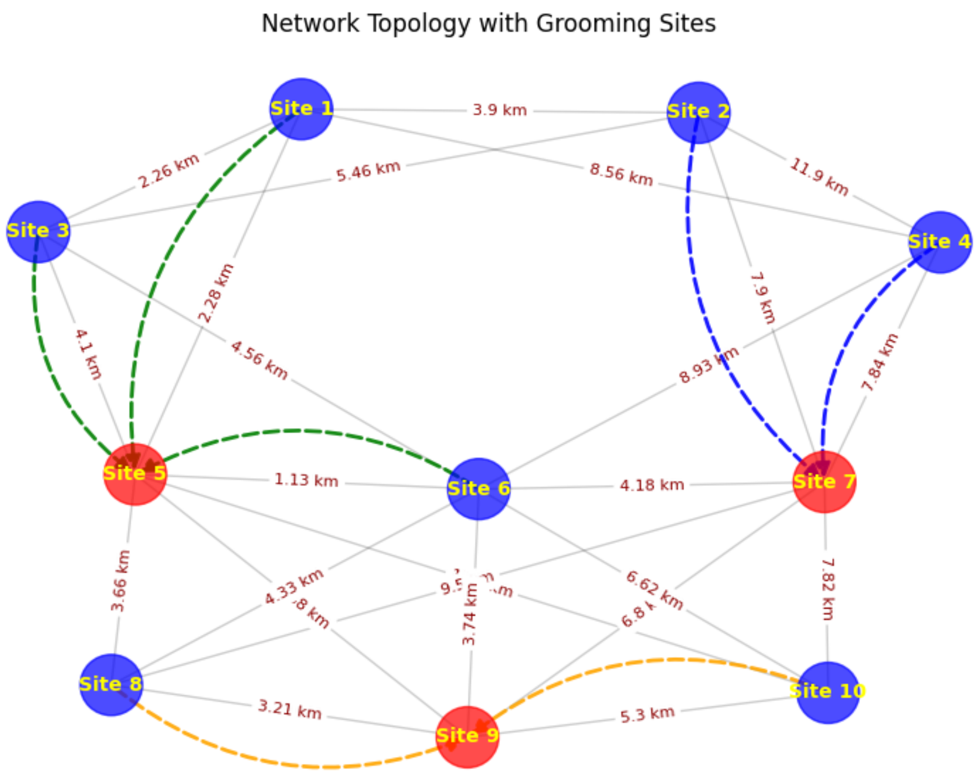

Figure 4.1: Selected grooming sites of A.A

N.B. The original names of the nodes in figure 4.1 are replaced by Sn in figure 4.2 as requested by the service provider. The ”n” represent the number of the nodes in the network.

4.1.2 K-means Algorithm for Ring Topology

The K-means algorithm can be adapted to optimize traffic grooming in optical networks by clustering nodes into groups that minimize intra-cluster latency, balance traffic load, and reduce resource overhead. This research took a ring topology which contain 46 nodes for its case study. Since the number of the nodes in the network leads to the need for algorithm for the site selection, K-means algorithm is used. The purpose of K-means is for the clustering of nodes into different clusters. The pyhsical topology of the ring network is shown below.

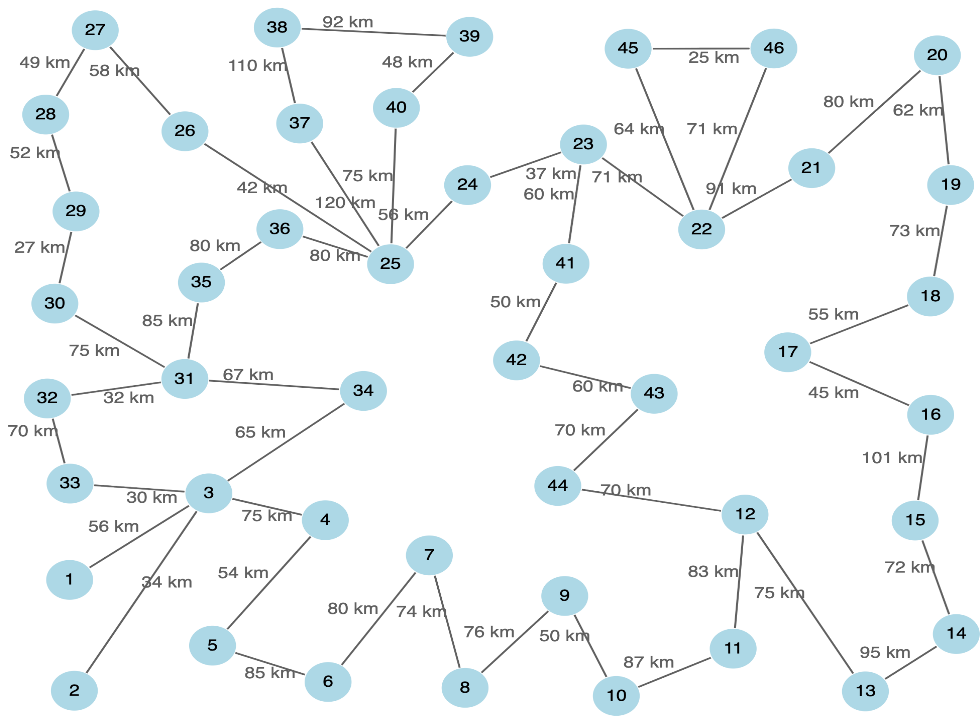

Figure 4.2: Ring topology of Country side Network

The original names of the nodes are replaced by Sn as requested by the service provider. The "n" represent the number of the nodes in the network.

The clustering will be based on the parameters such as traffic volume/demand, available capacity and centrality. To notice the difference on the clustering, each parameters were used as clustering method. The next step taken was choosing the value of K. The value of K represents the number of clusters that the algorithm is designed to create. K values can be set either manually or using elbow method. For this research elbow method is used to find the value of k. Elbow method is used to find the optimal value of K. After the clusters made, hub nodes will be identified so that other sites will backhaul their traffic to those sites.

Elbow method

The elbow method is a graphical method for finding the optimal K value in a k-means clustering algorithm. The elbow graph shows the within-cluster-sum-of-square (WCSS) values on the y-axis corresponding to the different values of K (on the x-axis). The optimal K value is the point at which the graph forms an elbow.

How it works:

- Calculate Within-Cluster Sum of Squares (WCSS): For a range of potential cluster numbers (k), calculate the WCSS for each k. WCSS measures the variance within each cluster.
- Plot WCSS: Plot the WCSS values against the corresponding k values.
- Identify the elbow: Look for the point on the curve where the decrease in WCSS begins to level off, forming an "elbow" shape.

- Choose k: The k value at the elbow point is often considered the optimal number of clusters.

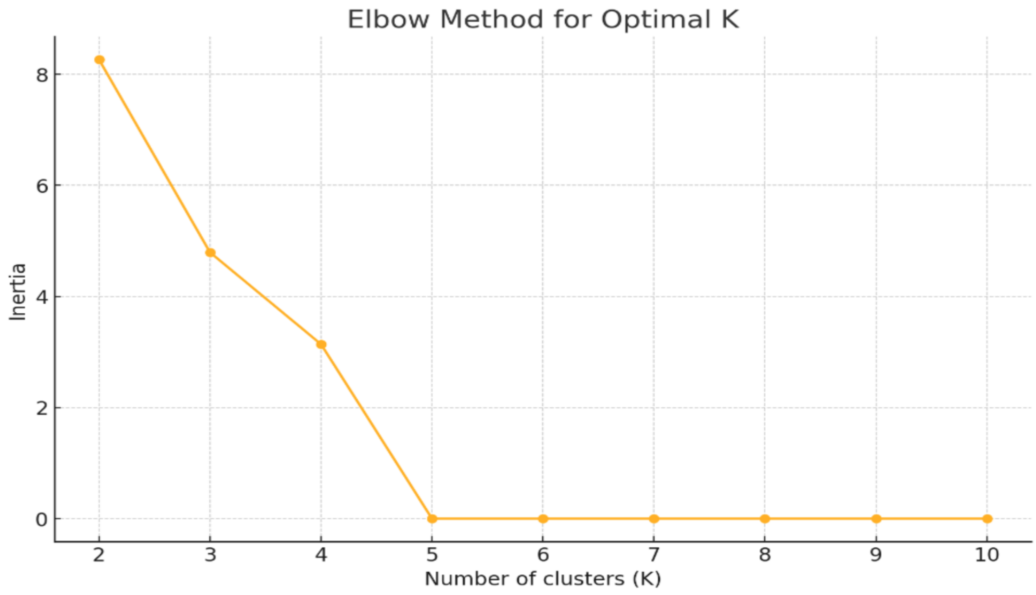

Figure 4.3: Value of k based on elbow method

After choosing the value k which is five for this research, the next step will be using the parameters to form cluster using k-means. Let us see each of the parameters one by one.

Traffic Volume

Traffic volume in a network refers to the total amount of data that is moving across a network within a specific period of time, essentially measuring how much data is being transferred at any given moment, often measured in units like megabits per second (Mbps) or gigabits per second (Gbps). There are two conflicting suggestions in selecting traffic grooming based on traffic volume. The one is that, nodes with high traffic volume are not good candidate for the traffic grooming as there will be high probability of congestion as a result of additionally groomed traffics. On the other hand, those site might be good for traffic since backhauling of those high volume traffics will be troublesome. But here other parameters also should be considered, specially available capacity of the site.

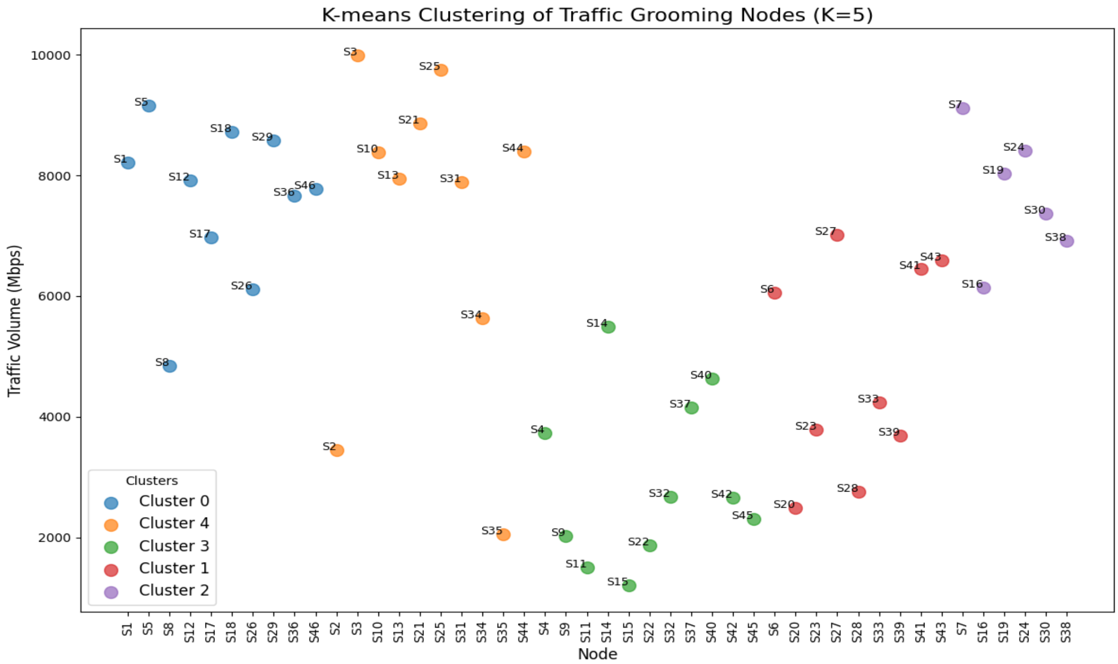

Figure 4.4: K-means clustering based on traffic volume

In the above figure, the total 46 nodes of the ring topology is clustered based on traffic volume. The position of the nodes is shifted from the original physical topology of the network.

Available Capacity

Available capacity in optical networking refers to the remaining data transmission capacity on an optical fiber network, essentially the amount of bandwidth that is not currently being used and can be allocated for new data traffic, measured typically in gigabits per second (Gbps) or terabits per second (Tbps). Available capacity of a give node is highly crucial in determining the ability of the node in traffic grooming. In practical terms, a node with plenty of available resources is usually chosen as a grooming site, while a node with limited resources may not be the best option. However, the decision should not be based only on available resources. Other factors also matter. For example, a node with lots of resources but already handling heavy traffic might not be a good choice because adding more traffic could cause congestion and delays. Therefore, a well-balanced approach should consider multiple factors to make the best decision for traffic grooming.

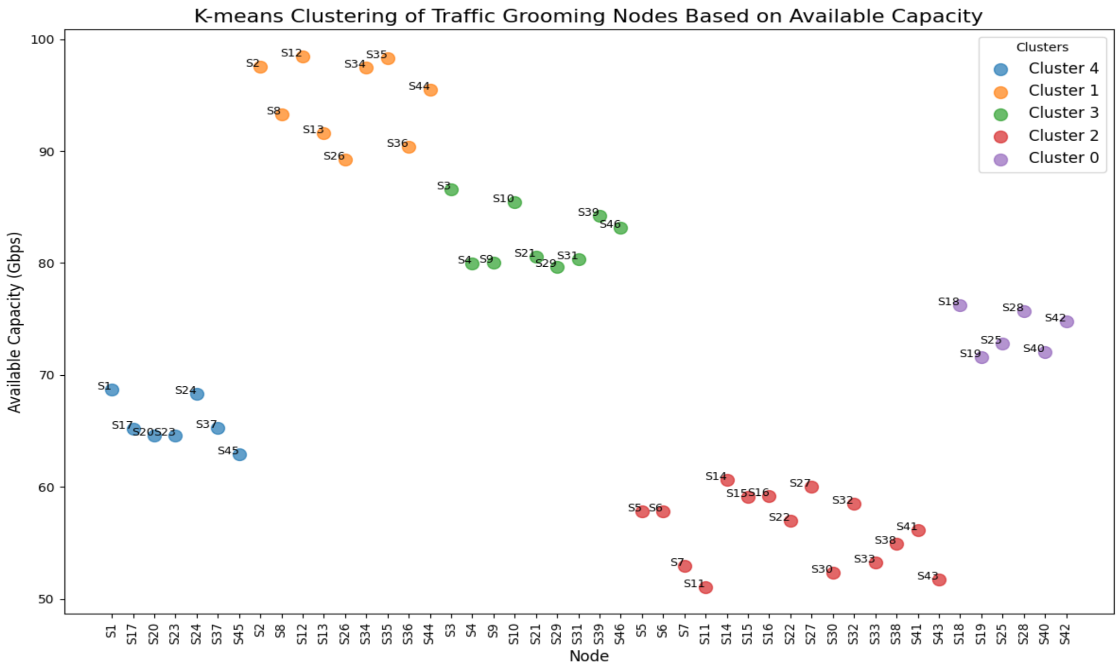

Figure 4.5: K-means clustering based on Available capacity

In the above figure, nodes are clustered into 5 clusters based on the available capacity of the node.

Centrality

Centrality originally referred to how central actors are in a network's structure. It has become abstracted as a term from its topological origins and now refers very generally to how important actors are to a network. There are four well-known centrality measures: degree, betweennes, closeness and eigenvector.From those centrality measures this research used closeness centrality. This centrality measure evaluates how close a node is to all other nodes in the graph, considering the shortest paths and the weights (in this case, distances) of those paths. Closeness centrality for a node v is defined as the reciprocal of the sum of the shortest path lengths from that node to all other nodes. For weighted graphs, it is calculated as:

$$C(v) = \frac{1}{\sum_{u \neq v} d(u, v)} \tag{4.1}$$

Where:

d(v,u) : the shortest path distance from node v to node u.

$\sum_{u \neq v} d(u, v)$: the sum of the shortest path distances from node v to all other nodes.

Based on centrality calculation performed the above cluster of nodes are selected. From here we can notice that different clusters are formed using different clustering parameters. But we should keep in mind that a single parameter will not satisfy the condition in which effective grooming mechanism is required. Another parameters like number of incident link and number of regenarators in given node can also be used as selection mechanism.

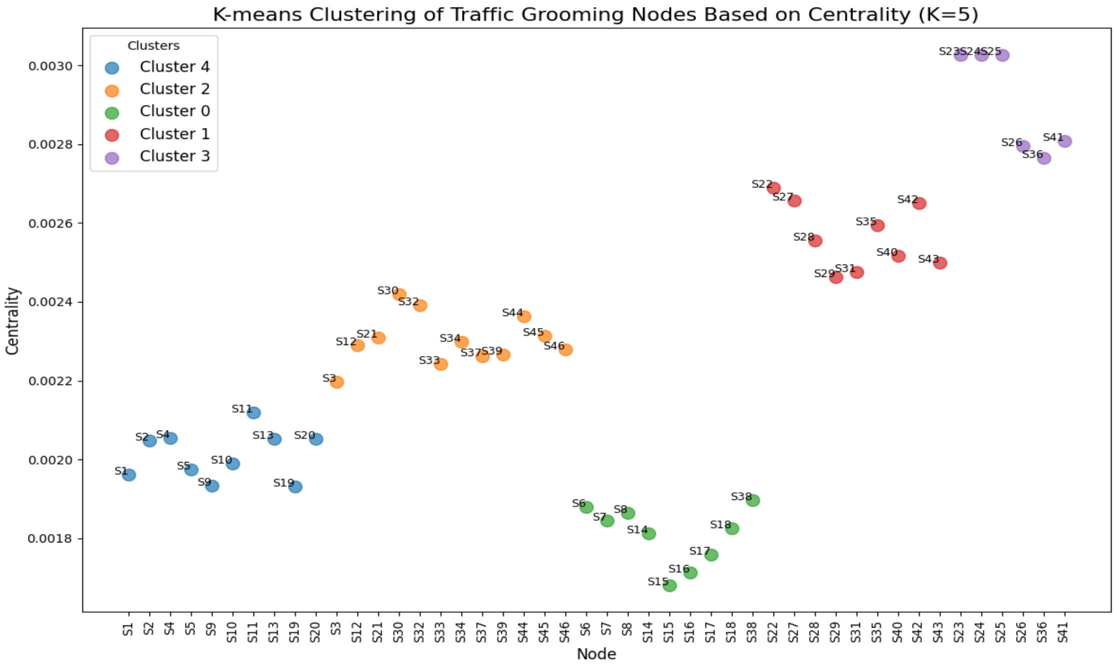

Figure 4.6: K-means clustering based on Centrality

The above figure shows the resulted clustering from considering all parameters at once. But here it should be kept in mind that k - means clustering is not last step in the traffic grooming site selection process. The purpose of the k means is to cluster the set of nodes so that those nodes with same feature will be treated together in the grooming processes. So single of few nodes will be selected from each cluster which will be used as a hub for the grooming process.

The next step after the clustering process is selection of node with in the given cluster. To do the selection available capacity, number of incident links and number of regenerators are widely used parameters. But in this research, available capacity and number of incident links are used. The reason behind the number of regenerator is excluded is the fact that ETC network do not have plenty amount of regenerators as the distance between the nodes is short.

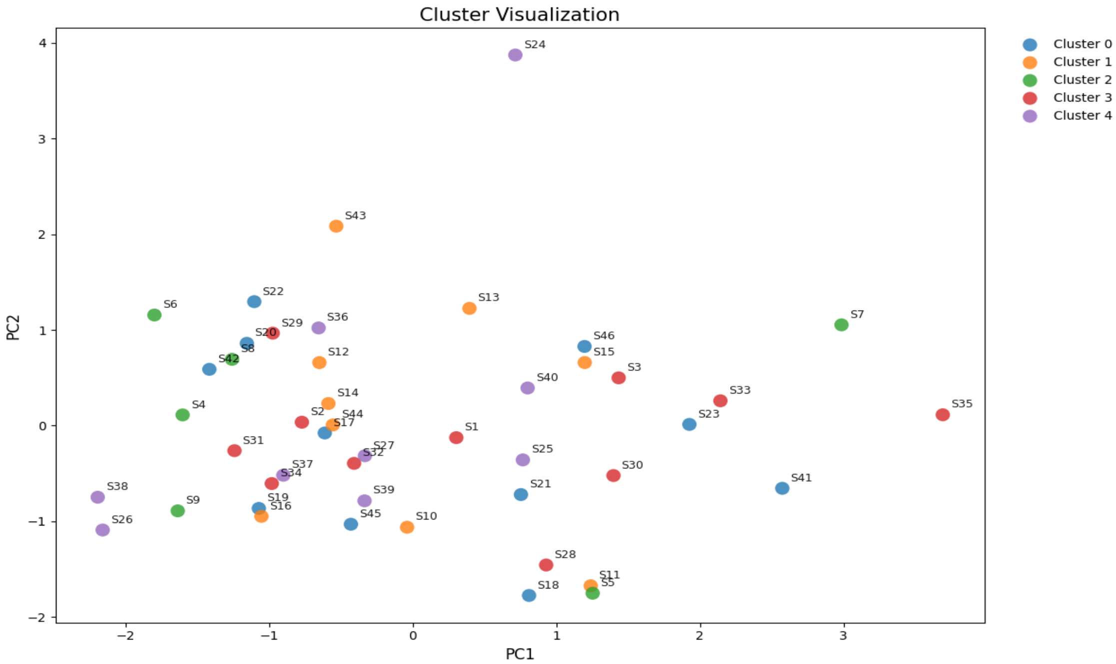

Figure 4.7: K-means clustering based on all parameters

Cluster No	Member nodes	Grooming nodes
0	S23,S22,S45,S46,S21,S41,S20,S19,S42,S18,S17	S22,S18
1	S16,S43,S15,S44,S14,S13,S12,S11,S10	S12
2	S8,S7,S6,S5,S4,S9	S6
3	S3,S1,S2,S34,S33,S32,S31,S30,S29,S35,S28	S3,S31
4	S36,S27,S26,S25,S40,S37,S38,S39,S24	S25

Table 4.1: Clusters and Grooming Nodes

- From cluster 0 which contain 11 nodes in total, S22 and S18 are selected as grooming sites.
- From cluster 1 which contain 9 nodes in total, S12 is selected as grooming site.
- From cluster 2 which contain 6 nodes in total, S6 is selected as grooming sites.
- From cluster 3 which contain 11 nodes in total, S3 and S31 are selected as grooming

sites.

- From cluster 4 which contain 9 nodes in total, S25 is selected as grooming site.

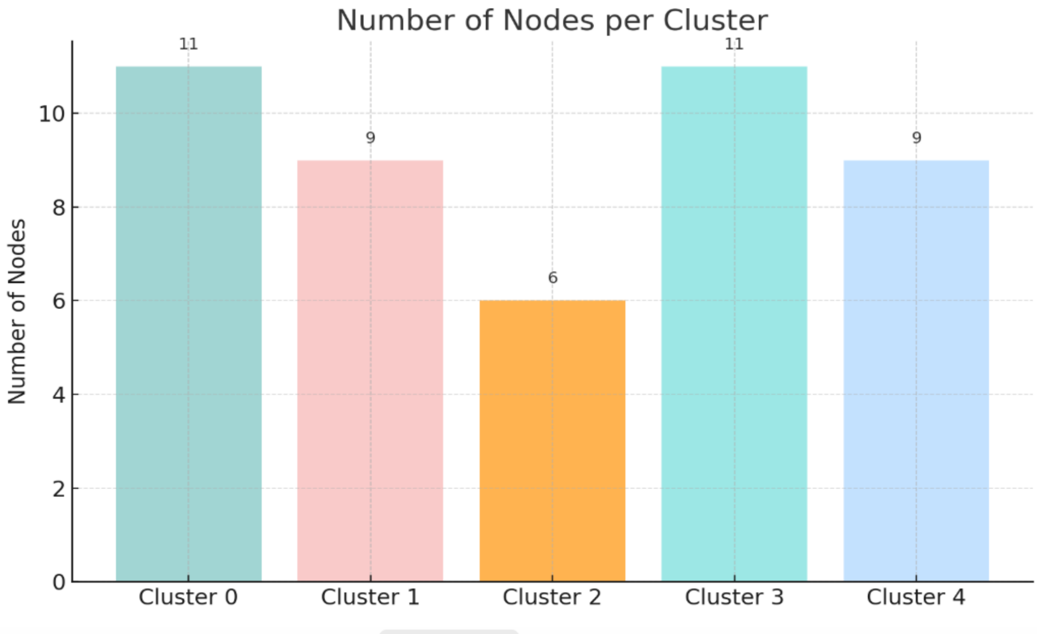

Figure 4.8: Number of nodes in each clusters

4.2 Mathematical Modeling

The evaluation of and reduction in energy consumption of backbone telecommunication networks has been a popular subject of academic research for the last decade. A critical parameter in these studies is the power consumption of the individual network devices. It appears that across different studies, a wide range of power values for similar equipment is used [47]. The power consumption of the optical core network segment is divided into four layers; IP/MPLS, Ethernet, OTN and WDM. For each layer power consumption of each component involved is taken from data sheets. The total power is thus given as the sum of the power consumption in the constituting layers [5].

$$P_{core} = P_{IP} + P_{ethernet} + P_{wdm} + P_{OTN} \tag{4.2}$$

Where:

P_{IP} is the power consumed in IP layer

$P_{ethernet}$ is the power consumed by layer 2 switching

P_{wdm} is the power consumed by wdm devices

P_{OTN} is the power consumed by OTN system processes

The word OTN used here is to indicate the power consumption due to FEC, management and other miscellaneous systems in OTN technology. For the power consumption of the entire network segment authors use mainly two profile. The first one is the ON-OFF power consumption profile which states that if an optical network component is in operational state it consumes the maximum stated power consumption for that component and when it is not in operation its power consumption is zero. Whereas the second model, proportional power consumption profile, states that the power consumption of an optical network component is proportional to the amount of traffic it carries with a residual/idle constant power consumption that is consumed by the component while it is operating in sleep mode [5]. Power consumption model using both of the model discussed above, ON-OFF and proportional power model is discussed as follows. Both of the models are used due to the fact that the devices in backbone network can not be summarized in a single model as their working principle differ from each other. For example transponders, OXCs ana roadms can be modeled as their traffic might change with the change of the traffic. On the other hand regenerators and amplifiers fall under the ON-OFF approach.

$$P_{backbone} = P_{wdm} + P_{OTN} \tag{4.3}$$

Now let us develop power consumption model using each device in the network based on their working principle.

$$P_{backbone} = P_{tp} + P_{OXC_s} + P_{ROADM} + P_{OTN} + P_{mux/demux} + P_{amp} + P_{reg} \tag{4.4}$$

Where:

$$P_{tp} = N_{tp_a} \times P \tag{4.5}$$

P_{tp} is total power consumed by transponder cards in the given node

N_{tp_a} is number of active transponder cards.

P is power consumed by single transponder card.

$$P_{oxc_s} = N_{oxc_s} \times P \tag{4.6}$$

P_{oxc_s} is the total power consumed by OXC

N_{oxc_s} is the number of OXC ports

P is power consumed by single OXC port

$$P_{ROADM} = N_{ROADM_{port}} \times P \tag{4.7}$$

P_{ROADM_S} is the total power consumed by ROADM ports

$N_{ROADM_{port}}$ is the number of active ROADM ports

P is power consumed by single ROADM port

$$P_{OTN} = N_{tp_a} \times P_{tp} \tag{4.8}$$

P_{OTN} is the total power consumed for Traf mgmt, FEC, Monitoring and signaling

N_{tp_a} is the number of active transponders

P_{tp} power consumed by single transponder slot

$$P_{mux} = N_{mux/demux_a} \times P \tag{4.9}$$

$P_{mux/demux}$ is power consumed by multiplexers or demultiplexers

N_{mux_a} is number of active multiplexers or demultiplexers

P is the power consumed by single multiplexer or demultiplexer

$$P_{amp} = N_{amp_a} \times P \tag{4.10}$$

P_{amp} is power consumed by active amplifiers

N_{amp_a} is number of active amplifiers

P is Power consumed by single amplifier

$$P_{reg} = N_{rega} \times P \tag{4.11}$$

P_{reg} is power consumed by active regenerators

N_{reg_a} is number of active regenerators

P is power consumed by single regenerator

4.3 Power Consumption as a Function of Resource Utilization

4.3.1 Transponder

$$N_{tp_a} = \frac{N_{wl}}{N_{sl}} \tag{4.12}$$

N_{tp_a} is number of active transponder cards.

N_{wl} is the number of active wavelength

N_{sl} is number of slots per transponder

$$N_{wl} = \frac{T_{td}}{C_{wl}} \tag{4.13}$$

T_{td} is traffic total demand

C_{wl} is capacity per wavelength

$$T_{td} = \sum_{i=0}^{N_{OTU}} C_{OTU_i} \tag{4.14}$$

C_{OTU} is capacity of single OTU (Gbps)

Therefore:

$$N_{wl} = \frac{\sum_{i=0}^{N_{OTU}} \times C_{OTU_i}}{C_{wl}} \tag{4.15}$$

Power consumption model for transponders :

$$P_{tp} = (\frac{N_{wl}}{N_{sl}}) \times P \tag{4.16}$$

$$P_{tp} = \frac{\sum_{i=0}^{N_{OTU}} \times C_{OTU_i}}{C_{wl} \times N_{sl}} \times P \tag{4.17}$$

4.3.2 OXCs

$$N_{OXC_a} = \frac{N_{wl,av}}{C_{swt_{OXC}}} \tag{4.18}$$

Where:

N_{OXC_a} is the number of active OXC

$N_{wl,av}$ is number of active wavelength

$C_{swt_{OXC}}$ is switching capacity of OXC

$$N_{wl,av} = \frac{T_{td}}{C_{wl}} \tag{4.19}$$

$$P_{OXC} = P_{static} + N_{OXC_a} \times P_{per_{wl}} \tag{4.20}$$

P_{OXC} is Power of OXC

P_{static} is static power of OXC

$$P_{OXC} = P_{static} + (\frac{\frac{T_{td}}{C_{wl}}}{C_{swt_{OXC}}}) \times P_{per_wl} \quad (4.21)$$

Condition for the algorithm

$$P_{OXC} = P_{static} + P_{per_wl}[\frac{N_{wl,av}}{C_{swtOXC}} + max(0, N_{wl,in} - N_{wl,av})] \quad (4.22)$$

Where:

N_{OXC_a} is number of active OXC port

T_{td} is total traffic demand (Gbps) arriving at this OXC

C_{wl} is capacity per wavelength (GPS)

$N_{wl,in} = [\frac{T_{td}}{C_{wl}}]$ is number of wavelengths needed by the new demand

$N_{wl,av}$ number of wavelength already active on this OXC (is carrying other traffic)

C_{swtoxc} is max wavelength this OXC can switch

P_{static} is static (baseline) power of the OXC chasis (W)

P_{per_wl} is incremental power per active wavelength

4.3.3 ROADM

$$P_{ROADM} = P_{static} + (N_{wl} \times P_{ch}) \quad (4.23)$$

$$N_{wl} = \frac{T_{td}}{C_{wl}} \tag{4.24}$$

$$P_{ch} = P_{WSS} + P_{amp} + P_{OPM} \tag{4.25}$$

Where:

P_{static} is static power of ROADM independent of traffic

N_{wl}number of active wavelength

P_{WSS} is for Wavelength-Selective Switch (WSS) Ports

P_{ch} is per-channel

P_{omp} is Optical performance monitors (OPMs)

P_{amp} is ROADMs usually include booster/pre-amp and typical values are

P_{WSS} 2.5 W/port

P_{amp} 7.0 W/channel

P_{OPM} 0.5 W/channel

$Thus:$

P_{ch} 10 W per active wavelength

4.3.4 OTN

$$P_{OTN} = P_{base} + N_{port} \times P_{port} + N_{FEC} \times P_{FEC} \tag{4.26}$$

Where:

P_{OTN} is total power consumption of the OTN equipment

P_{base} is base power consumption independent of traffic load

N_{ports} is number of active portsP_{port} is power consumption per active port

N_{FEC} is number of FEC processing units in operation

P_{FEC} is power consumption per FEC unit

4.3.5 Multiplexer or De-multiplexer

In optical networking, active and passive multiplexer/demultiplexer (mux/demux) devices refer to how they manage optical signals. Active mux/demux requires a power supply while passive mux/demux relies on passive components like filters and prisms, and doesn't need a power supply.

For active MUX/DEMUX :

$$P_{mux/demux} = P_{static} + N_{port} \times P_{per_port} \tag{4.27}$$

The number of Multiplexer or demultiplexer used is proportional to number of walength to be multiplexd or demultiplexed.

$$P_{mux/demux} = P_{static} + (N_{wl} \times P_{per_port}) \tag{4.28}$$

P_{static} is static power of multiplex or de-multiplexer.

4.3.6 Amplifiers

$$P_{ampOLA} = N_{fspan}(P_{base} + N_{ch} \times P_{ch} + G \times P_{gain}) \tag{4.29}$$

Where:

P_{OLA} is total power of OLA

N_{amp} is number of amplifiers in the system

P_{base} is base power consumption per amplifier (is independent of traffic)

N_{ch} is number of active channels (wavelengths)

P_{ch} is additional power consumption per active channel

G is gain per amplifier in dB

P_{gain} is additional power consumption per dB of gain

4.3.7 Regenerators

$$P_{reg} = N_{reg} \times P \tag{4.30}$$

$$N_{reg} = \frac{N_{wl}}{D_{rth}} \tag{4.31}$$

Where:

N_{reg} is number of regenerator

D_{rth} is the maximum distance a signal can travel before regeneration

$$P_{reg} = \frac{N_{wl}}{D_{rth}} \times P \tag{4.32}$$

4.4 Optimization Problem

An optimization problem is the problem of finding the best feasible solution from all possible choices that satisfy the constraints [39]. An optimization problem is a task that finds the best solution from a set of possible solutions. It involves finding the best values for decision variables to either maximize or minimize a fitness function.

Components of an optimization problem

- Objective function: The function that is being maximized or minimized
- Decision variables: The variables whose values are being optimized
- Constraints: The conditions that the solution must meet.

In this section, optimization problem based on the power consumption model is formed. This optimization problem clearly demonstrate the relationship between the resource utilization and power consumption in one hand and in the other hand demonstrate the trade off with latency and blocking probability. The reason for including latency and blocking probability is the fact that those parameters are conflicting parameters with power consumption as a result of the combined method used in this research.

Traffic grooming along with sleep mode result in blocking probability as resources get shutdown. The blocking probability in optical backbone networks is a measure of the likelihood that a connection request will be denied due to insufficient resources (e.g., lack of available wavelengths or insufficient capacity). On other hand latency will be introduced due to the new route/path and nodes the traffic has to traverse as a result of the grooming. To put into account conflicting nature of the parameters, multi-objective optimization problem is considered.

A multi-objective (MOOP) optimization problem involves a number of objective functions which are to be either minimized or maximized. As in a single-objective optimization problem, the multi-objective optimization problem may contain a number of constraints which any feasible solution (including all optimal solutions) must satisfy [40]. A weighted multi-objective optimization problem" is a type of optimization problem where you have multiple conflicting objectives, but each objective is assigned a specific "weight" to indicate its relative importance, essentially allowing you to prioritize one objective over another when searching for the best solution. So here in this research even the main objective is reducing the energy consumption, weights will be used for the parameters to observe the effect of the latency and blocking probability in power consumption and vice versa.

The Optimization problem is defined as follow:

$$\mathbf{min}\ w1 \times f_1 + w2 \times f_2 + w3 \times f_3 \tag{4.33}$$

Here, f1, f2, and f3 represent the objectives to be optimized, while w1, w2 and w3 are the corresponding weights for these objectives. In this study, the objectives are power consumption, latency, and blocking probability."

$$\mathbf{min}\ w1 \times P_{total} + w2 \times L + w3 \times P_b \tag{4.34}$$

Where:

P_{total} is total power of the network devices

L is total latency

P_b is blocking probability

$w1$ is the weight of Power

$w2$ is the weight of Latency

$w3$ is the weight of blocking probability

Power

$$\sum_{w} P_w \times y_w + \sum_{n} P_n \times (1 - z_n) + \sum_{l} P_l \times (1 - z_l) \tag{4.35}$$

Where:

y_w is binary variable for wavelength w (1 = active, 0 = inactive)

z_n is binary variable for node n (1 = sleep mode, 0 = active)

z_l is binary variable for link l (1 = sleep mode, 0 = active)

P_w is used to express energy consumption of device that are directly related with wavelength

P_n is used to express energy consumption of device that are directly related with node

P_l is used to express energy consumption of device that are directly related with link

Blocking Probability

$$Pb_{A,n} = \frac{\frac{A^n}{n!}}{\sum_{k=0}^{n} \frac{A^k}{k!}} \tag{4.36}$$

Where:

$Pb_{A,n}$ is the blocking probability

A is the load offered

n is number of active wavelength/light path

k is the summation index

Latency

$$L_w = \sum_{all,links} L_{prop} + \sum_{all,nodes} L_{proc} \tag{4.37}$$

Where:

L_{prop} is propagation delay

L_{proc} is processing delay

$$L_w = \sum_{i=1}^{H} \frac{d_i}{v} + \sum_{i=1}^{N} d_{proc,i} \tag{4.38}$$

Where:

H is number of hops the path

di is distance of hop "i"

v is speed of light in fiber

N is number of nodes in the path

$d_{proc,i}$ is the processing delay in each node

Constraints:

- Traffic demand satisfaction

$$\sum_{w} x_{sd}^{w} \times B_{sd} \geq T_{sd} \forall s, d \tag{4.39}$$

Where:

B_{sd} is bandwidth per wavelength

T_{sd} is andwidth demand / traffic request

$x_{sd}^{w} \in 0, 1$ is binary variable indicating whether traffic from S to D is groomed onto w

$y_{w} \in 0, 1$ is binary variable indicating whether wavelength w is active

Meaning: For every source–destination pair (s,d), the total bandwidth allocated (via binary variables $x_{w,s,d}$) must at least meet the requested traffic$T_{s,d}$.

- Wavelength capacity

$$\sum_{s,d} x_{sd}^{w} \times B_{sd} \leq C_{w} \times y_{w} \tag{4.40}$$

C_{w} is capacity of wavelength

$y_{w} \in 0, 1$ is binary variable indicating whether wavelength w is active

B_{sd} is bandwidth per wavelength

$x_{sd}^{w} \in 0, 1$ is binary variable indicating whether traffic from S to D is groomed onto w

C_w if and only if wavelength w is active($y_w = 1$).

Meaning: The total bandwidth groomed onto wavelength w cannot exceed its capacity.

- Sleep mode activation

$$z_n \leq 1 - \sum_{w} y_w \quad \forall n, \quad z_l \leq 1 - \sum_{w} y_w \quad \forall l \tag{4.41}$$

Where:

$z_n \in 0, 1$ is binary variable indicating whether node n is in sleep mode

$z_l \in 0, 1$ is binary variable indicating whether link l is in sleep mode

Meaning: If any wavelength w traversing node n (or link l) is active ($y_w = 1$), then the node/link canno

0) Conversely, if $z_n = 1$, then all $y_w = 0$.

- Latency Constraint

$$\sum_{w} x_{sd}^{w} \times L_w \leq L_{max} \quad \forall s, d \tag{4.42}$$

Where:

L_w is total latency (propagation + processing)

L_{max} maximum latency

- Blocking Probability Constraint

$$\sum_{w} x_{sd}^{w} \times P_b \leq P_{max} \quad \forall s, d \tag{4.43}$$

Where:

P_b is total blocking probability

p_{max} maximum blocking probability

Chapter 5: **Results**

The amount of traffic incident on a network is usually captured in the form of a traffic matrix (TM). A TM consists of the amount of traffic between each pair of nodes in a network [41]. The TM of semi meshed network and the corresponding traffic mapping are presented in the subsequent chapters. The demand matrix is generated for three times of day, at 4:00 am, 2:00 pm and 21:00 pm. It can also be performed for other times of the day, too, but here for the sake of comparison it was generated during high, moderate and low BW utilization.

5.1 Traffic Mapping

The traffic mapping of the sites during grooming is illustrated as follows using some of the sites from the case study. The grooming used the following mapping of OTN containers.

ODU Level	ODU Rate (Gbps)	OTU Level	OTU Rate (Gbps)	Difference
ODU0	1.244	-	-	-
ODU1	2.498	OTU1	2.666	0.168 (FEC)
ODU2	10.037	OTU2	10.709	0.672(FEC)
ODU3	40.319	OTU3	43.018	2.699(FEC)
ODU4	104.794	OTU4	111.810	7.016(FEC)

Table 5.1: ODU and OTU levels and capacities

5.2 Traffic Mapping for Semi-Mesh Topology Under Low Load Conditions

Traffic Mapping from Site 1 to Site 5

Based on grooming site selection, one of the grooming site is S5 and S1,S3,S6 are the sites that backhaul their traffic to site 5. To do so there will be mapping of ODU to OTU. The mapping will be based on the following traffic demand matrix generated.

From \ To	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
Site 1	0.0000	7.6127	7.7925	7.3430	4.3518	0.0000	0.0000	0.0000	0.0000	0.0000
Site 2	6.7617	0.0000	6.4872	6.1130	0.0000	0.0000	6.0381	0.0000	0.0000	0.0000
Site 3	7.3997	6.9355	0.0000	0.0000	3.9647	7.7001	0.0000	0.0000	0.0000	0.0000
Site 4	6.3294	5.9323	0.0000	0.0000	0.0000	6.5863	5.6521	0.0000	0.0000	0.0000
Site 5	2.8083	0.0000	2.6943	0.0000	0.0000	2.9222	0.0000	1.5274	2.7295	1.8383
Site 6	0.0000	0.0000	7.2374	6.1902	2.8927	0.0000	5.0001	3.7545	7.0275	3.7510
Site 7	0.0000	5.9791	0.0000	5.4140	0.0000	6.6563	0.0000	3.9905	6.3503	4.0520
Site 8	0.0000	0.0000	0.0000	0.0000	5.1589	8.5410	7.2066	0.0000	7.9145	0.0000
Site 9	0.0000	0.0000	0.0000	0.0000	7.6126	9.8489	8.2866	6.1854	0.0000	6.5755
Site 10	0.0000	0.0000	0.0000	0.0000	3.5842	6.1615	4.3010	0.0000	7.2561	0.0000

Figure 5.1: Traffic demand matrix at off-peak hour

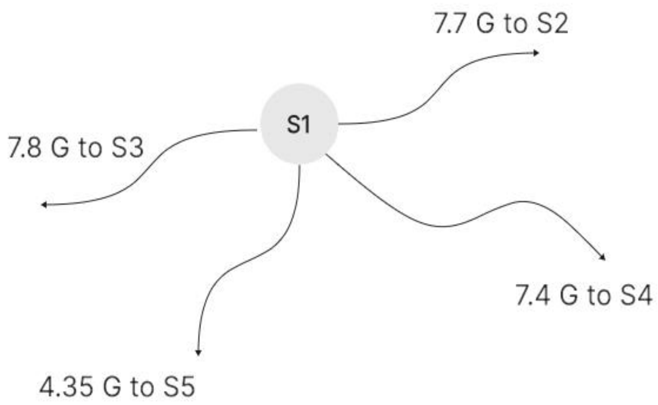

Figure 5.2: Traffic flow of Site 1

As it is shown in the figure, S1 has traffic demands toward S2,S3,S4 and S5. From those demands, the demand to S3,S4 and S5 will be groomed togather. To do so the traffic toward S3(7.8G),S4(7.4G) and S5(4.35G) will be aggregated togather. The ODU levels for each of those traffic demand is ODU-2. Now in order for all of the traffics aggregate togather, three ODU-2 level can be aggregated to a single ODU-3 and then OTU-3. This can be transported using single fiber .

Traffic Mapping from Site 3 to Site S5

Based on our grooming and non - grooming site selection, S3 will be back-hauled to S5. So that every traffic flow to and from S3 will be analyzed and will be first assigned to ODU containers and then assigned to OTU containers by encapsulating FEC with it. As we can see from the figure the traffic flows from S1,S2,S5 and S6 to S6 are 7.4G,6.94G,7.7G and 4G respectively. Each of the traffic flow can be contained with in ODU-2 since the the traffics are below 10Gbps. To aggregate the those traffic we need to map them to ODU-3 which is capable of 40Gbps.

Traffic Mapping from Site 6 to S5

Site 6 have seven links with seven backbone nodes. Consequently, it will be difficult to map all of its traffic to site 5 only. Some of its traffic should be back-hauled to another grooming site. Since two sites S5 and S7 are convenient for S6, some of the traffic will be groomed to S5 and some to S7. Let us now see the mapping of the traffic. The traffic flow from S3 (7.2G), S8 (3.8G), S9(7G) aggregated to site 5. The traffic flow from S4(6.2G) and S10(3.8G) will be groomed to S7. Traffic flow from site 3,8 and 9 will be encapsulated in ODU-2 level individually, then to ODU-3 which will then be encapsulated FEC bits to form OTU-3. The same mapping applied to traffics from site 4 and 10 with each contained in ODU-2 and then to a single ODU-3 level to form OTU-3.

5.3 Traffic Mapping for Semi-Mesh Topology Under Moderate Traffic Load

Traffic Mapping from Site 1 to Site 5

At moderate traffic load the traffic flow S2,S3,S4 and S5 are 19.71G,34.47G,8.91G and 22.82G respectively. The traffic from S3,S4 and S5 are aggregated togather using single

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
S1	0.00	19.71	34.47	8.91	22.82	0.00	0.00	0.00	0.00	0.00
S2	33.56	0.00	23.50	10.55	0.00	0.00	15.49	0.00	0.00	0.00
S3	37.20	14.90	0.00	0.00	13.42	18.67	0.00	0.00	0.00	0.00
S4	22.35	15.55	0.00	0.00	0.00	21.69	22.81	0.00	0.00	0.00
S5	12.01	0.00	6.55	0.00	0.00	24.55	0.00	4.50	6.99	1.63
S6	0.00	0.00	11.49	5.74	30.96	0.00	11.95	7.42	14.14	5.29
S7	0.00	12.61	0.00	12.60	0.00	24.96	0.00	6.52	14.99	8.62
S8	0.00	0.00	0.00	0.00	11.28	14.75	6.20	0.00	19.43	0.00
S9	0.00	0.00	0.00	0.00	16.15	25.93	13.16	17.94	0.00	11.82
S10	0.00	0.00	0.00	0.00	6.45	16.58	12.96	0.00	20.24	0.00

Figure 5.3: Traffic demand matrix at moderate traffic

OTU level. The traffic from S3 (34.47G) is mapped to ODU-3 and then to OTU-3. The traffic from S4 (8.91G) is contained in ODU-2 and then mapped to OTU-2. The traffic flow toward S5(22.82G) can be mapped into two different way. one is to use a single ODU-3 container and map it to OTU-3 or to use three ODU-2 containers and then mapped to three OTU-2 containers. The difference is choosing between BW efficiency or simplicity.

Traffic 1	Rate (Gbps)	Mapped ODU	ODU Rate(Gbps)	BW Utilization
1	34.47	ODU3	40.15	86%
2	8.91	ODU2	10.3	89%
3	22.82	ODU2(3)	30.09	76%

Table 5.2: Mapping traffic to standard ODU levels (S1 to S5)

ODU Type	ODU Rate(Gbps)	OTU Mapping	Utilization
ODU3	40.15	OTU4	86 % ODU3
3×ODU2	30.09 (3×10.03)	OTU4	76 % ODU2 (wastes 7.27 Gbps)
ODU2	10.03	OTU4	89 % ODU2
—	80.27 Gbps	OTU4 (111.80 Gbps)	24.52 Gbps unused in ODU4

Table 5.3: ODU and OTU mapping of Site 1 to Site 5

Traffic Mapping from Site 3 to Site 5

The traffics from S1,S5 and S6 are aggregated together and used a single link to site 5. The traffic to S1(37.2G) is contained in ODU-3 container and then mapped to OTU-3. The traffic from to S5 (grooming node it self), could be mapped using two methods. One is to use single ODU-3 container and mapp the ODU-3 to OTU-3 directly. The second method is to use two ODU-2 containers and map it to OTU-4 with other traffics using Generic Mapping Procedure (GMP). The difference between the two methods is that, The first is suitable for simple mapping and the second for efficiency of utilization. In this research the second method is used since efficiency in resource utilization is the objective. The traffic to S6 is contained into two ODU-2 containers and then mapped to OTU-4.

Traffic 288	Rate (Gbps)	Mapped ODU	ODU Rate(Gbps)	BW Utilization
1	37.2	ODU3	40.15	92.7%
2	13.42	ODU2(2)	20.06	66.9%
3	18.67	ODU2(2)	20.06	93.1%

Table 5.4: Mapping traffic to standard ODU levels (S3 to S5)

ODU Type	ODU Rate(Gbps)	OTU Mapping	Utilization
ODU3	40.15	OTU4	92.7 %
2×ODU2	20.06 (2×10.03)	OTU4	93.1%
2×ODU2	20.06 (2×10.03)	OTU4	66.9%
—	80.27 Gbps	OTU4 (111.80 Gbps)	24.52 Gbps unused in ODU4

Table 5.5: ODU and OTU mapping of Site 3 to Site 5

As we can see from the above table, the ODU and OTU levels can still contain another traffic volume which can be used for scalability purpose.

Traffic Mapping from Site 6 to Site 5

The traffic flow of site 6 include traffics to S3,S4,S5,S7,S8,S9 and S10. This site has lots of incident links, so that some traffics should be groomed to S5 and some to S6. The traffics to S3(11.49G), S5(30.96G),S8(7.42G) and S9(14.14) are groomed together to S5. The mapping of the traffics is as follows.

Traffic 1	Rate (Gbps)	Mapped ODU	ODU Rate(Gbps)	BW Utilization
1	11.49	ODU2(2)	20.06	57.3%
2	30.96	ODU3	40.12	77.2%
3	7.42	ODU2	10.03	74%
4	14.14	ODU2(2)	20.06	70.5%

Table 5.6: Mapping traffic to standard ODU levels (S6 to S5)

.

ODU Type	ODU Rate(Gbps)	OTU Mapping	Utilization
2×ODU2	20.07	OTU4	57.3 %
1×ODU3	40.32	OTU4	77.2 %
1×ODU2	10.03	OTU4	74%
2×ODU2	20.07	OTU4	70.5%

Table 5.7: ODU and OTU mapping of Site 6 to Site 5

From \ To	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
Site 1	0.00	35.01	35.55	34.58	20.87	0.00	0.00	0.00	0.00	0.00
Site 2	31.52	0.00	30.99	30.14	0.00	0.00	29.34	0.00	0.00	0.00
Site 3	34.83	33.72	0.00	0.00	20.10	35.24	0.00	0.00	0.00	0.00
Site 4	30.81	29.83	0.00	0.00	0.00	31.18	28.68	0.00	0.00	0.00
Site 5	14.48	0.00	14.23	0.00	0.00	14.65	0.00	6.00	14.39	8.98
Site 6	0.00	0.00	22.89	22.27	13.44	0.00	21.68	9.65	23.14	14.44
Site 7	0.00	22.88	0.00	22.59	0.00	23.91	0.00	9.79	23.48	14.65
Site 8	0.00	0.00	0.00	0.00	8.58	15.04	13.83	0.00	14.77	0.00
Site 9	0.00	0.00	0.00	0.00	20.33	35.65	32.80	14.60	0.00	21.85
Site 10	0.00	0.00	0.00	0.00	12.83	22.50	20.70	0.00	22.10	0.00

Figure 5.4: Traffic demand matrix at peak hour

Source ⇔ Groom	Demand (Source→Groom)	Demand (Groom→Source)	Total Demand (Gbps)
1 ⇔ 5	4.3518	2.8083	7.1601
3 ⇔ 5	3.9647	2.6943	6.6590
6 ⇔ 5	2.8927	2.9222	5.8149
2 ⇔ 7	6.0381	5.9791	12.0172
4 ⇔ 7	5.6521	5.4140	11.0661
8 ⇔ 9	7.9145	6.1854	14.0999
10 ⇔ 9	7.2561	6.5755	13.8316

Figure 5.5: Traffic demand at off-peak hour

Source ↔ Groom	Demand (S→G)	Demand (G→S)	Total (Gbps)
1 ↔ 5	20.87	14.48	35.35
3 ↔ 5	20.10	14.23	34.33
6 ↔ 5	13.44	14.65	28.09
2 ↔ 7	29.34	22.88	52.22
4 ↔ 7	28.68	22.59	51.27
8 ↔ 9	14.77	14.60	29.37
10 ↔ 9	22.10	21.85	43.95

Figure 5.6: Traffic demand at peak hour

5.4 Latency Calculations of Sites

5.4.1 Latency of Site 3

To demonstrate the latency resulted from the traffic grooming, each latencies introduced in every aggregated links of site 3, are presented here. Site 3 have four incident links in total connecting it to site 1, site 2, site 5 and site 6. All traffics toward site 1, 5 and 6 uses only one link after grooming. The latency before and after the grooming will be discussed below.

Before Grooming

Latency before grooming include the delay due to propagation and processing.

Site 3 to Site 1

$$L = L_{prop} + L_{proc}$$

$$L_w = \sum_{i=1}^{H} \frac{d_i}{v} + \sum_{i=1}^{N} d_{proc,i}$$

$$L_w = (\frac{2.26 \times 10^3 m}{2 \times 10^8 \frac{m}{s}}) + (271\mu s) = 11.3\mu s + 271\mu s = 282.3\mu s$$

The latencies of site 3 for traffics to site 2,5 and 6 are 298.3 µs, 291.5 µs and 293.8 µs respectively.

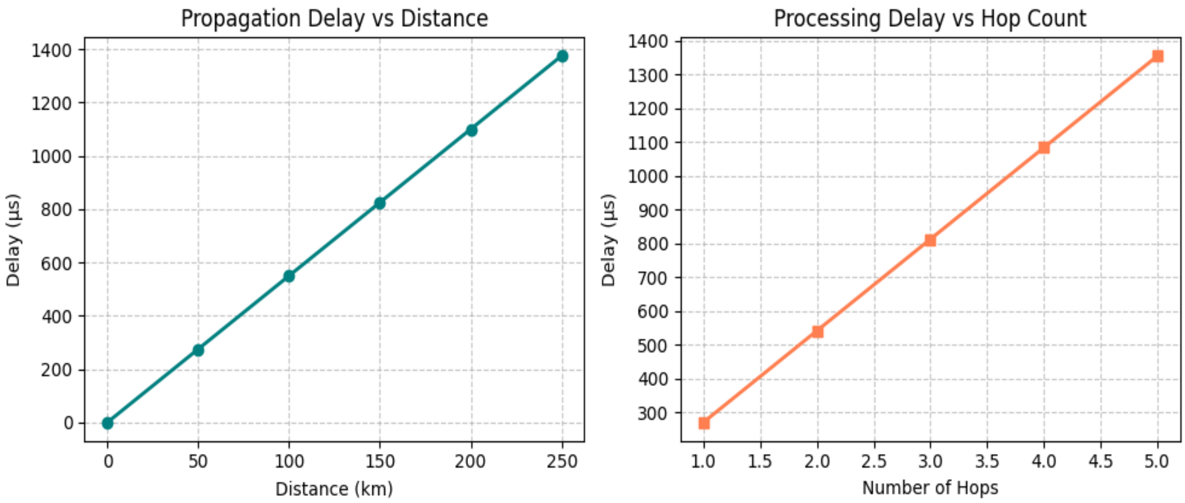

Figure 5.7: Latency vs Hop Count

After Grooming

Since new propagation and processing delays are introduced due to the change in route, the latency of the nodes got increased. Propagation delay is due to the longer paths chosen to aggregate traffics which contributed 5.5 µs for every kilometers. The processing delay elevated as a result of time taken by devices in new routes.

Site 3 to Site 1

$$L_w = (\frac{4.1 \times 10^3 m}{2 \times 10^3 \frac{m}{s}}) + (\frac{2.28 \times 10^3 m}{2 \times 10^3 \frac{m}{s}}) + (542 \mu s)$$

$$20.5 \mu s + 11.4 \mu s + 542 \mu s = 573.9 \mu s$$

Site 3 to Site 2

$$L_w = (\frac{4.1 \times 10^3 m}{2 \times 10^3 \frac{m}{s}}) + (\frac{1.13 \times 10^3 m}{2 \times 10^3 \frac{m}{s}}) + (\frac{4.18 \times 10^3 m}{2 \times 10^3 \frac{m}{s}}) + \frac{7.84 \times 10^3 m}{2 \times 10^3 \frac{m}{s}}) + \frac{11.9 \times 10^3 m}{2 \times 10^3 \frac{m}{s}}) + (813 \mu s)$$

$$20.5 \mu s + 5.65 \mu s + 20.9 \mu s + 39.2 \mu s + 59.5 \mu s + 1355 \mu s = 1500.75 \mu s = 1.5 ms$$

Latencies introduced b/n Site 3 and S1,S2,S5 and S6 after the traffic grooming are 573.9 µs, 1.5 ms, 20.5 µs and 568.15 µs respectively. The latency difference is resulted from the new routes chosen after traffic grooming.

5.5 Blocking Probability

Blocking probability occurs when incoming traffic exceeds the network's available resources. In this research, blocking probability arose from the traffic grooming process, which involved switching off some resources for conservation purposes. As traffic demand increases, the available resources may become insufficient for processing and transporting the traffic, leading to blocked incoming requests. The following section examines how blocking probability increased from midnight to midday and during peak hours, reflecting changes in traffic demand throughout the day."

Blocking Probability of site 1 before grooming

To evaluate the blocking probability, Erlang B formula is used in this research. The computational values of blocking probabilities during different traffic loads is illustrated as follows.

$$Pb_{A,n} = \frac{\frac{A^n}{n!}}{\sum_{k=0}^{n} \frac{A^k}{k!}}$$

Traffic Load (Gbps)	Offered Load (Erl)	Pb (Before grooming)	Pb (After grooming)
Site 1 - Site 2 (7.61)	0.07610	0.0001 %	0.2684 %
Site 1 - Site 3 (7.79)	0.07790	0.0001 %	0.2807 %
Site 1 - Site 4 (7.34)	0.07340	0.0001 %	0.2503 %
Site 1 - Site 5 (4.35)	0.043350	0 %	0.0906 %

Table 5.8: Blocking probability of S1 at low traffic

In the above table it is shown that the blocking probability of site 1 before and after grooming is low. This is because there is very low traffic during that time of the day and the resources available before and after the grooming are sufficient for the traffic demand and less amount of traffic will be blocked.

Traffic Load (Gbps)	Offered Load (Erl)	Pb (Before grooming)	Pb (After grooming)
Site 1 - Site 2 (19.71)	0.19710	0.0052 %	1.5967 %
Site 1 - Site 3 (34.47)	0.34470	0.0417 %	4.2311 %
Site 1 - Site 4 (8.91)	0.08910	0.0002 %	0.3631 %
Site 1 - Site 5 (22.82)	0.22820	0.0090 %	2.0760 %

Table 5.9: Blocking probability of S1 at moderate traffic

The above table illustrated that traffic grooming in moderate level of traffic demand, will result in higher blocking probabilities. The table shows the blocking probability of the site both before and after traffic grooming. The Blocking probability before grooming is quite low, while after grooming, it falls within an acceptable range.

Traffic Load (Gbps)	Offered Load (Erl)	Pb (Before grooming)	Pb (After grooming)
Site 1 - Site 2 (35.01)	0.35010	0.2920%	4.3422%
Site 1 - Site 3 (35.55)	0.35550	0.3112 %	4.4541 %
Site 1 - Site 4 (34.58)	0.34580	0.2813%	4.2536 %
Site 1 - Site 5 (20.87)	0.20870	0.0547 %	1.7699 %

Table 5.10: Blocking probability of S1 at peak hour

The above table illustrated that traffic grooming during peak hours may not only result in congestion but also blocking of traffic.

Below are snippets of the results from the optimization problem. The conflicting nature of power and latency is illustrated as follows. The first figure shows the power consumption of site 3 before grooming at off-peak and peak hours.

The second is shows that if the priority is fully dedicated to conserve power, then the latency is elevated as number of hops increased.

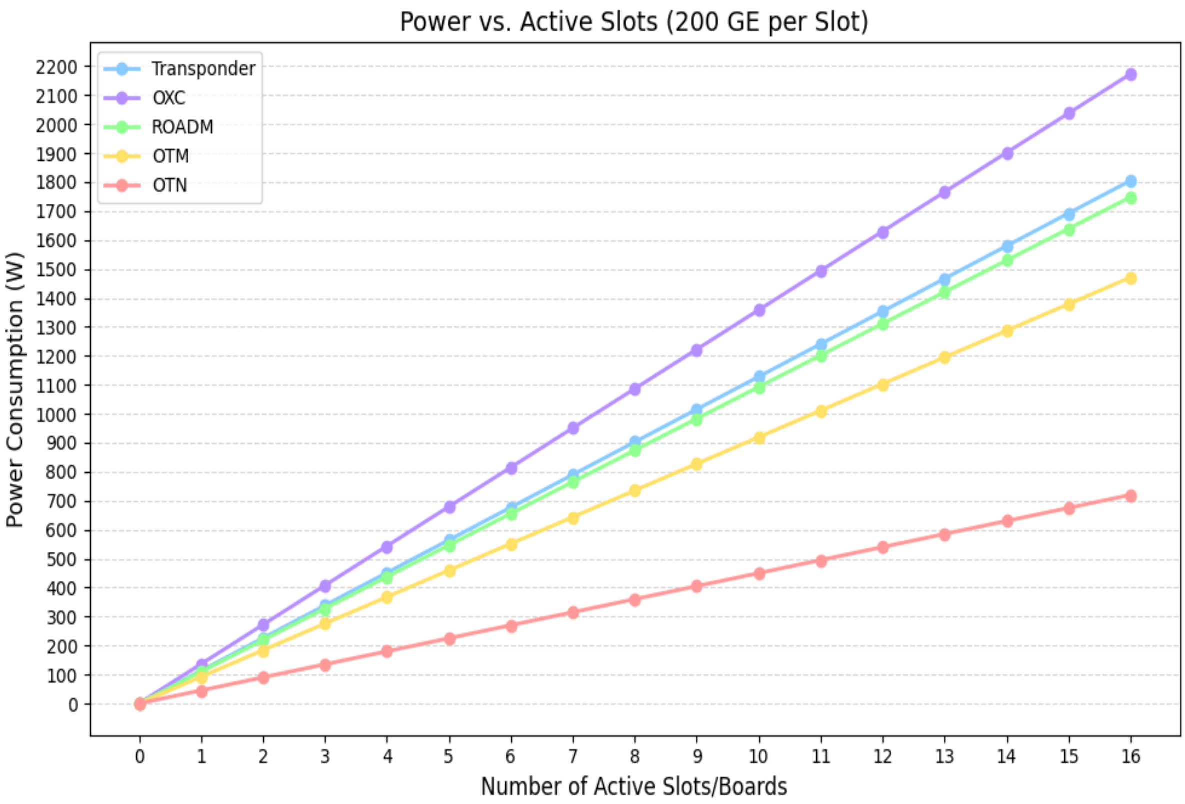

Figure 5.8: Power vs Wavelength/slot

The last figure shows the result when the weight of power is 0.7 and the weight of latency is 0.3.

To quantitatively compare the effectiveness of the model with its three conflicting parameters, Different configuration should be used. Among those configuration, three of them are presented here.

Weight Configuration (1, 0, 0)

The weight of power is 1 and the weights of latency and blocking probability are 0. This configuration focuses on purely minimizing energy consumption. It can be called aggressive optimization since it did not consider latency and blocking probability of the

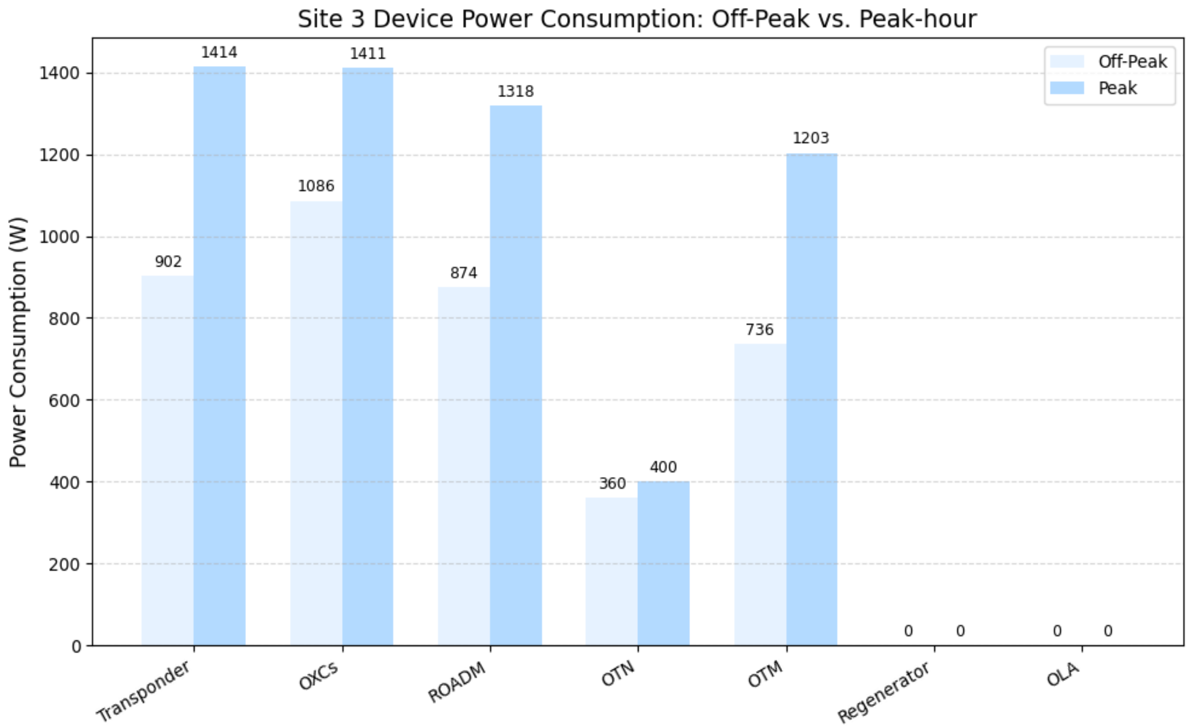

Figure 5.9: Power Consumption of Site 3 before grooming

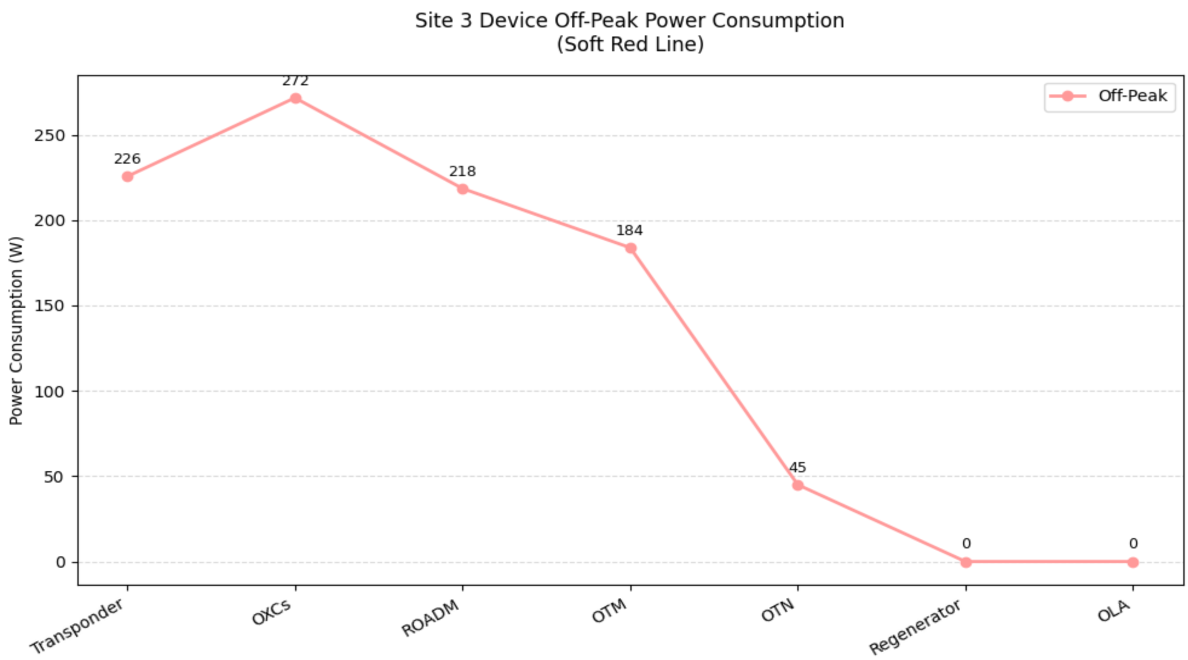

Figure 5.10: Power Consumption of Site 3 after grooming

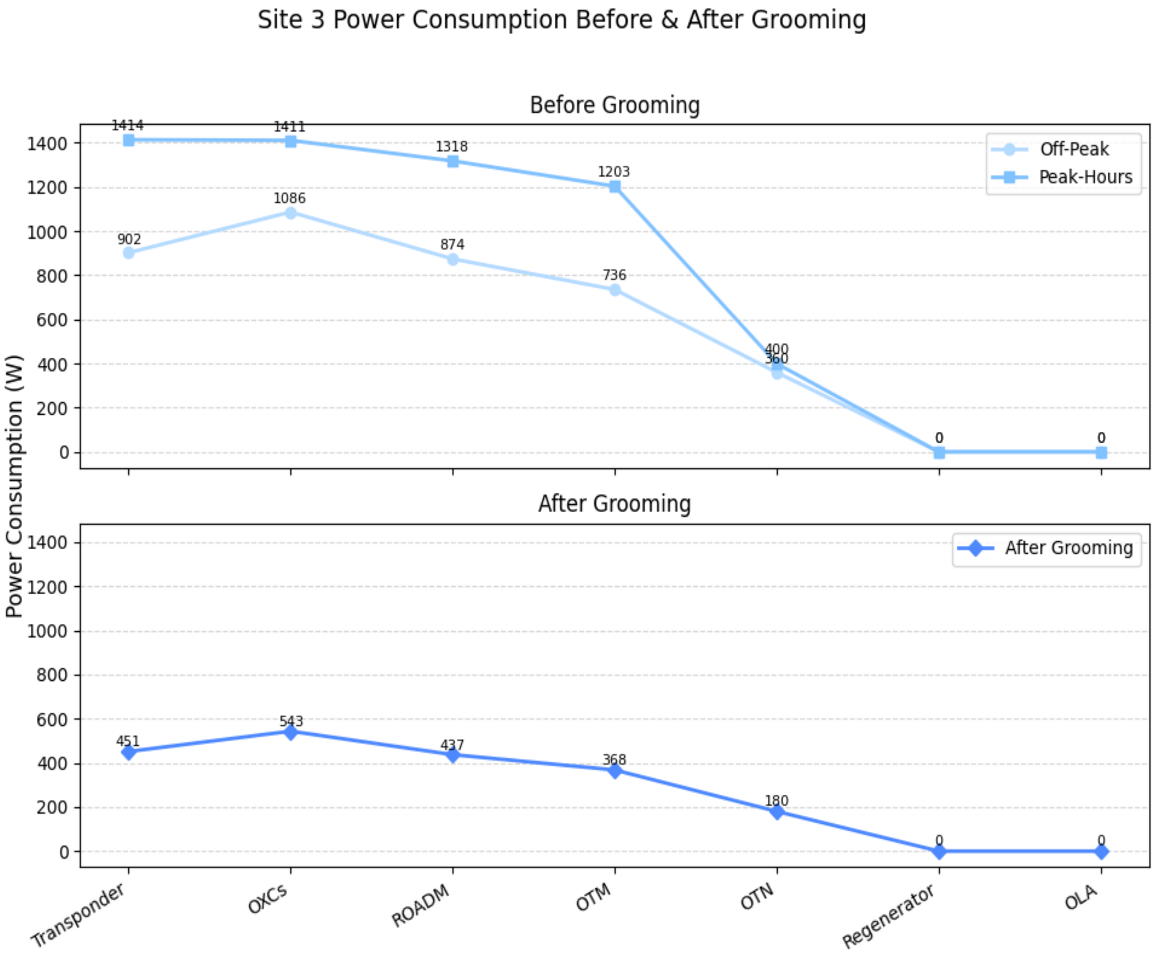

Figure 5.11: Power Consumption of Site 3 after grooming (latency considered)

proposed algorithm. The energy reduction is around 75% from baseline across each generation of the result. Latency increased by double and blocking probability could reach 4% and above.

Weight Configuration (0.7, 0.15, 0.15)

The weight of power is 0.7 and the weights of latency and blocking probability are 0.15. This configuration balances energy reduction with QoS constraints. It do have a

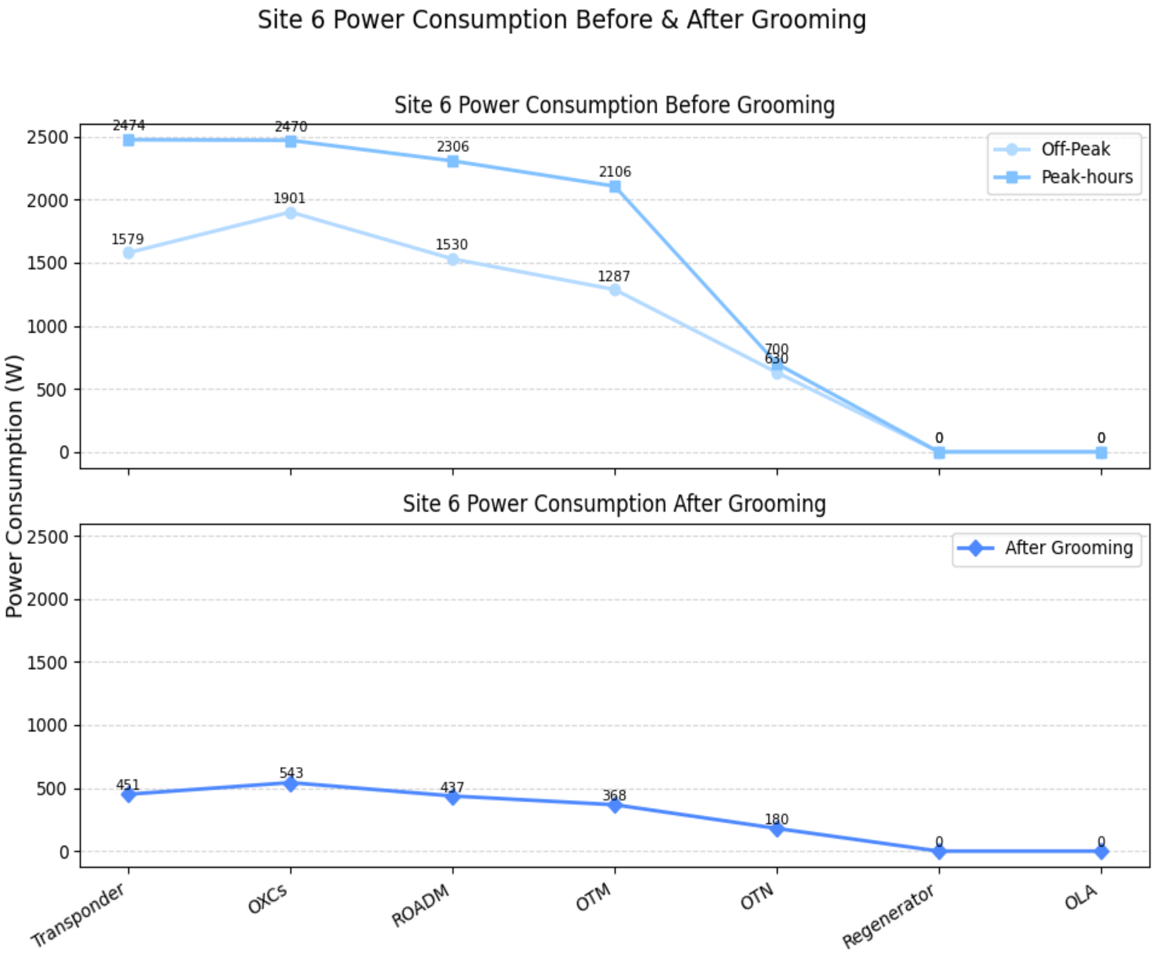

Figure 5.12: Power Consumption of Site 6 after grooming

relatively lower energy reduction (energy is prioritized but not exclusive). The energy reduction is above 60 % from the base line. Latency is under control which is less that less than 1 ms. And also the blocking probability maintained below 4 percent.

Weight Configuration (0.34, 0.33, 0.33)

The weight of energy is 0.34 and the weights of latency and blocking probability is 0.33. This configuration balance out the three conflicting parameter with through its equal

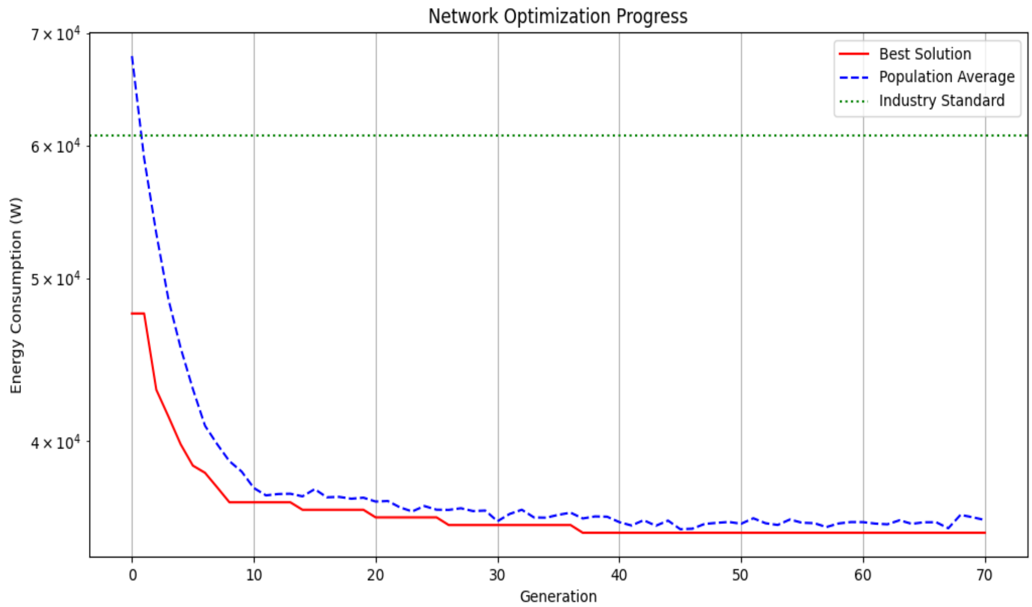

Figure 5.13: Model result with Weight Configuration (1, 0, 0)

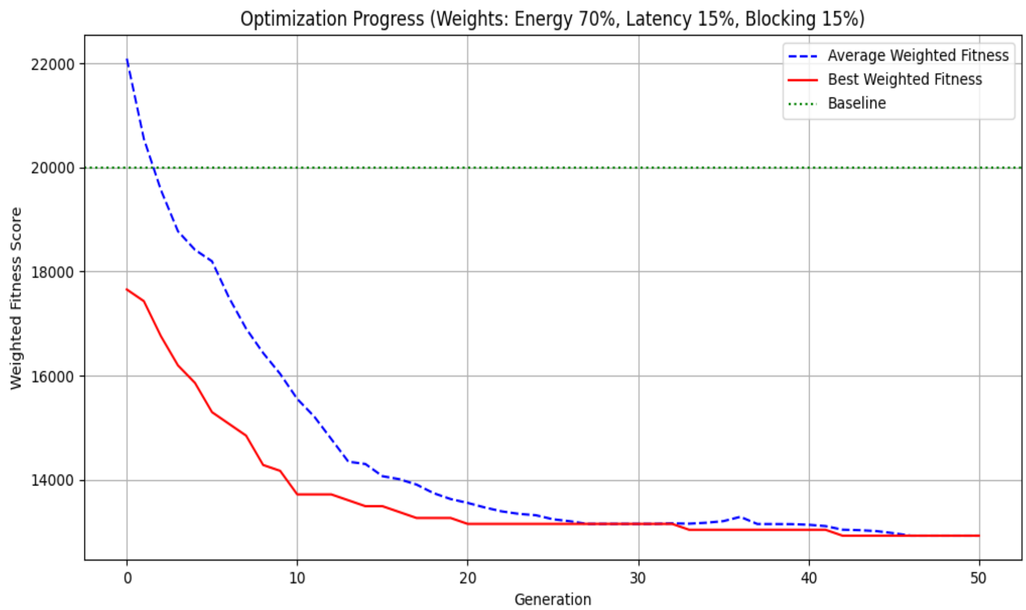

Figure 5.14: Model result with Weight Configuration (0.7, 0.15, 0.15)

weight. The power reduction percentage is less compared to the other two configurations. This configuration attains up to 25 percent power reduction with very minimal latency and blocking probability.

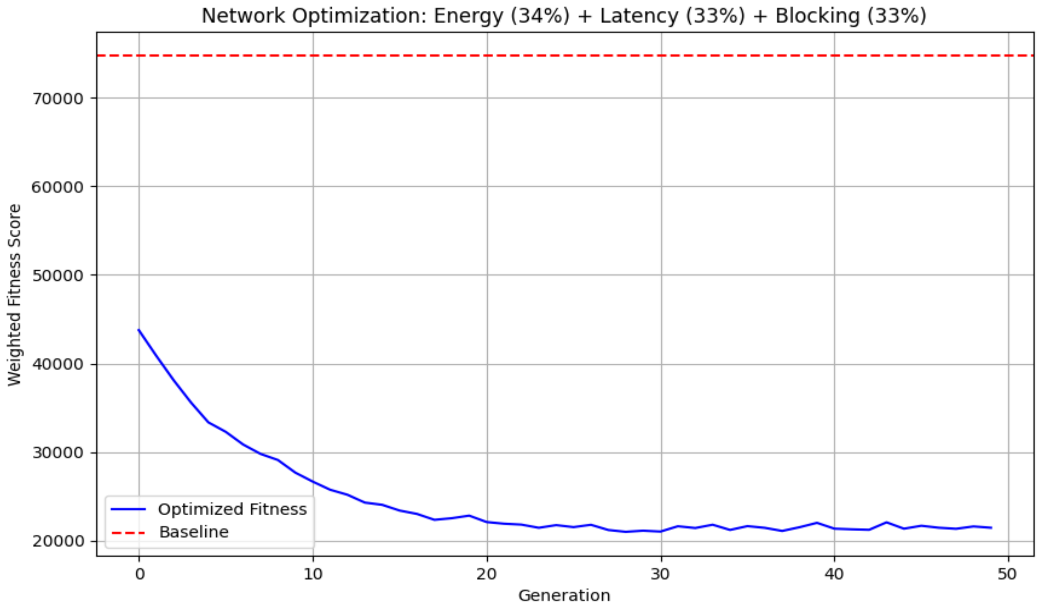

Figure 5.15: Model result with Weight Configuration (0.34, 0.33, 0.33)

Weight Configuration (0.5, 0.25, 0.25)

The weight of power is 0.5 and the weight of conflicting parameters is also 0.5 (0.25 for latency and 0.25 for blocking probability). Here as a result of the NSGA-ii, the pareto front has optimal values which means the proposed model have best efficiency at this point.

3D Plot Axes: X: Power (W) Y: Latency (µs) Z: Blocking probability (%)

From the plot in the above we can conclude that optimal solutions lie in the "Green Spotted" with optimal values on all axes. The solutions form a Pareto front – no single solution dominates in all three objectives. The values of power, latency and blocking probability at this point are 1979.04W, 573.9 µs and 0.2745 - 0.3 % respectively.

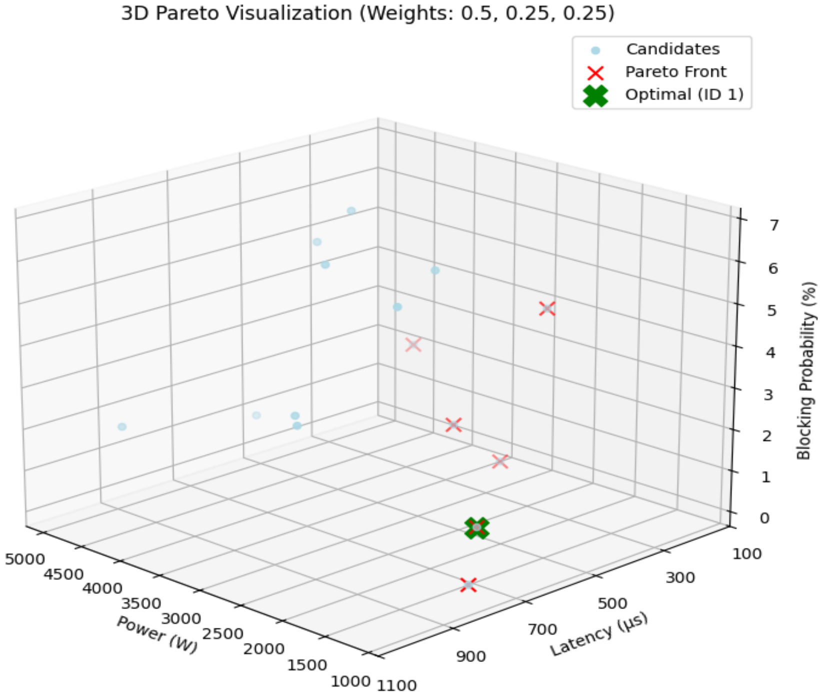

Figure 5.16: 3-D visualization of power, latency and blocking probability

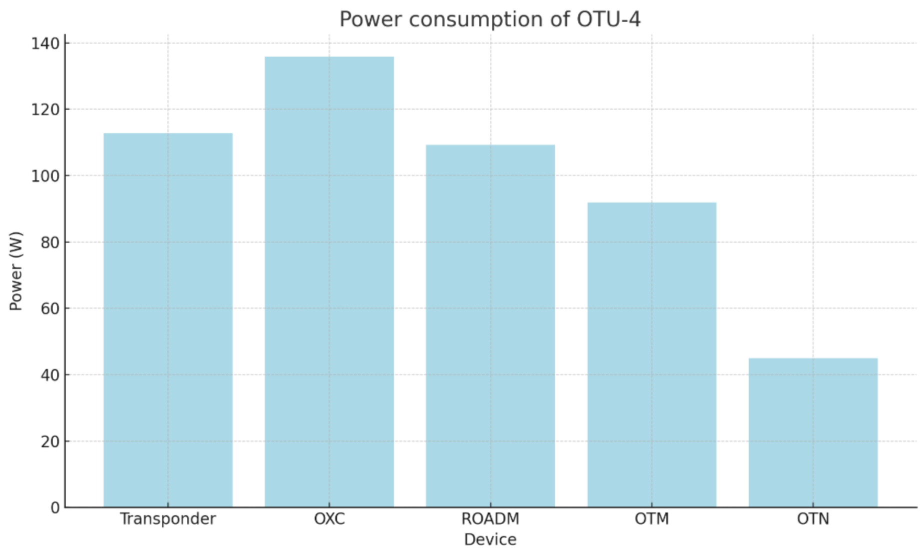

Figure 5.17: Power Consumption vs OTU level

This plot illustrates the relationship between the number of OTU4 slots (100G capacity per slot) and the total power consumption (in kilowatts). The green-shaded region (80–120 slots) represents the sweet spot for balancing capacity and power efficiency. The Optimal Zone (Green Highlight) in the Power vs OTU Allocation plot represents the range of OTU slot configurations that achieve the best balance between power efficiency, capacity, and operational costs in a carrier-grade network.

5.6 Cost

To satisfy the demands of heterogeneous services that have different applications and varied bandwidth requirements, networks have adopted an MLR (Mixed Line Rate) strategy. The legacy 10 Gbit/s transport optical networks have been upgraded to 40 and/or 100 Gbit/s networks [42]. As line capacity increases, the OTN can support larger volumes of traffic, but this comes at the expense of higher power consumption. In an optical backbone network, the monetary cost of power consumption arises directly from the energy drawn by each active device which gets multiplied by the utility's tariff. Each installed active optical device has its own instantaneous power consumption, contributing to the overall total power usage. In electrical-engineering and energy-modeling literature, instantaneous power P(t) is defined as the rate at which a device uses energy at a specific moment in time. In contrast, energy (what we are billed for) is the integral of power over a period of time [43].

$$Cost_{Energy} = \sum_{i \in devices} P_i \times T(h) \times tariff/Kwh$$

The cost calculation for power consumption is determined as described in [44]. It involves multiplying the power consumed by devices over a specified period by the tariff established by the service provider for the respective industrial sector. Based on this concept, the cost of power consumption for the ETC network, both before and after the proposed method, is presented as follows. The power consumption for different sites has been calculated in previous sections, and the tariff set by the Ethiopia Electric Utility for this sector is 4.06 ETB per kW. Let us use power consumption during 1:00 am to 6:00 am which is for five hours of site 3 from semi meshed network. In this research, the power consumption of nodes relays on the given priority for power through its weight in the model. Consequently the cost of the power will also be indirectly depend on the weight given to power. So couples of demonstrations are discussed as follows. The energy cost of a given node on the network before and after grooming is 81.403 ETB and 19.99 ETB, at weight configuration (1,0,0). For another groomed site, the cost of energy drops from 140.611 ETB to 40.17 ETB. This model enables different levels of power conservation for various nodes, leading to a reduction in overall Operating Expenditure (OPEX) .

Another cost reduction can be observed from the perspective of available device cards, resulting from traffic grooming and sleep mode mechanisms. This can be thought as the possibility created for the the network to have scalability to add more traffic demands. This can be seen as an opportunity for the network to scale and accommodate increasing traffic demands. Thus, the need to purchase new network device cards is reduced, resulting in cost savings on Capital Expenditure (CAPEX).

#No	Part Number	Model	Description	List Price (USD)	Our Price		Quote Sheet
1	82601208	NSDSSDHENC06	OptiX OSN 9800-M/9600-M platform SDH encapsulation capability (per board).	$32,058.00		Get Discount	☐
2	88035MUC	TNVSSDH100G01	OSN 9800/9600 Line Card SDH encapsulation capability (per board).	$20,000.00		Get Discount	☐
3	03021QRG	TNV1EFI01	OptiX OSN 9800 TNV1EFI01 EMI Filter Interface Board.	$2,204.00		Get Discount	☐
4	21138097	DKBA41312775	OptiX OSN 9800 blank panel of service board(HUAWEI GRAY).	$9.00		Get Discount	☐

Figure 5.18: Cost of optical card [45]

The cost of cards are actually very expensive for service providers including ETC to purchase it from vendors like huawei. The demonstration of cost of OSN cards is show in the above figure.

Chapter 6: **Conclusions and Future Work**

6.1 Conclusions

This research demonstrates that integrating traffic grooming with sleep mode strategies in optical backbone networks optimize resource utilization and energy efficiency. This done by aggregating low-rate flows and selectively powering down underutilized equipment. Significant reductions in active wavelengths and electronic switching instances lead to meaningful energy savings. It ensured the adaptability of the network to fluctuating traffic demands while maintaining the quality of service. The proposed combined method outperforms traditional single-strategy approaches, offering a scalable solution for the operation of the sustainable backbone network. The following points are summarized as conclusions:

- Over-provisioning of resources to handle bursty traffic in optical backbone networks leads to high resource utilization. To improve resource utilization, it is essential to conduct power and traffic analysis of the network.
- The joint application of grooming and sleep modes optimize energy gains beyond what each technique achieves independently, facilitating up to 70 percent of line cards to be

switched off during off-peak hours and achieving an overall energy reduction of 25 - 75 percent in ETC optical back-bones network. Researches which have been done on the effectiveness of sleep mode shows an average of 30 % of power reduction. Moreover some compromise the Qos of the network as line with small amount of sub-rate traffic might be turned off to reduce power consumption. On the other hand, research on traffic grooming shows up to a maximum of 40 % energy saving when it integrated with some routing policies. The model used in this research demonstrates an average power saving of 50 %, and in some sites using a more aggressive approach savings can reach up to 75 %. Beside the idle link it left after traffic grooming and sleep mode can be used for further scalability of the network.

- By aggregating fine-grained flows into higher-rate trunks, traffic grooming consolidates workloads onto fewer electronic and optical ports, reducing the number of active transponders, ROADMs, and amplifiers needed at any given time .
- Traffic grooming enhances the network's scalability potential by creating capacity for more traffic during low and moderate traffic loads.
- By accounting for latency and blocking probability in this research, it successfully balanced power conservation with quality of service.
- The efficiency of this method in meshed topology is greater than the ring topology. This is due to the fact that the mesh topology has multiple incident links and routes which can be used for grooming.

6.2 Future Work

increasing demand for higher bandwidth and capacity to handle ever-growing traffic, as well as the energy-intensive components within these networks, will result in high resource utilization. Therefore, developing more resource conservation methods is essential to support the telecom sector economically and environmentally. Resource conservation methods can be implemented at both the design and operational levels. Based on the results of this research, future studies can focus on the following aspects:

- Real world traffic fluctuations and prediction errors may impact the optimal timing for switching devices into sleep mode; future work should integrate machine learning-based forecasting to further optimize activation schedules.
- Dynamic traffic grooming site selection can be used instead of using fixed grooming hubs.
- Incorporating a Software Defined Network SDN controller for implementation can simplify the process and monitoring, as it provides access to each device in the network.

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