



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
TELECOMMUNICATION ENGINEERING GRADUATE PROGRAM

**Energy-Aware Resilience Approach for Survivable
Optical Network Design with Dedicated path protection:
a case study of Ethio Telecom**

A Thesis Submitted to the School of Electrical and Computer Engineering of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Telecommunication Network Engineering

By: **Birtukan Gezie**

Advisor: **Dr. Yalemzewd Negash**

December 2021

Addis Ababa, Ethiopia



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
TELECOMMUNICATION ENGINEERING GRADUATE PROGRAM

**Energy-Aware Resilience Approach for Survivable
Optical Network Design with Dedicated path protection:
a case study of Ethio Telecom**

By: **Birtukan Gezie**

Approval by Board of Examiners

Dean, School of Electrical & Computer Engineering

Signature

Committee

Dr. Yalemzewd Negash

Advisor

Signature

Examiner

Signature

Examiner

Signature



Declaration

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

Birtukan Gezie

Name

Signature

Place: Addis Ababa, Ethiopia

Date of Submission: December 2021

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

Dr. Yalemzewd Negash

Advisor's name

Signature



Abstract

Today's optical backbone telecommunication network infrastructures are deployed with redundant resources considering the backup resources for protection to be resilient against link failures and serving a tremendous amount of data transmission. Due to the rapidly increasing traffic demand and the deployed redundant resources, the energy consumption of telecommunication networks is increased. Energy costs contribute significantly to the operational expenditures of telecom network operators and global climate change; energy consumption has become a vital economic interest of network operators today. Recently, the desire for "Green backbone networks" stimulated research efforts to find new solutions to deal with power consumption and sustainability issues.

In this thesis, the energy-efficient resilience approach, which is Energy-Aware Dedicated Path Protection (EADPP) for survivable optical Wavelength Division Multiplexing (WDM) networks, is investigated. The sleep mode and energy-aware routing strategies are taken into account for the energy consumption minimization method with 1:1 dedicated path protection (DPP). The research work proposes and formulated a Mixed Integer Linear Programming (MILP) model to minimize the energy consumption of active network devices while putting idle and redundant backup resources to sleep mode, which takes link utilization and a link disjoint backup path together with other constraints. The proposed model's evaluation is implemented using MATLAB toolbox, taking Ethio telecom Addis Ababa optical backbone network topology as a case study. The result is compared with the energy-unaware model and the other power consumption minimization model. The optimization result shows that the proposed model can achieve up to 35% energy saving.

Additionally, the thesis studied the trade-off between energy consumption and blocking probability and finds the optimal trade-off problems by formulating the multi-objective MILP optimization model. The optimal result shows that it can achieve considerable energy savings with a minor impact on network performance.

Keywords: - Energy-aware, Energy efficient, Resilience, Survivable WDM network, Dedicated Path Protection, QoS, MILP.



Acknowledgment

First and foremost, I would like to express my enormous thankfulness to the Almighty God for everything in my life. My special and priceless thanks go to my thesis advisor Dr. Yalemzewd Negash for his endless support for giving a significant amount of his time to guide my work tirelessly, providing valuable suggestions, and constructive criticism, for the improvement of this thesis. Another gratitude goes to my examiners Dr. Surafel and Dr. Sosina to provide valuable suggestions and constructive criticism for improving this research.

I would like to express heartfelt gratitude to Mr. Mulugeta Mihiret for their valuable and kind support and willingness to provide me with the necessary input for this thesis. I want to extend my gratitude to Ethio telecom for providing me with the opportunity to pursue my M.Sc.

My profound appreciation goes to my spouse Mr. Muluken Zewdie and my lovely daughters (Nablis and Yohanna Muluken) for their encouragement, support, and being key to my life and source of strength. I would like to express my gratitude to all of my beloved family members for their help and concern in achieving this research.

Finally, a great thank you to AAiT, friends, and colleagues for providing the emotional support I needed to finish this thesis work, both directly and indirectly.



Table of Contents

Abstract	i
Acknowledgment.....	ii
Table of Contents	iii
List of Figures	vi
List of Tables.....	vii
Acronyms.....	viii
Chapter 1	1
Introduction	1
1.1 Background.....	1
1.2 Motivation	3
1.3 Problem Statement	4
1.4 Objectives	5
1.4.1 General Objective	5
1.4.2 Specific Objectives	5
1.5 Related Works	6
1.6 Methodology.....	8
1.7 Contribution of the Thesis	8
1.8 Organization of the Thesis	9
Chapter 2.....	10
General Overview of Optical Backbone Networks.....	10
2.1 Introduction	10
2.2 Optical WDM Networks	11
2.3 Network Resilience/Survivability Mechanisms	13
2.4 Network Performance or QoS Parameters	15



Chapter 3	17
Energy-Aware Survivable Optical Network	17
3.1 Network Model.....	17
3.2 Power Consumption Model in Optical Network	17
3.3 Optical Network Power Consumption Analysis.....	20
3.4 Optical Network Power Consumption Minimization Approach	23
3.5 Energy Efficient Resilience Approaches.....	25
3.5.1 Energy-Aware Routing	25
3.5.2 Sleeping Mode	26
3.6 Energy-Aware protection provisioning with sleep mode.....	26
3.7 Network Survivability Challenges Under Energy-Saving Operation	28
Chapter 4.....	30
Problem Formulation	30
4.1 Linear Programming (LP)	30
4.1.1 Integer Linear Programming (ILP)	32
4.1.2 Multi-Commodity Flow Problem	32
4.2 Mathematical Formulation	33
4.2.1 EADPP Model	34
4.2.2 MILP Mathematical Model	34
4.2.3 Problem Formulation for EADPP	36
4.2.4 Trade-off Optimization Problem	39
Chapter 5.....	41
Result and Discussion.....	41
5.1 Experimental Topology and Network Configuration	41
5.2 Optimization Result and Discussion	44
5.2.1 Energy Consumption	45



5.2.2	Link Usage	47
5.2.3	Trade-off: optimization result	49
Chapter 6.....		51
Conclusion and Future Work		51
6.1	Conclusion.....	51
6.2	Future Work.....	52
References.....		53



List of Figures

Figure 1.1: Energy consumption trend of telecommunication networks [5].	2
Figure 2.1: IP over WDM systems [21][39].	11
Figure 3.1: Comparison of an energy-aware and an energy-unaware routing with 1:1 DPP.	27
Figure 4.1: Nomenclature in linear programming problem [45].	31
Figure 5.1: AA Optical Backbone network topology.	42
Figure 5.2: Total Energy Consumption Vs. Connection Request for the AA backbone network.	45
Figure 5.3: Total number of links whose devices are set active and sleep mode for a different connection request.	47
Figure 5.4: Optimization of AA Optical Backbone network topology with turn-off links.	48
Figure 5.5: Energy consumption Vs. Blocking probability at 40 Gbit connection request.	50



List of Tables

Table 3.1: Power consumption in different modes [13] [17].	19
Table 3.2: ROADM site device Power Consumption (PC) [33] [39].....	21
Table 5.1: Sample network traffic demand matrix.....	43
Table 5.2: The value of power model parameters.....	44



Acronyms

DPP	Dedicated Path Protection
EA-AR	Energy-Aware- Adaptive Routing
EADPP	Energy-Aware Dedicated Path Protection
EASPP	Energy-Aware Shared Path Protection
EAR	Energy-Aware Routing
EA-TE	Energy-Aware – Traffic Engineering
EDFA	Erbium-Doped Fiber Amplifier
GHG	Green House Gas
GMPL	GNU Mathematical Programming Language
GMPLS	Generalized Multi Packet Label Switching
HLD	High Level Design
ICT	Information Communication Technology
ILP	Integer Linear Programming
IP	Internet Protocol
LLD	Low Level Design
LP	Linear Programming
MCF	Multi-Commodity Flow
MILP	Mixed Integer Linear Programming
MPLS	Multi Packet Label Switching
MTBF	Mean Time Before Failure
MTTR	Mean Time to Repair
OADM _s	Optical Add/Drop Multiplexers
O/E/O	Optical-Electrical-Optical conversion
OLA	Optical Line Amplifier
OTM	Optical Transmission Module



OTN	Optical Transport Network
OXC	Optical Cross-Connect
PA	Power-Aware
PA-RWA	Power-Aware - Routing and Wavelength Assignment
QoS	Quality of Service
RWA	Routing and Wavelength Assignment
SPP	Shared Path Protection
TE	Traffic Engineering
WDM	Wavelength Division Multiplexing



Chapter 1

Introduction

1.1 Background

In recent years, there has been a rise in concern about energy consumption. The Information and Communication Technology (ICT) sector's energy consumption is rising very fast, mainly as a consequence of a rapidly growing number of devices and the development of the latest (new) applications, resulting in a rapidly increasing network traffic [1]. Information and Communication Technology (ICT) plays a fundamental role in increasing energy consumption. However, ICT itself is responsible for a significant share of global energy consumption. For instance, telecommunication networks are estimated to be responsible for around 3% of the global CO₂ emissions or the worldwide energy consumption [2].

According to the global connectivity via massive networks and explosive growth of communication technologies, the high bit-rate services (like video-streaming, cloud computing, and so on) and the information exchange through the Internet have been highly increased [3]. It implies that high bandwidth-consuming applications will be expanded. New network technologies and infrastructures needed to be developed to keep up with the sustained growth of data traffic. Due to this, the traffic volume of broadband telecom networks is increasing, as are network capacity expansion, both of which significantly increase operational expenditure (OpEx) and the greenhouse gas emission to the environment. Energy efficiency does not improve with newly designed network equipment; it is predicted that energy consumption will be one of the critical constraints for network operators [4].

The following Figure 1.1 shows the energy consumption growth of telecommunication networks and its trend. The energy demand is forecasted until 2020 with respect to the reference for 2011.

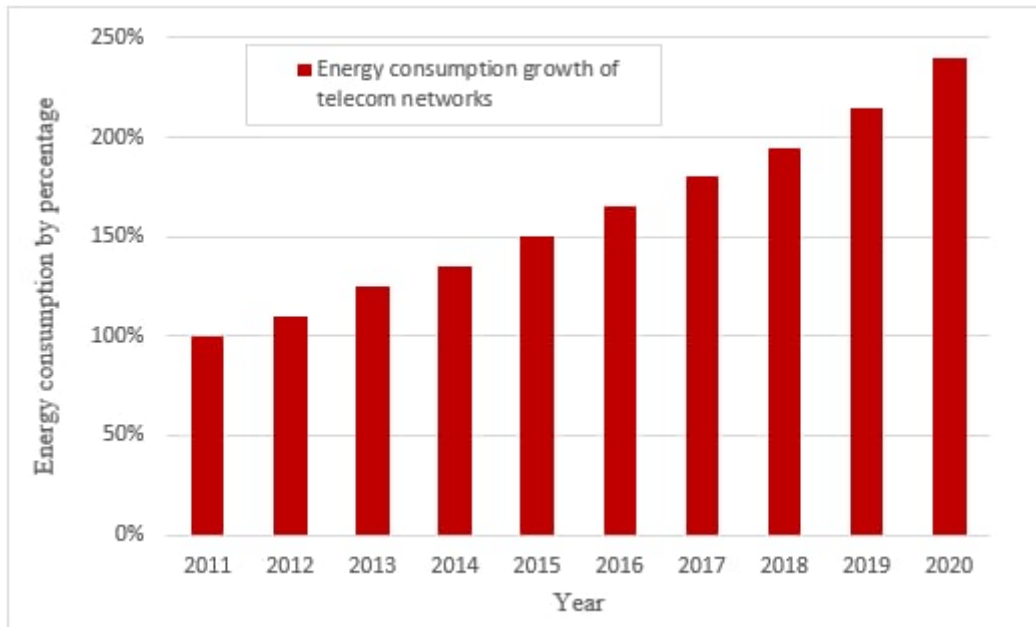


Figure 1.1: Energy consumption trend of telecommunication networks [5].

In order to avoid an explosion of the energy consumption of telecom networks, traffic needs to be transported through the network with more power-efficient techniques and at reasonable costs. Optical communication networks based on wavelength division multiplexing (WDM) provide massive transmission capacity. That is used to carry a vast amount of data which is expected to solve many problems in the next-generation Internet network infrastructure [6] and play an essential role in reducing the power consumption of Telecom networks [7].

In an effort to reduce the power consumption of communication networks, WDM technology is recognized as a power-efficient choice [8] compared to its power-hungry electronic-based IP network counterpart. As a result, in order to achieve further improvements, energy efficiency in the optical layer has gotten a lot of attention, and a wide range of related topics are addressed in the literature.

The contribution of the backbone network to total network power consumption is increasing rapidly in line with traffic growth [9]. Optical backbone networks Energy consumption was increasing because of the exponential growth of bandwidth demands and increased availability to ensure the protection of high-capacity optical networks [10] [17].



The energy efficiency of optical networks and new energy-aware systems can be achieved through design solutions and optimization techniques. Different studies have been conducted on optical networks to improve energy efficiency using energy-saving approaches from a service provider's perspective. The first is the design approach, which includes changing the network architecture, traffic grooming, and topology optimization. The operational strategy includes sleep mode operation, energy-aware routing, energy-aware resilience, and dynamic operation [11] is the second approach.

This thesis investigated the energy-efficient resilience by considering the sleep mode and energy-aware routing strategies is taken into account for the energy consumption minimization method with 1:1 dedicated path protection (DPP); which focuses on evaluating and proposing Energy-aware dedicated path protection (EADPP) considering the Ethio telecom Addis Ababa optical backbone network topology.

1.2 Motivation

Reducing the power consumption of optical backbone networks has been a crucial part of networking research. Today's optical backbone networks are designed and operated to carry the most traffic most reliably without considerations of energy efficiency. A network usually builds many redundant links, and the backbone network's capacity is an over-provisioned link to accommodate potential link failures and traffic bursts. While these redundant links and bandwidth significantly improve the network reliability, they also greatly degrade the network's energy efficiency because all network devices are active or turned on at maximum capacity but highly under-utilized most of the time. Although the state-of-the-art reliability mechanisms are very efficient in ensuring high network availability, the impact of protection resources on the network's energy consumption is not considered. According to the rule of thumb, the average link utilization in backbone networks is 40% or less in their capacity [12].



1.3 Problem Statement

The energy consumption of the Optical backbone network is increasing due to the increase in availability requirements to ensure the protection of the ultra-high capacity optical channels provided by survivable optical WDM networks and the deployment of overprovisioned idle network devices. Most of the deployed optical transport network (OTN)/WDM network supports protection and restoration schemes used to implement network survivability. Survivability to device failures is a fundamental requirement in WDM optical networks. Survivability is achieved by deploying/reserving redundant (protection) resources that will only be needed to restore the affected connections in the case of a failure. The protection paths comprise up to one-third of the links available with some protection mechanisms. Most of the time, these links are idle unless a failure occurs; on the other hand, such resources are typically maintained active, independently of the failure pattern, and thus consume a considerable amount of power even when unutilized. Because of the high path redundancy and low link utilization, the network can be designed to be both energy-efficient and resilient.

The previous energy-aware approaches only consider the power minimization at protection devices, but when a low connection request (low traffic demands) the idle network devices or lightly loaded links are not efficiently utilized. Due to this, the telecom operators are subjected to high power consumption in network survivability (protection mechanism) and idle network devices at low traffic demands. Furthermore, one way to save energy in optical networks is to reduce the number of active network devices by aggregating the light paths on the lowest possible number of active links. This intuition is useful in terms of energy saving. Still, on the other hand, it may have an impact on the network performance, so there is always a trade-off problem between energy efficiency and network survivability in optical networks. The question originating from the problems mentioned above is how to minimize the power consumption of redundant backup devices and idle network elements at lightly loaded traffic demands, and how to improve both the network energy efficiency and network resiliency. The difficulty of developing survivable networks with energy efficiency is explored in light of the trade-off between network resiliency and energy efficiency. So, we must apply the best knowledge of power consumption minimization using Energy-aware protection mechanisms. This research work will address essential solutions



for fulfilling requirements of better energy efficient and survivable networks by proposing an energy-aware resilience approach considering network performance like blocking probability and link utilization of the network.

1.4 Objectives

1.4.1 General Objective

The main objective of this thesis is to propose an Energy-Aware Resilience approach to investigate power consumption minimization and study the trade-off problem between energy-saving and network resilience in optical networks. The analysis of this approach on the operation of an entire network will be assessed, taking the Ethio telecom's optical backbone network topology as a case study.

1.4.2 Specific Objectives

The thesis also has the following specific objectives:

- To analyze the power consumption of optical backbone networks. The analysis includes the power consumption of the entire network segment, node, link, and each component considering the equipment deployed at Ethio telecom optical backbone network.
- To formulate and model the optimization problem, i.e., the power consumption of optical networks.
- To study the trade-off problems between Energy efficiency & network Resiliency and analyze the impact of energy consumption minimization on the network performance.
- Propose the Energy-Aware Dedicated Path Protection (EADPP) approach, which considers network performance in optical networks regarding link utilization and blocking probability.
- To evaluate the performance of the proposed approach.



1.5 Related Works

Some of the existing literature for Energy-Aware approaches focusing on resilience may come in place to reduce the power that is consumed with current protection schemes. The majority of these solutions aim to save energy by concentrating backup paths in separate fibers, and devices on these links can be set into sleep mode without being constrained by the presence of working paths.

The authors in [13] presented an energy-efficient planning strategy for survivable WDM networks and proposed ILP formulation. They suggest putting devices used for network protection, such as optical switches, into sleep mode. When the active network devices failed, it was expected that they could be turned on immediately. The author achieved 25% of power-saving that devices for network protection are set into sleep mode. Similarly, the authors in [14] studied the energy-efficient design of survivable WDM networks using shared backup resources considering both energy efficiency and network survivability. The paper focused on energy-efficient survivable network design where backup resources are shared for efficient capacity consumption. ILP model for energy-efficient shared backup protection is proposed to minimize both capital and operational expenditures and enable the sleep mode operation for the links associated only with the backup paths. And also can be achieved up to 40% energy savings compared to the energy-unaware shared backup protection approach. Both the research works on the above only considered energy-saving without considering the network performance.

Research paper [15] studied the Energy-aware survivable Routing approach for Next Generation Network design. The authors proposed three energy-aware survivable routing algorithms: Energy-Aware 1+1 Backup Protection (EABP 1+1), Energy-Aware 1:1 Backup Protection (EABP 1:1), and Energy-Aware Shared Backup Protection (EASBP), which considered energy reduction and take network survivability. They developed an ILP formulation for the three energy-aware models to address the trade-off problem between energy efficiency and network survivability. Finally, the authors compared the performance of three routing algorithms by simulating the models using two network topologies. EABP 1:1 is the most energy-efficient model and could save 90% of energy costs. EASBP could be the most effective way to address the trade-off between energy efficiency and network survivability.



The authors in [18] proposed MILP models for obtaining optimum solutions under various objectives and analyzed the trade-off between capacity and power consumption of different survivability schemes. Due to the packing of primary paths, power minimization hurts sharing capability in Shared Backup Protection (SBP) and capacity consumption in both Dedicated Path Protection (DPP) and SBP. A novel multi-objective model is developed to address this trade-off, and the optimal solution is found for different survivability schemes. The authors proposed a novel energy-efficient algorithm called energy-aware shared path protection (EASPP), addressing the trade-off caused by conflicting green and resilient network planning objectives. The author tested the performance of the EASPP algorithm and observed that a good balance between power and capacity usage can be accomplished by trading a minimal amount of capacity for significant power savings. The above two researchers considered only capacity consumption on the network performance metrics.

Energy efficiency in protected WDM networks has also been studied under dynamic traffic conditions [17]. The study focused on the power consumption of survivable WDM networks with 1:1 dedicated path protection (1:1 DPP) and the traffic is rerouting using a predefined and already reserved secondary path in the case of failures. The authors proposed different energy-aware dedicated path algorithms, i.e., energy-aware dedicated path protection (EA-DPP), energy-aware dedicated path protection with differentiation of primary and secondary paths (EA-DPP-Dif), and energy-aware dedicated path protection with mixing secondary with primary paths (EA-DPP-MixS), and discussed the trade-off between energy-saving and blocking probability. Finally, the proposed sleep-aware algorithms are compared with another energy-aware connection provisioning algorithm; the power consumption reduction of up to 25% can be achieved by setting protection resources in a sleep mode.

The authors in [18], study the energy efficiency of protected IP-over-WDM networks by comparing four different protection strategies, such as Shared-Link, Shared-Path, Dedicated-Link, and Dedicated-Path Protection. The authors provided ILP formulations to accomplish a power-aware network design that enabled low-power sleep mode for backup paths devices. Enabling sleep-mode for protection resources would lead to a lower percentage saving in SPP cases for DPP. Power savings of up to 60% are achieved by setting protection devices into sleep mode. The



authors only considered sleep mode operation without considering QoS metrics or network survivability.

1.6 Methodology

The thesis will follow the below methodologies:

- Literature review: read the supporting documents, related papers, journals, and review the state of the art of green networking researches.
- Data collection is done: OTN devices power consumption from equipment manual and Ethio telecom design documents such as Low-Level Design (LLD) and High-Level Design (HLD) document, actual network topology includes a number of links, nodes, and service type from network management system (NMS).
- Data analysis: optical network power consumption analysis is done using Ethio telecom, Addis Ababa backbone network.
- Problem formulation: the identified energy-efficient resilience mechanisms, i.e., the EADPP model, were formulated as Mixed integer linear programming (MILP).
- Evaluation: evaluate the performance of the proposed approach.

1.7 Contribution of the Thesis

The contribution of this thesis is: formulate a Mixed integer linear programming (MILP) model for EADPP to interpret the goal of minimizing the energy consumption of used active network devices while putting idle and redundant backup devices to sleep mode under constraints of link utilization and a link disjoint backup path for each request. This thesis also proposes a multi-objective Mixed Integer Linear programming model to find the optimal trade-off between power consumption and blocking probability.



1.8 Organization of the Thesis

The first chapter introduces the problem area of this thesis by presenting a statement of the problem, objectives, and some related works. The remaining chapters in the thesis work are organized as follows. Chapter 2 of this thesis presents a general overview of optical backbone networks, WDM systems, and network resiliency mechanisms. Chapter 3 discusses the power consumption modeling and devices power consumption in the optical backbone network, analyses the power consumption of the systems under case study, Addis Ababa Ethio telecom optical backbone network, and approaches employed to save energy in the backbone network. Chapter 4 introduces some basics on LP and presents a brief discussion on the problem formulation. Chapter 5 evaluates the proposed approach, and the detailed results of the research are discussed. Finally, conclusions are drawn based on the previously mentioned chapters, and possible future works are discussed in chapter 6.



Chapter 2

General Overview of Optical Backbone Networks

2.1 Introduction

Communication networks can be divided into three major domains: access networks that enable end-users to connect with the rest of the communication infrastructure, metro networks that span over a metropolitan area covering distances up to a few hundred kilometers (e.g., a city or several closely located cities), and backbone networks (also referred to as core networks) that carry traffic over hundreds/thousands of kilometers (e.g., within or among countries) [19].

The continuous growth of demand on the Internet with multimedia services and various intelligent appliances such as smart TVs, tablet PCs, mobile phones, cloud systems, smart home appliances that require high-speed connection, and larger capacity on a telecommunications network [20]. In general, with the development of telecommunication networks, network traffic has increased significantly, resulting in rapid growth in the bandwidth required in telecommunication networks. In order to satisfy these increasing connection requests, optical networks have been developed a new transmission technique.

An optical backbone network is a system that uses optical fiber as a medium of transmission. One fiber can multiplex and carry several optical signals over very long distances using Wavelength Division Multiplexing (WDM). Optical technologies provide very high capacity, long reach, and high reliability compared to other access technologies supported, e.g., twisted-pair cables (e.g., xDSL), coaxial cables, or microwave links [22]. For these reasons, fiber access networks provide broadband connectivity to residential users and commercial customers. In addition, fiber access networks are a perfect choice for front haul and backhaul in mobile networks [22]. Because the traffic in mobile networks rises very rapidly, the requirements placed on both front haul and backhaul networks in terms of required capacity increase.

The optical transmission consists of an optical transmitter, a receiver, and the transmission medium. Backbone networks transporting Internet (IP) traffic, possibly upgraded with Multi-Protocol Label Switching (MPLS) capabilities, are supported by Optical Transport Networks (OTNs) that provide transmission links between IP routers. OTNs can transmit several independent channels on different wavelengths over a single optical fiber by using Wavelength Division Multiplexing (WDM) [21]. This allows the network to carry or move massive amounts of data while also providing critical communication services to many of our daily social and economic activities.

The optical backbone network, including different components at the optical layer to interconnect core network devices within the IP layer, is depicted in Figure 2.1.

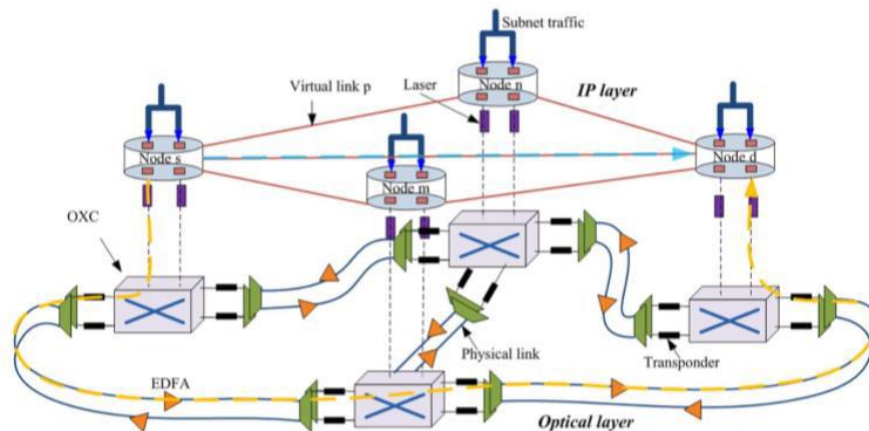


Figure 2.1: IP over WDM systems [21][39].

Optical cross-connects (OXC), optical line amplifiers i.e., EDFA (Erbium-doped fiber amplifiers), optical transponders, and optical fibers (physical link) all have various functions in optical backbone networks.

2.2 Optical WDM Networks

Internet applications with high data rates have introduced a dramatic increase in traffic in today's telecom networks. Optical networks are thought to be the best backbone networks for such bandwidth-hungry applications. In an optical WDM network, each fiber link carries information on multiple wavelengths, where each wavelength reaches up to 1Tbps of capacity. The WDM network divides the optical backbone network's huge bandwidth into multiple tiny bandwidth



optical channels. It enables the simultaneous transfer of numerous data streams over the same fiber cable. Multiplexers at the transmitter end multiplex multiple optical signals onto a single fiber and demultiplexers at the receiving end separate them in a WDM system [20] [21].

WDM is a multiplexing technology that combines, transmits, and then separates multiple optical signals with different wavelengths [20]. Each fiber can contain several different wavelengths (or channels) for carrying data. WDM allows the bidirectional flow of data and expands the capacity of the optical network without having any additional fiber strands to hold data.

A wavelength-routed optical WDM network is composed of network nodes, which are optical cross-connect switches connected by fiber cables [10]. The central unit of information transfer in a wavelength-routed optical WDM network is an all-optical communication channel called lightpath, which is established between the source and destination nodes and should undergo more than one fiber link. Without wavelength-conversion capability, the light path must utilize the same wavelength throughout the whole path, a condition known as the wavelength-continuity.

High-speed and all-optical end-to-end channels, also known as a light path, are crucial services supplied by WDM networks. Light paths are dynamically formed between node pairs to provide the necessary network connectivity and handle traffic demands. The routing and wavelength assignment (RWA) problem assigns a route and a wavelength to each light path that needs to be made in a WDM network.

Optical WDM networks are widely deployed within the backbone domain to solve the increasing traffic demand. They can scale bandwidth, meet traffic requirements at reasonable costs, and reduce the need for Optical/Electronic/Optical (OEO) signal conversions and electronic processing by leveraging optical switching capability [23]

Optical WDM networks contain very high capacity links and nodes where a single point of failure in a network may cause loss of connection, interrupt a vast number of services [4], and affect the Quality of Service (QoS) offered to the end-user. This issue is critical from the service-provider point of view. Many network components may cause connection failure like switches, fiber cuts, transceivers, etc.; the major common failure may be a link failure. To deal with the difficulty, i.e., recovering from these failures, different protection mechanisms or backup resources for survivability have been developed for WDM networks to enable the rerouting of the affected traffic



upon a failure. In backbone network design, ensuring robustness against network outages is critical [23]. It necessitates the deployment of extra backup devices in addition to the primary (working) devices in the event of a failure.

2.3 Network Resilience/Survivability Mechanisms

Network Resilience (sometimes called survivability) is defined as the ability of a network to recover from a failure or to provide uninterrupted service in the presence of failure [24] [25]. A complete survivability mechanism includes fault detection, localization, notification, and recovery steps. Network resilience may be a key parameter to account for when planning and design of optical networks. It is becoming even more critical as the traffic carried in a fiber increases. Fault recovery is the most crucial issue in survivability strategy. Based on their recovery path or link provisioning time for survivability mechanisms can be divided into two broad groups: restoration (reactive) and protection (proactive).

Restoration is a fault recovery mechanism that computes and establishes backup paths dynamically after a failure has occurred; it doesn't use pre-allocated backup resources [25].

In protection, redundant backup network resources are preplanned, precomputed, and reserved in advance [25] [26]. That means protection schemes do not need any information update on the network topology and resources after a failure has occurred. This mechanism can switch the traffic from the primary path to a backup path as soon as possible. The protection switching time is fast, usually less than 50ms, in which the impact of the failure can be ignored. But, the resource utilization in the protection scheme is inefficient since it requires resources for its backup path. Restoration is less reliable and takes longer to recover; protection is more commonly used or preferred by the operators. It entails a much faster and more secure solution than restoration. Therefore, the only protection is considered in this study.

Depending on the configuration of backup resources, the protection schemes can be classified into two broad groups: dedicated and shared path protection.

Dedicated Path Protection (DPP) Schemes



In DPP, a primary path and an end-to-end backup path are established, and spectral resources are reserved along the working (primary) and protection (link-disjoint backup) paths, which are dedicated to a particular traffic demand [25] [27]. DPP schemes can be distinguished according to the strategy adopted for the transmission on the backup path configuration, i.e., 1+1 DPP and 1:1 DPP.

1+1 DPP employs precomputed and pre-allocated dedicated backup paths to a particular primary path [25] [27]. In the former, the transmission is active on both the working path (WP) and the protection path (PP). The two paths are used in parallel; traffic is sent and transported simultaneously on both paths, and the receiving node selects the traffic from only one of the paths based on some selection criteria. On the other hand, 1:1 DPP also uses pre-allocated and precomputed dedicated backup path protection and assumes that the transmission is carried out either on the WP or on the PP at a given time. But in 1:1 DPP, the traffic on the primary path is sent along the backup path only when the primary path fails. That means traffic on the primary path is switched to the backup path after a failure occurs.

DPP implies that working and a protection path (which must ultimately link disjoint to the working one) must be computed for network planning. In 1:1 DPP, the demand's connection is routed with two disjoint paths, where the whole set of connections optimizes energy usage. In the normal state, the shorter disjoint paths are employed as a working path, and therefore, the other (a backup path) isn't used. This means the backup capacity must be reserved; it does not use energy if not needed [17], which is almost always (since failures are rare events). The requested traffic demand can transmit through its backup path if a fiber or link is broken on the working path.

Shared Path Protection (SPP) Schemes

In shared path protection, backup paths are precomputed, and sufficient resources for single link failure are pre-allocated [25], [16]. These backup paths are assigned to particular shared protection paths only after the occurrence of failure. One or more backup paths may be shared by many primary paths depending on the configuration requirement. There are many different ways of sharing the backup path resources. In the 1: N SPP scheme, N primary, and one backup resource paths are preassigned. M: N SPP ($M < N$) is a general case of 1: N protection, where M shared



backup paths are predefined to protect N primary paths. Since shared backup systems protect several working paths, it is better in network resource utilization.

In selecting a protection scheme, the protection-switching time or recovery time (RT) is one of the critical parameters, i.e., the interval between a failure and recovery of the connection. RT is essential for critical and non-delay tolerant services like voice, trading, or financial transactions. The operators have built their networks to provide RT values shorter than 50ms [11].

Telecom operators are commonly implemented that protection schemes to guarantee the required service availability. Each connection request in a healthy communication network normally has two link or node-disjoint paths: one active working path and the other backup path. If the active path fails, the service flow will be switched to the backup path. A disjoint path routing is a technique to enhance network survivability. Link disjoint Path is the path with no common (overlapping) links between a given pair of source and destination nodes in a network and node disjoint if they have no commonly used nodes in the network [25].

This thesis selects the 1:1 Dedicated Path Protection (1:1 DPP) Schemes and assumes the working and backup paths to link disjoint, which protects against any single link failure.

2.4 Network Performance or QoS Parameters

The performance of optical networks is often measured using different parameters related to QoS and resource utilization. Different authors define the quality of service (QoS) differently based on their technology or service type considerations. The ability of a network to deliver better service to selected network traffic using various technologies is referred to as QoS [28]. QoS evaluation metrics are the possibility of implementing an energy-aware (EA) approach in operational networks strictly depending on its impact on network performance [6]. Due to the aggregate traffic flow within the optical network and its connection-oriented nature, the foremost commonly used QoS parameters in optical networks are bandwidth utilization, delay, blocking probability, recoverability, reliability, recovery time, packet loss, fault tolerance, and Bit Error Rate (BER) [29].



Link Utilization is the most common metric to analyze how the proposed approaches impact this aspect. This metric ensures that the specific EA approach avoids packet loss or maintains a residual available bandwidth for unexpected peak periods [12].

Blocking probability is an important network performance parameter that expresses the probability of blocking a connection request due to resource unavailability. When a connection request or Demands are assumed to arrive randomly at its source node, some routing procedure is executed to find an available route over the network, and they must be served as they are received. [30] [31]. When the network does not contain enough free resources (wavelength) to establish the connection request, that connection is blocked. So the blocking probability is the probability of randomly refusing (block) a connection request; that is, the amount of blocked connections is divided into the number of connections requested.

Network reliability is the main QoS parameter which refers to the reliability of the overall network to provide a service without service outage even if a failure occurs in the network [28], [31]. Reliability is a technique used to determine how long a particular component is functioning or measure the degree of resilience to a failure.

Bit Error Rate (BER) is One of the most important factors to consider when measuring signal quality [28]. BER is analogous to the signal-to-noise ratio in an analog system. In networks, transmitted packets may fail to reach their intended destination, resulting in packet loss. Packet loss is the failure of one or more transmitted packets to arrive at their destination, which affects the QoS in networks [33].

Network delay is a crucial characteristic of a network. A network's delay is defined as the time it takes for a bit of data to travel from one endpoint to another in fractions of seconds, usually milliseconds [34]. Recoverability is another QoS parameter used to measure the performance of a network and is used to determine the degree of failure recovery in a network.



Chapter 3

Energy-Aware Survivable Optical Network

3.1 Network Model

An optical backbone WDM network is the network studied in this thesis. The physical network topology was modeled using the graph $G(N, E)$, where N represents nodes and E represents links. Each link $(x, y) \in E$ contains C capacity and W wavelength channels with the same bandwidth. A set of demands D is used to represent traffic. A source node s and a destination node d describe each traffic demand or a connection request $r \in D$.

The network employs the 1:1 dedicated path protection (1:1 DPP) design, in which each primary path is protected by a backup path. As a trade-off between energy consumption and network resiliency, each connection request (demands) has two disjoint (primary and backup) paths from source node s to destination node d . If the primary (active) path failure happened, the backup path is utilized to reroute the request. So energy-aware routing with disjoint backup paths can ensure the network is resilient to single link failure. Assumptions are made as follows:

1. Each connection request considered always has two disjoint link paths and can only be transported via active path. If the active path fails, it switches to the backup path.
2. Each link device can be set into sleep mode independently. If there is no traffic on a link, it can go to sleep.

3.2 Power Consumption Model in Optical Network

A power model or correct data for devices' power consumption values is required to compute the total power consumption of the network and an approach to reduce this consumption. This data is used to enable decision-making that will help apply power consumption minimization approaches to ICT sectors. Additionally, important for equipment vendors, service providers, and researchers



to plan solutions that will reduce the power consumption of specific equipment, the segment under question, or the entire network in general.

The overall network power consumption can be calculated as the sum of the power consumption of the network devices or components. Some devices like the fibers are passive and do not consume power. In previous studies, different power consumption models, which are almost similar, have been used for optical network segments that follow the same pattern as those applied for the general telecommunication network.

The authors in [32] [33] use an analytical power model to determine the power consumption and power-saving potential of a backbone in an IP over a WDM optical system. In an IP-over-WDM network analytical model, overall power consumption equals the sum of the power consumption of the constituting layers:

$$P_{backbone} = P_{IP} + P_{WDM} \quad (3.1)$$

$$P_{WDM} = P_{oxc} + P_{amp} + P_{tsp} + P_{reg}$$

Where P_{IP} represent the IP power consumption, P_{WDM} is the power consumption of WDM, P_{oxc} is the power consumption of optical cross-connection (OXC), P_{amp} is the power consumption of amplifier, P_{tsp} and P_{reg} the power consumption of transponder and regeneration respectively.

The total network power consumption in [34] is the sum of the power required by all currently provisioned connection requests. The power required to provide one connection request equals the sum of the transceiver power consumption, the energy needed to optically switch the signal at intermediate nodes (i.e., OXCs), and the power consumed by the inline optical amplifiers alongside each fiber link within the path.

The research work in [13] [17] [35], the total power consumption of the network is the sum of power consumption of all active nodes and links.

$$P_{total} = \sum_{n \in N} (P_{node,n} \cdot x_n) + \sum_{e \in E} (P_{amp,e} \cdot y_e) \quad (3.2)$$

Where $P_{node,n}$ is the power consumed by node $n \in N$ and $P_{amp,e}$ is the power consumed by amplifiers in link $e \in E$. The x_n and y_e are two binary variables equal to 1 if node n and link e are active, respectively.

$$P_{node,n} = P_{OXC} + P_{TX}(c_n + d_n) + P_{RX}(\bar{c}_n + \bar{d}_n) + c_n * P_{WC} \quad (3.3)$$

where P_{OXC} is the switching fabric power consumption, c_n and \bar{c}_n are respectively the number of working lightpaths beginning from and finishing at n , d_n and \bar{d}_n are the number of backup lightpaths starting from and ending at node n respectively. P_{TX} and P_{RX} are a transmitter and a receiver power consumption. P_{WC} is represent a wavelength converter power consumption.

$$P_{amp,e} = k_e \cdot P_{amp} , \quad (3.4)$$

$$k_e = \left(2 * \frac{d_e}{d_{span}} \right) + 2$$

Where P_{amp} is represent the power consumed by an optical amplifier, k_e represent the total number of amplifiers along with link e , d_e and d_{span} represents the total link length and the fiber span length respectively [17].

This thesis applies the power model used in [13] [17]. The amount of power consumed by the network devices depends on their operational modes. Table 3.1 summarizes the three power modes for optical devices (link or node) in this model: active, sleep, and off mode.

Table 3.1: Power consumption in different modes [13] [17].

Mode	Functionality	Power Consumption
Off	Null	None
Sleep	Prompt switching to active mode	Negligible
Active	Full	Fixed power + Proportional Power

If a working light path passes through a device, it is an active mode. Nodes consume a certain amount of power in this mode, which is split into two parts: traffic independent power



consumption, which is provided by optical exchange devices, and traffic dependent power consumption, which is proportional to the number of lightpaths that use the node. In an active mode, the power consumption of links is proportional to their physical length. If only backup lightpaths are in use during sleep mode, each device can be activated instantly in the case of a fault within the network. In sleep mode, the quantity of power consumed is negligible. If there is no light path going through a device, it will be in off mode; in this case, devices will not consume any power. The overall or total power consumed by the optical WDM network is, thus, given by the power consumed by the active devices installed in links and nodes [13] [17].

This thesis is based on the assumption that network devices in sleep mode consume a negligible amount of energy. Under this premise, an optical WDM network's overall energy consumption can be calculated as the sum of the energy spent by active devices. As a result, decreasing the number of devices in active mode is comparable to minimizing energy consumption. This problem can be tackled by maximizing the number of network devices potentially put into sleep mode and off mode. The idea of an energy-aware resilience lies behind the effort of separating primary and secondary paths and maximizing the resources that can be turned off.

3.3 Optical Network Power Consumption Analysis

Any power consumption analysis task must include the power consumption values for each device. This section gives the power consumption values of the devices used in Ethio Telecom's optical backbone network at the Addis Ababa optical backbone network. There are two types of equipment in this backbone network: Huawei equipment OSN 8800 V100R008C00 and OSN 6800 V100R008C00 [36] [37]. The total power consumption of given equipment is the sum of the power consumption of the devices found in the equipment. The power consumption of deployed network elements is determined by the configuration at the specified site. The equipment can be configured as Optical Terminal Multiplexer (OTM), Optical Add Drop Multiplexer (OADM), Reconfigurable Optical Add Drop Multiplexer (ROADM), or OADM/OTM. Generally, the power consumption of optical network equipment depends on the installed capacity of the ultimate technology, the site's configuration, and the cards used [6]. The card power consumption also differs from card to card, with the line cards and cross-connection cards consuming the highest amount of power. The



following table lists the devices found in each piece of equipment ROADM site device power consumption:

Table 3.2: ROADM site device Power Consumption (PC) [33] [39].

No.	Category	Board Type	Typical PC (W)	Maximum PC (W)
1	OADM	Fiber Interface Board	0.2	0.3
2	OADM	Inter leaver Board (optional)	0.2	0.3
3	OADM	9-Port Wavelength selective multiplexing and Demultiplexing board	25.0	27.5
4	OADM	40-channel Multiplexing Board	10.0	13
5	OADM	40-channel Demultiplexing Board	10.0	13
6	Tributary module	Interface Board of Alarm & Timing	0.3	0.3
7	Tributary module	EMI Filter Interface Board	5.0/13.0	7.0/15.0
8	Tributary module	Power Interface Unit	3.0	3.6
9	Tributary module	Synchronous Timing Interface Board	1.5	1.5
10	Tributary module	Bidirectional optical supervisory channel and timing transmission unit	17.5	19.5
11	Tributary module	System Auxiliary Interface Board	15.0	20.0
12	Tributary module	Clock Board		
13	Tributary module	System Control and Communication Board	23.0	25.1
14	Tributary module	8-channel Optical Power Monitor Board	12.0	15.0
15	OA	C-BAND Optical Booster Unit(MAX -1dBm IN and 16dBm OUT, Gain 17dB)	10.0	12.0
16	OA	C-BAND Optical Amplifier Unit(MAX 0dBm IN and 20dBm OUT, Gain 20 to 31dB)	12.0	15.0
17	OA	C-BAND Optical Amplifier Unit(MAX 4dBm IN and 20dBm OUT, Gain 16 to 23dB)	12.0	15.0
18	OTU	8 x Any-rate Ports Service Processing Board	23.0	25.0



19	OTU	40GE Tributary Service Processing Board	58.0	64.0
20	OTU	40Gbit/s Line Service Processing Board	99.0	103.0

The total power consumption of a given optical backbone network segment is the sum of devices deployed in each site within the segment. The Equation below shows that the total network segment power consumption comprises transponders, amplifiers, optical switches, and multiplexer/demultiplexer units [39].

$$P_{total} = (P_{tra} * P_{tn}) + (P_{OXC} * OXC_n) + (P_{m/d} * m/d_n) + (P_{amp} * Am_n f_{pq}) \quad (3.5)$$

Where, P_{tra} is the power consumption of transponder, P_{tn} is the number of transponders, P_{OXC} is the power consumption of optical cross-connect, OXC_n is a number of optical cross-connects, $P_{m/d}$ is the power consumption of multiplexer/demultiplexer, m/d_n is a number of multiplexer demultiplexers, P_{amp} is the power consumption of amplifier, Am_n is the number of the optical amplifiers, including a booster and preamplifiers, f_{pq} is the number of fibers between two neighboring nodes.

Energy Consuming Devices

Many power-consuming devices or cards are used in optical networks, such as amplifiers, transceivers, transponders, and OXC (Optical Cross Connection).

Amplifiers: Optical amplifiers are the devices used in optical networks to amplify the degraded signal when the signal power falls below a specified threshold. Inline optical amplifiers can amplify the signal directly in the optical signal without converting it into the electrical signal. These devices can be used as pre/post amplifiers with line cards or stand-alone optical line amplifiers. The optical WDM links power consumption is mainly due to EDFAs and is considered independent of carried traffic. However, it is related to the physical length of the optical fiber link, as an optical line amplifier (OLA) is deployed every 80 km and consumes 12W [38].

Transceivers: are the devices used in optical networks to terminate the light paths at each end. These transceivers are optoelectric equipment that converts the optical signals to electrical signals



for further processing [38] [40]. It converts the electrical signal from a switch or router to an optical signal transmitted and received.

Transponders: The devices used in optical fiber service processing are used to send and receive signals in the optical fiber. The service processing is done from the client-side to the line-side or vice versa. The transponders perform the same function as transceivers, converting an electrical signal into an optical signal [38] [40]. However, unlike transceivers, these transponders can convert the signal from one wavelength to another, converting client-side services into optical signals carried over WDM wavelengths after mapping, multiplexing, convergence, and other operations. A pair of transponders are used whenever a light path passes through a fiber link.

Optical Cross Connection- The devices in this category are used for cross-connecting services of lower or higher granularity from a specific source port to a particular destination port. In an optical network, an optical cross-connect switch is used to switch high-speed optical signals [40]. The connections between de-multiplexers outputs and multiplexers inputs determine how the signals on the input fibers are routed to the output fibers. According to [38], the OXC power consumption depends on the number of router-side and network-side fibers at each node.

3.4 Optical Network Power Consumption Minimization Approach

The energy efficiency design for reducing energy consumption has been studied widely in the telecommunication and ICT industries. Since the development of ICT and telecommunication services is growing, Internet usage is highly increased. This increment impacts operators' expenditures and the environmental problem known as global warming [3]. Optical backbone networks are currently designed and deployed with an over-provision considering the worst-case state of high traffic demand. Additionally, resources are deployed to ensure the reliability of the service, such as protection and restoration resources that only kick in when there is a fault in the network but idle otherwise [33]. Thus this creates a large gap between the actual usage of network resources and the deployed capacity. The main idea of Energy-Aware (EA) network design and operation is to minimize the gap between the utilization of the network and the offered capacity. In [6], presented an in-depth survey of optical networks energy consumption reduction approaches.



Current works of literature in [5] [16] [40] reported four strategies to energy-efficient network approaches according to the observations on the root causes of energy waste. The four strategies consist of Adaptive Link Rate (ALR), Interface proxying, Energy-aware infrastructures, and Energy-aware applications.

Adaptive Link Rate is a strategy to reduce energy consumption considering low resource utilization. Adaptive link rate (ALR) normally activates sleeping mode for links that are in idle periods or use rate switching to turn off links with low utilization periods [5]. The rate switch algorithm reduces energy consumption by determining the links with low utilizations.

The Interface proxying strategy assigns network-related traffic processing from power-hungry main board CPUs to low-power devices onboard NIC or external proxy devices [33] [40].

Energy-aware infrastructure strategy is classified into Energy-aware architecture and Energy-aware routing. Building the energy-aware architecture makes the energy-aware architecture over existing infrastructures; on the other hand, the complete redesign of a new architecture. Energy-aware routing focuses on combining traffic flows over a subset of the network devices and links, allowing other links and devices without carrying traffic to be switched off. This strategy is applied to the problems of assigning capacity to multi-commodity flow [16] [40].

Energy-aware applications: The last strategy for green networking is energy-aware software and application. The idea of this strategy is to reduce energy waste by examining the load imposed by the applications.

The energy efficiency of survivable optical backbone networks can be improved by using various techniques. The solution consists of planning or operating the optical WDM network to minimize power consumption instead of reducing the resource installation or utilization [14] [31] [32]. Additional improvement can be achieved by enabling a sleep mode state where network resources enter a low-power state during inactivity [14] [33]. Another option is to use proportional energy mechanisms, which involve designing the device architecture to make energy consumption proportional to the actual load [43].



Energy-aware routing techniques have been implemented, and a sleep mode of operation has been proposed for use in network equipment to reduce the energy consumption of optical WDM networks [42].

This thesis considers the energy-efficient routing by considering the Adaptive link rate and energy-aware routing strategies. ALR normally activates sleeping mode for idle links, and the energy-aware routing aggregate traffic flow to network devices and allow other devices to be switched off.

Two issues need to be addressed to make sleep mode effective in survivable optical networks. First, it is necessary to ensure that the devices in sleep mode can become promptly operative (typically within 50ms) in case of a failure. Second, it's essential to ensure that devices in working paths do not support sleep mode [13]. For each connection request, link-disjoint working and protection paths need to be provisioned to ensure 100% single link failure survivability.

3.5 Energy Efficient Resilience Approaches

This section discusses the energy-efficient strategies for developing the proposed energy-aware approaches in this thesis. This proposed approach within the energy-saving aspect integrates both the energy-aware routing and sleeping mode strategies. To enhance energy saving within the 1:1 DPP scheme obtained by provisioning a link disjoint working and protection paths and setting protection resources in sleep mode.

3.5.1 Energy-Aware Routing

Energy-aware routing aims at aggregating traffic flows over a subset of the network devices and links, allowing other links and interconnection devices to be switched off [44]. By limiting the maximum utilization over any link or ensuring a minimum level of path diversity, these solutions should preserve connectivity and QoS.

The energy-aware routing with 1:1 dedicated path protection (DPP) is an energy-aware survivable routing strategy that aims to route a primary path, using already provisioned working resources, and routing a secondary path using already provided protection resources [17].



Energy-Aware Routing (EAR) strategy refers to well-routed traffic supported energy-saving objectives. A typical EAR example is modifying the network protocol and turning off unused network devices to route traffic over energy-efficient paths [15].

3.5.2 Sleeping Mode

One of the most promising energy-saving approaches in communication networks is setting idle devices into a low power mode called sleep mode [42] [4]. Sleep mode represents a low power, inactive state from which devices can rapidly awaken when necessary. As redundant resources are unused until a failure occurs, they can be set in sleep mode, provided that each connection can still be satisfied; that is, resources in sleep mode can be back in operation mode within certain time limits. Indeed, devices are often put to sleep mode when they support only the idle protection paths. The topic of designing an optical WDM network that supports sleep mode has received a lot of attention in the literature. Some research works explore ways to improve the energy efficiency in all-optical WDM networks with dedicated path protection [13] [17] [35]. In contrast, others investigate dedicated and shared path protection schemes used in IP-over-WDM networks [18].

3.6 Energy-Aware protection provisioning with sleep mode

This thesis considers an optical WDM network, resilience against single-link failure is provided through dedicated 1:1 path protection. Primary (working) paths must be provisioned and protected by dedicated link-disjoint backup (protection) paths for each connection request.

In order to save energy, energy-aware routing with the 1:1 DPP approach applies two ways.

1. Tries to route the connection requests using the minimum number of network devices and Switching off redundant links.
2. Provision primary and backup paths on separate links, then put sleep mode for backup path devices.

Figure 3.1 depicts an example where a comparison of an energy-aware and an energy-unaware routing approach with 1:1 DPP for three connection requests r_1 , r_2 , and r_3 . The first three

connection requests for the specified source and destination node pairs are $r_1(2, 7)$, $r_2(2, 8)$, and $r_3(4, 9)$. All of the links in the example network are considered to be the same physical length and represent bidirectional fibers [17].

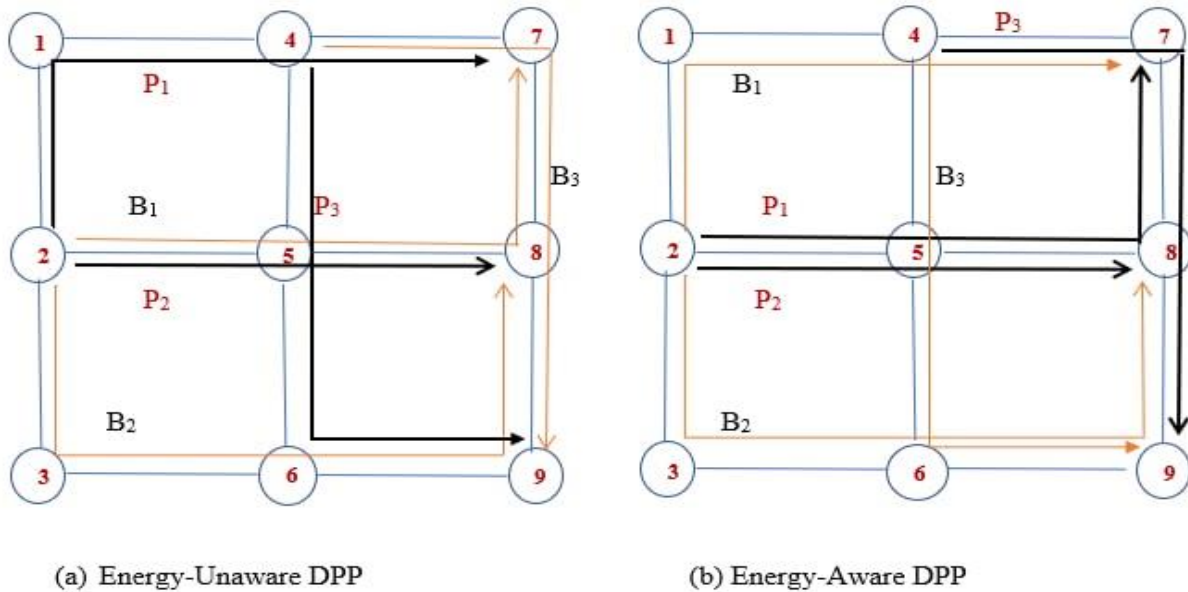


Figure 3.1: Comparison of an energy-aware and an energy-unaware routing with 1:1 DPP.

When r_1 arrives, the energy-unaware approach selects the shortest link-disjoint path pair without distinguishing between free links, used by primary paths and backup paths. As a result, the energy-unaware strategy chooses $P_1(2-1-4-7)$ as the primary path and $B_1(2-5-8-7)$ as the backup path (see Fig. 3.1(a)). The energy-aware approach, on the other hand, shown in Fig. 3.1(b) chooses the route that makes use of already-provisioned working resources, such as $P_1(2-5-8-7)$ is chosen as the primary path, and $B_1(2-1-4-7)$ is chosen as the backup path.

When r_2 arrives, both the energy-aware and energy-unaware routing strategies assign $P_2(2-5-8)$ as the primary path and $B_2(2-3-6-9-8)$ as the backup path. Lastly, when r_3 arrives, the energy-aware method, like with r_1 , route $P_3(4-7-8-9)$ is chosen as the primary path, whereas route $B_3(4-5-6-9)$ is chosen as the backup path. The energy-unaware approach allocates $P_3(4-5-6-9)$ as the primary path and $B_3(4-7-8-9)$ as the backup path, respectively.



Figure 3.1 shows that the number of active links using the energy-aware strategy is 5, while the number of links used only by backup paths, which might potentially be switched to sleep mode, is 7. The energy-unaware strategy, on the other hand, requires 8 active links and only 4 links that can be switched to sleep mode. The energy-aware approach aims to reduce the number of network elements traversed by both primary and secondary paths, resulting in greater energy savings.

3.7 Network Survivability Challenges Under Energy-Saving

Operation

The gap between traditional network design concepts and network greening techniques makes green networking challenging. Through over-provisioning and utilization of redundant network resources, the current network architecture aims to provide Quality of Service (QoS) and fault tolerance, respectively. Survivability to device failures could be a fundamental requirement in WDM core networks. Installing or reserving redundant (protection) resources, which can be used during a failure to restore the affected connections, will accomplish it. Such resources, on the other hand, are often kept active regardless of the failure pattern, consuming energy even when not in use [41]. As a result, there is a contradiction between greening network strategies and standard network design methodologies for QoS provisioning and fault tolerance [35]. The selection of specific network architecture with the common resilient strategies (i.e., dedicated versus shared protection) will affect the overall network energy consumption [41]. For example, changing the protection scheme from the most reliable but also the most energy-consuming scheme, i.e., 1+1 DPP, to more energy-efficient ones like 1:1 DPP or SPP will obtain additional energy savings depending on the network architecture.

Energy consumption optimization in optical WDM networks for gaining energy saving is important to reduce network operators' capital expenditures. Turning off idle devices is a common strategy for reducing the power wasted by the optical layer in survivable optical WDM networks. Because most of the time (in the absence of failures), the deployed protection devices are idle or unused, they can be put to sleep and reactivated as soon as the recovery is triggered. However, carrying out these operations while ensuring that another network performance is not impacted necessitates careful planning and provisioning. However, turning off or sleeping network



equipment for energy saving can raise some challenges for network survivability. For example, turning off or sleeping network equipment will affect network connectivity, affecting network survivability. When implementing energy saving, it is necessary to consider network survivability [7].



Chapter 4

Problem Formulation

Reducing energy consumption for survivable networks is required due to a trade-off between energy efficiency and network resiliency. The difficulty of managing the network power consumption reduction can be modeled as a mathematical programming problem. The formulation varies in line with the thought of the network scenario to include all the matter options, e.g., routing scheme, energy components, performance measures [44]. This chapter first introduces A Linear Programming (LP). It then discusses the mathematical formulation of the proposed energy-aware resilience approach to be evaluated in this thesis and its problem-solving approach.

4.1 Linear Programming (LP)

Linear Programming is a mathematical optimization technique used to find the optimal solution which takes various linear constraints with inequalities and equalities and determines the best obtainable result of the objective function [31] [33] [45]. Linear programming is used to describe many combinatorial optimization issues. The method of searching for maxima (or minima) of an objective function F whose domain is a discrete but vast configuration space is known as combinatorial optimization [15]. The objective function of an LP function can be a maximization or minimization of a linear problem with linear constraints that can be drawn as a linear graph. For a general LP problem that minimizes an objective function, the following formula is presented [45]:

Objective:

$$\text{Minimize} \quad c_1x_1 + c_2x_2 + \dots + c_nx_n$$

Constraints:

$$a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n \geq b_1$$

$$a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n \geq b_2$$

$$\begin{aligned} & \dots \\ & a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n \geq b_m \\ & x_1 \geq 0 \\ & x_2 \geq 0 \\ & \dots \\ & x_n \geq 0 \end{aligned}$$

The nomenclature for an LP problem with two decision variables is shown in Figure 4.1. A boundary is a constraint that denotes the upper or lower bound of inequality or equality. The feasible region is defined as the area bounded by the lines. The intersection of the boundaries is referred to as a corner point [45].

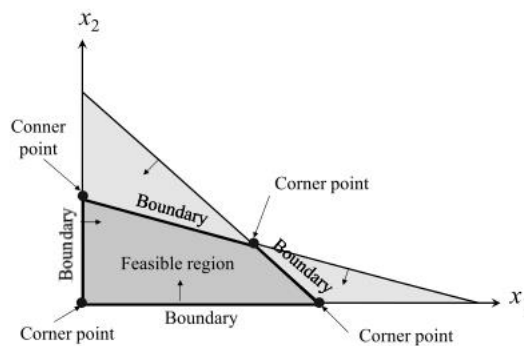


Figure 4.1: Nomenclature in linear programming problem [45].

For a linear optimization problem with a small number of decision variables and constraints, it is possible finding an optimum solution by drawing a graph and examining all corner points. However, when the number of decision variables and constraints increases, finding an optimal solution via obtaining the corner points becomes more difficult. As a result, the computation times are so long that the solution cannot be found in a reasonable amount of time. To address this type of problem, completely different algorithms or strategies were developed. The simplex method is one of the more efficient methods for finding the best LP problem solution. This method is used to solve linear programming problems with a large number of decision variables and constraints based on the above assumption of finding the optimum solution in corner points of a feasible region [31] [33] [45].



4.1.1 Integer Linear Programming (ILP)

If all decision variables of an LP optimization problem are restricted to an integer value, the LP problem becomes ILP (Integer Linear Programming). On the other hand, when the integer restriction is applied only to some of the decision variables, the ILP problem becomes a Mixed Integer Linear Programming (MILP). When compared to LP, solving MILP problems is more difficult or NP-hard. Linear relaxation is a possible approach to acquire feasible solutions to NP-hard MILP problems. MILP is useful to solve many practical optimization problems, including economic problems, control problems, and network optimization problems.

In general cases, MILP problems are NP-hard; linear relaxation is possible to get feasible solutions for this category of problems. The linear relaxation ignores the integer constraints and treats the problems as LP and uses algorithms such as the simplex algorithm to find the solution. There are various algorithms available for the solution of integer programming problems. The reason for this abundance is that no one algorithm has proved to be computationally efficient for all problems [31] [33].

Branch and Bound Algorithm

The branch and bound algorithm is a general optimization algorithm that uses intelligent investigation to find the best solution to combinatorial optimization problems. B&B divides the original problem's search space into sub-problems using the divide-and-conquer strategy [33]. The building of a search tree is required for this system. Each node represents a constrained MIP problem that includes the specific constraints as well as some additional constraints on the integer variable boundaries. The algorithm solves the restricted sub-problem with all variables relaxed to be continuous at each node, i.e., it solves the linear programming relaxation at each node. B&B starts by solving the root node at the top of the tree, with all variables set to continuous values.

4.1.2 Multi-Commodity Flow Problem

Network flow is one of the problem domains that telecommunication networks need to address and hence is a topic of interest in many works. There are different kinds of network flow approaches depending on the problem [33] [47]. The Multi-commodity flow problem (MCF)



seems like a combination of several single commodity flow problems [46]. Multi-commodity network flow problems involve many flow varieties or commodities that simultaneously use the network and are coupled through link capacities or cost functions.

Optical network problems are similar to other communication problems, as mentioned in [45-47], can be formulated mathematically as a multi-commodity flow (MCF) type of integer linear programming (ILP) optimization problem with different constraints related to the optical network problem. In this thesis, the proposed optimization problem arising in telecommunication networks is formalized as a Linear Programming (LP) formulation, a modelization using LP of the so-called multi-commodity flow (MCF) problem, is that the basis of most of the problems studied in this thesis.

4.2 Mathematical Formulation

This section will discuss the mathematical problem formulation of the energy-aware resilience mechanisms that will be evaluated. An optimization problem is a problem that aims to find the best solution from all feasible solutions [39]. An optimization problem can be solved by mathematical programming, which expresses and solves problems as mathematic models. Like other telecommunication optimization problems, the optical network optimization problem of managing the network to reduce its power consumption can be modeled as a mathematical programming problem. The formulation varies according to the considered network scenario to include all the problem features, e.g., routing scheme, energy components, performance measures. Different researches on power consumption minimization for IP over WDM network are formulated as a MILP problem (optimization problem) based on the multi-commodity flow model.

This thesis proposes MILP formulations for energy-efficient survivable optical networks with 1:1 DPP to protect against single-link failures and formulated as multi-commodity flow (MCF) with different commodities or constraints such as link capacity, traffic demand/request, and other constraints. The proposed MILP solution finds a link disjoint primary and backup routes for each connection request to minimize the network's energy consumption. The mathematical problem of the EADPP is formulated considering a network topology $G(N, E)$ with $|N|$ the number of nodes and $|E|$ the number of links. The optimization problem is formulated as an MCF model consisting



of input parameters, objective function, and constraints. Once the model is developed, the problem is solved using the MATLAB optimization toolbox.

4.2.1 EADPP Model

This thesis proposed the energy-aware resilience approach with a 1:1 dedicated path protection, i.e., the Energy-Aware Dedicated Path Protection (EADPP) model. This Energy-aware approach is used to minimize the energy consumption of active network devices by rerouting traffic that each request r has an active or primary path p_{xy} and by switching off the link disjoint backup path b_{xy} and the maximum link utilization is no more than T_L ($0 < T_L < 1$). The general EADPP model problem uses input information such as network topology and traffic demand for each connection request's source and destination nodes. This model can be formulated based on the input data to provide a link disjoint primary and secondary (backup) paths.

This model aims to find energy-efficient link disjoint path pair, working path (WP), and backup path (BP). It can achieve optimal energy saving in the network by putting sleep mode for redundant backup devices; and satisfying performance constraints that apply to energy-optimized routing, including link utilization and link disjoint path, given the input network topology and the traffic matrix to find an optimized routing solution.

4.2.2 MILP Mathematical Model

In this section, two objective functions: minimization of power consumption and blocking probability, are evaluated in the MILP optimization model. The first objective function with the total power consumption minimization aims to minimize total active power-consuming components in the network. The second objective function with the minimization of total blocking probability aims to reduce the total number of blocked requests, which means maximizing the number of successfully provisioned requests or served demands.

The notation, input variables, and decision variables used in the MILP formulation of the EADPP are given below.



Notation

- (s, d) : The source and destination nodes of a connection request.
- (x, y) and (m, n) : The links in the physical network topology used by primary and backup path routes, respectively.

Given parameters

- $G(N, E)$: Physical network topology consisting of N nodes and set E of links (Edges represent link devices).
- W : Maximum number of wavelengths supported on each link.
- C_{xy} : Capacity of each link.
- D : Set of connection/lightpath requests or demand.
- r : A request r from source s to destination d .
- d_r : traffic demand of request r .
- λ_r : denotes the traffic in the number of lightpath requests r between any source-destination pair to set up paths allocated on wavelength w . It represents the number of lightpaths that are successfully provisioned a w .
- M : Constant value used in the Big-M constraints (i.e., greater than twice the maximum node capacities) for the MILP formulation.
- ϵ_t : Energy consumption per traffic flow for a transmitter in a node.
- ϵ_r : Energy consumption per traffic flow for a receiver in a node.
- ϵ_s : Energy consumption per traffic flow for switching devices (i.e., optical switches and wavelength converter) in a node.
- ϵ_a : Energy consumption of an inline amplifier on the link (x, y) .
- \emptyset_n : Wavelength traffic independent (idle power) energy consumption in node n by the active devices.
- α : The adjustment parameter that trades off between the objectives of the optimization model.

Variables

The model includes the following decision variables.



-
- p_{xy} : Number of resources used by primary paths/flows on the link (x, y) .
 - b_{mn} : Number of resources used by backup paths/flows on the link (m, n) .
 - p_{xy}^r : Number of lightpath requests r from s to d passes through a primary physical link (x, y) . (Primary path routing variable).
 - b_{mn}^r : Number of lightpath requests r from s to d passes through a backup wavelength on the physical link (m, n) when the physical link (x, y) fails. (Backup path routing variable).
 - lp_{xy} : Binary variable is 1 if a resource on the link (x, y) is used by a primary flow of a connection request, link (x, y) is powered on.
 - lb_{mn} : Binary variable is 1 if a resource on the link (m, n) is used by a backup flow of a connection request or if a link (x, y) is powered on.
 - lp_n : Binary variable is 1 if node $n \in N$ is used by any incoming or outgoing primary flows of a connection request or if node n is powered on.
 - s_{xy} : Binary variable is 1 a resource on the link (x, y) is in sleeping state for backup protection, it indicates whether a link (x, y) is in sleeping mode or not.
 - s_n : Binary variable is 1 a resource on node n is in sleeping state for backup protection, it indicates whether a node n is in sleeping mode or not.
 - E_{total} : The total energy consumption of active network devices.
 - A_r : Binary variable is 1 if a request r is successfully provisioned.
 - T_L : Link maximum utilization threshold; $0 \leq T_L \leq 1$.

4.2.3 Problem Formulation for EADPP

The MILP formulation of the EADPP considered in this thesis is formulated based on the generic MILP formulation given in different kinds of literature by adding additional constraints that make the MILP formulation more practical, such as link utilization, a link disjoint, and sleeping state constraints. Another constraint is added by considering network performance.

As shown below, the optimization problem can be formulated as a MILP problem with constraints with the above input parameters and decision variables.

Objective function:

Minimize

$$E_{total} = \sum_{n \in N} \phi_n \cdot lp_n + \sum_{(x,y) \in E} (\epsilon_t + \epsilon_r) \cdot p_{xy} + \sum_{(x,y) \in E} \epsilon_s p_{xy} + \sum_{(x,y) \in E} \epsilon_a \cdot lp_{xy} \quad (4.1)$$

With the given input parameters and decision variables stated above, the objective function for the MILP formulation given in Equation 4.1 is used to minimize the total energy consumption of active network devices.

Constraints:

$$\sum_{x \in N} p_{xk}^r - \sum_{y \in N} p_{ky}^r = \begin{cases} \lambda_r, & k = d \\ -\lambda_r, & k = s, \forall k, r \in D \\ 0, & k \neq s, d \end{cases} \quad (4.2)$$

$$\sum_{m \in N} b_{mk}^r - \sum_{n \in N} b_{kn}^r = \begin{cases} \lambda_r, & k = d \\ -\lambda_r, & k = s, \forall k \in N, \forall r \in D \\ 0, & k \neq s, d \end{cases} \quad (4.3)$$

Constraints (4.2) and (4.3) are flow conservation constraints for routing λ_{sd} a number of connection requests/flow from source s to destination d node for primary and backup paths, respectively. These equations maintain traffic flow at the source node, destination, and intermediate nodes of the network. At the source node, the difference between the incoming traffic volume and outgoing traffic volume is λ_{sd} . Outgoing traffic volume and incoming traffic volume are equal on intermediate nodes. The difference between incoming and outgoing traffic is maintained by flow conservation constraint at 0 to ensure all the incoming traffic is going out of the nodes. The flow conservation constraint tries to maintain the condition of traffic flow at a destination node.

$$p_{xy}^r + b_{mn}^r \leq 1, \forall r \in D, \forall (m = x, n = y) \in E \quad (4.4)$$

$$p_{xy}^r, b_{mn}^r = \{0,1\}$$

Constraint (4.4) guarantees link disjointness of a failure in primary from the corresponding backup path, which assures that if a link (x, y) fails, the connection from s to d cannot be the route through

a link (x, y) . Besides energy consumption and QoS, network survivability is the main concern for network operators. For each connection request, link-disjoint working and protection lightpaths must be provided to guarantee 100% single link failure survivability.

$$p_{xy} = \sum_{r \in D} p_{xy}^r, \quad \forall (x, y) \in E \quad (4.5)$$

$$b_{mn} = \sum_{r \in D} b_{mn}^r, \quad \forall (m, n) \in E \quad (4.6)$$

$$p_{xy} + b_{mn} \leq W, \quad \forall (x, y) \in E, \quad \forall (m, n) \in E \quad (4.7)$$

Constraints (4.5) and (4.6) define the number of wavelengths employed by primary paths on the link (x, y) and backup wavelengths that require to be reserved on the link (m, n) , respectively. This Equation calculates the total traffic on a given link represented by the total flow of all demands passing through that link.

Constraint (4.7) defines the maximum amount of resources (wavelengths) assigned to the traffic flow, i.e., the total number of lightpaths traverse on the link (x, y) and link (m, n) for all source-destination pair connection requests on primary and backup paths. This Equation restricts the total number of wavelengths used to provide primary and backup paths not to exceed the total number of available wavelengths, W in the respective links.

$$\sum_{r \in D} (p_{xy}^r + b_{mn}^r) d_r \leq T_L C_{xy} W, \quad \forall (m = x, n = y) \in E \quad (4.8)$$

Equation (4.8) ensures maximum link utilization for a congestion reduction constraint, which means the total flow on the link (x, y) of the active and backup paths cannot exceed $T_L C_{xy} W$. If there is traffic on it, the link is in use, and the backup path should reserve d_r bandwidth for request r . This constraint also prevents routing a demand through a sleeping link.

$$M \cdot lp_{xy} \geq p_{xy}, \quad \forall (x, y) \in E \quad (4.9)$$

$$M \cdot lp_n \geq p_n, \quad n \in N \quad (4.10)$$



Equations (4.9) and (4.10) are constraints that define the value of decision variables to determine whether a link or node, respectively, are used by any primary path. Such constraints force devices supporting primary light paths to be active. Devices not supporting any light path are turned off.

$$lp_{xy} + s_{xy} \leq 1, \quad \forall (x, y) \in E \quad (4.11)$$

$$lp_n + s_n \leq 1, \quad \forall n \in N \quad (4.12)$$

$$b_{xy} - Mp_{xy} \leq Ms_{xy}, \quad \forall (x, y) \in E \quad (4.13)$$

Constraints (4.11) and (4.12) define that a link and node, respectively, are used in a primary path or switched into the sleeping mode or not. It means link (x, y) and node n cannot work and sleep. Constraint (4.13) sets link (x, y) in sleeping mode only when this node is not used as primary by any connection request. Only if the devices in links and nodes are utilized entirely for protection can they be put into sleep mode. The possibility of putting to sleep a network element is naturally constrained by the network's capability to provide the required QoS.

The constraints (4.8), (4.11) - (4.13) are additional constraints for this thesis that added for the general formulation for the energy-aware survivable routing with the DPP approach.

4.2.4 Trade-off Optimization Problem

In this section, the trade-off optimization problem is formulated as a multi-objective MILP optimization model to minimize the joint total network energy consumption and the blocking probability of connection requests via optimally routing a link disjoint working and backup paths. To develop the multi-objective MILP model, use the scalarization technique (α), and this problem formulation uses the same constraints to the above EADPP optimization model constraints and adds one constraint.

Objective function:

$$\text{Minimize} \quad \alpha \cdot E_{\text{total}} + (1 - \alpha)BP \quad (4.14)$$

The objective function for the MILP formulation given in Equation (4.14) above has two parts. The first part of the objective function is used to minimize the energy consumption of active network devices. The second part is used to minimize the number of blocked connection requests.

Constraints:

Constraints: (2) - (13)

$$BP = \left(|D| - \sum_{\forall r} A_r \right) \quad (4.15)$$

$$\sum_{w=1}^W \lambda_r = A_r, \forall r \in D \quad (4.16)$$

Equation (4.15) is the blocking probability that calculating the difference between the total number of connection demands or requests $|D|$ and the total number of successfully provisioned connection requests. In this Equation, α is the scalarization parameter that makes a trade-off between these objectives.

Scalarizing a multi-objective optimization problem is an a priori methodology, which implies formulating a single-objective optimization problem such optimum solutions to the single-objective optimization problem are Pareto optimal solutions to the multi-objective optimization problem [35]. Instead of a single solution that optimizes all criteria simultaneously, a set of tradeoff solutions can only be improved in one criterion by deteriorating another criterion simultaneously. These solutions are called Pareto optimal. Pareto optimal solutions of real-valued optimization problems usually form a manifold (i.e., collection of points forming a certain kind of set) within the objective space referred to as Pareto front.

Constraint (4.16) ensures that the total number of lightpaths/connection requests r from node s to node d are successfully provisioned and allocated on a wavelength.



Chapter 5

Result and Discussion

The mathematical formulation of the energy-aware model proposed in this thesis, including the input parameters, decision variables, and constraints is discussed in detail in Chapter 4. This section shows the results obtained for the proposed energy-aware approach and gives the proposed model's optimization using the MATLAB optimization toolbox. The results show that the energy-saving obtained by implementing the model and the impact on QoS parameters such as link congestion and blocking probability. The mathematical optimization of the model in Section 4.2 is implemented in the MATLAB optimization toolbox to mainly show the energy-saving and link sleep mode operation in the given network scenarios. Solve this problem in static scenarios. In addition to energy-saving, find the optimal trade-off between energy consumption and blocking probability.

5.1 Experimental Topology and Network Configuration

Ethio-telecom network topology, such as Addis Ababa (AA) optical backbone network topology shown in Figure 5.1, is considered as a reference topology. The AA network topology consists of 10 nodes and 48 unidirectional links. Each link supports 40 wavelengths, and each wavelength supports up to 40Gbps. The AA optical backbone network has no amplifiers (OLA sites) due to the short distance between nodes; the OLA nodes are given as input for the model to calculate the link power consumption. So the evaluation of the model using the total energy consumption of the AA optical backbone network does not use the link energy consumption and only uses the total energy consumption of active node devices or powered on devices supported on the operational network paths.

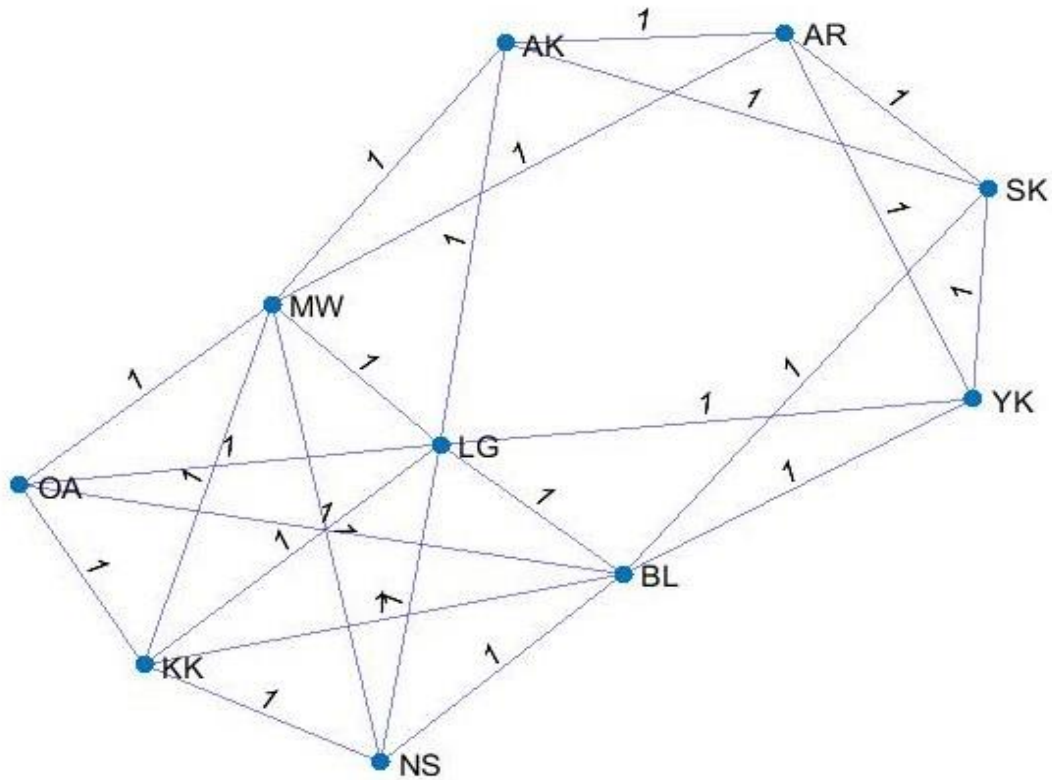


Figure 5.1: AA Optical Backbone network topology.

In addition to the network topology, the traffic demand profiles (traffic matrix), each link capacity, and other input parameters listed in Section 4 are also given as input to the optimization model. For different sets of connection requests, generated a traffic matrix based on a uniform distribution across source and destination nodes by using the MatPlanWDM tool. Each connection request requires one wavelength unit of bandwidth and a link-disjoint path pair where the secondary path is used as a dedicated protection path.



Table 5.1: Sample network traffic demand matrix

	AK	AR	SK	YK	BO	NS	KK	OA	MW	LG	Total
AK	0	40	40	0	0	0	0	0	40	40	160
AR	40	0	40	40	0	0	0	0	40	0	160
SK	40	40	0	40	40	0	0	0	0	0	160
YK	0	40	40	0	40	0	0	0	0	40	160
BO	0	0	40	40	0	40	40	40	0	40	240
NS	0	0	0	0	40	0	40	0	40	40	160
KK	0	0	0	0	40	40	0	40	40	40	200
OA	0	0	0	0	40	0	40	0	40	40	160
MW	40	40	0	0	0	40	40	40	0	40	240
LG	40	0	0	40	40	40	40	40	40	0	280
Total	160	160	160	160	240	160	200	160	240	280	1920

The energy consumption of the deployed network element depends on the configuration of the specified site. The optical network devices' power consumption values are chosen by averaging the data provided in [48]. It is assumed that the OXC and the transceiver's energy consumption are the same for all nodes. The power drained by transceivers, P_{Tx} and P_{Rx} is equal to 7W, respectively, an optical amplifier is 12 W, and the switching fabric P_{OXC} is 6.4 W. The power consumption parameters of the optical components are taken from [35], which are summarized in Table 5.1.



Table 5.2: The value of power model parameters

Parameter	Value (W)
ϵ_{oxc}	6.4
ϵ_s, ϵ_r	7
ϵ_s	1.757
ϵ_a	12
\varnothing_n	150

Another critical consideration in solving the optimization problems is the computation time. MATLAB's `intlinprog` uses branch and bound algorithm to solve MILPs model, and this algorithm suffers from exponential worst-case complexity. Finding a solution is, thus, time-consuming except for a few nodes network topology. The optimality gap option of the tool can be used to get the optimal solution in a reasonable amount of time. The optimality gap is defined as the difference between the upper and lower bands in the branch and bound algorithm. A tolerable 5 % is chosen in all scenarios to minimize the computation time.

5.2 Optimization Result and Discussion

In this section, the proposed energy-aware model is implemented in the Addis Ababa optical backbone network; the performance of the proposed energy-aware model is evaluated for different metrics, such as energy consumption, blocking probability, and link utilization. In addition to energy consumption minimization, analyze the impact of the energy-aware strategy on network performance. To evaluate the proposed model's energy efficiency, introduce the energy-unaware system (EUDPP) for comparison purposes. Another energy-saving method also uses minimum power with devices in sleep mode (MP-S) in 1:1 dedicated path protection [13], where the sleep mode status is accounted for protection devices only. The difference between the proposed energy-aware model in this thesis, i.e., EADPP, for the energy-saving aspect integrates Energy-aware routing and sleep mode operation with link utilization and link disjoint path constraints.

5.2.1 Energy Consumption

The Energy-saving scenario for AA optical backbone network is assessed using the given model. Energy consumption is one of the performance metrics to evaluate the proposed energy-aware model. The detailed result obtained for the proposed energy-aware model (EADPP), with compared to another energy-saving approach, i.e., minimum power with devices in sleep mode (MP-S), and also the energy-unaware (EUDPP) is discussed below. It shows that the AA optical backbone network has no OLA sites (inline amplifiers) due to the short distance between nodes, the evaluation of the model using power consumption calculation does not use the link power consumption. The total power consumption uses only the node power consumption; this means that energy saving is achieved by switching off node devices (i.e., the power consumed by sleep mode operating devices).

Figure 5.2 shows the total energy consumption of the Energy-aware model (EADPP) with energy unaware (EUDPP) and the power minimization model with sleep mode option applied to only backup devices (MP-S) according to different connection requests (traffic demands) in the AA optical backbone network.

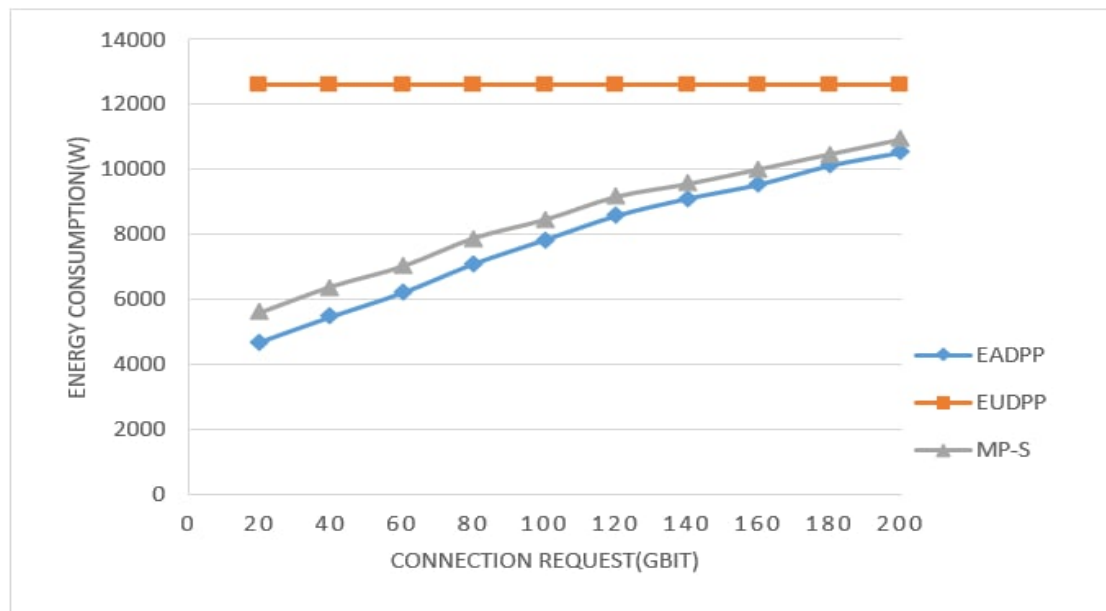


Figure 5.2: Total Energy Consumption Vs. Connection Request for the AA backbone network.



The above figure shows that the Energy unaware model consumes more power than the other two energy-aware models. In the EUDPP case, many resources (the protection resources) are reserved for each connection request, and the redundant idle resources (protection devices) are considered active or fully powered on. The EUDPP is applying the multi-commodity flow (MCF) algorithm, i.e., traditional telecommunication strategy, that is, the power consumption is independent of the traffic load.

In order to achieve energy-saving, the optimization of the proposed energy-aware model minimizes the number of active network devices by setting sleep mode for backup resources and sleeps some links (lightly loaded links), and shifts the traffic carried by those links to the remaining links. It can gain a visible reduction of total energy consumption of the networks, especially under low network traffic load. Because when low network traffic load (small connection request), there are many idle and redundant resources in the network and can be directly switched to sleep mode. Since when the redundant backup (protection) devices are set into sleep mode, energy consumption is consumed only for devices on the working paths. When a connection request increases, the value of Energy consumption of the Energy-aware model will increase. The gain of energy-saving decreases as the traffic load increases since primary and backup wavelengths utilize more links.

The result obtained shows that, by putting protection devices into sleep mode and considering energy efficiency in the routing phase, the proposed energy-aware model EADPP outperforms EUDPP & MP-S in terms of total energy consumption and can achieve energy saving up to 35% in comparison to EUDPP and 5-10% compared with MP-S. For a larger number of connection requests or high network traffic load, EADPP behaves close to MP-S. Because at a high load, all network resources need to be utilized, which reduces packing primary paths. The limitation of this thesis is more energy-saving at low traffic load or small connection requests.

5.2.2 Link Usage

Figure 5.3 illustrates the number of links used in the network (active and sleep links) based on network load. The previously displayed energy consumption is due to the efficient use of network devices that are already turned on, as explained previously. When a traffic load or connection request increases, many links are active, and thus more energy is consumed.

In order to achieve energy-saving, the model sleeps some links and shifts the traffic carried by those links to the remaining links. The number of links operating in sleep mode is proportional to the amount of power saving obtained.

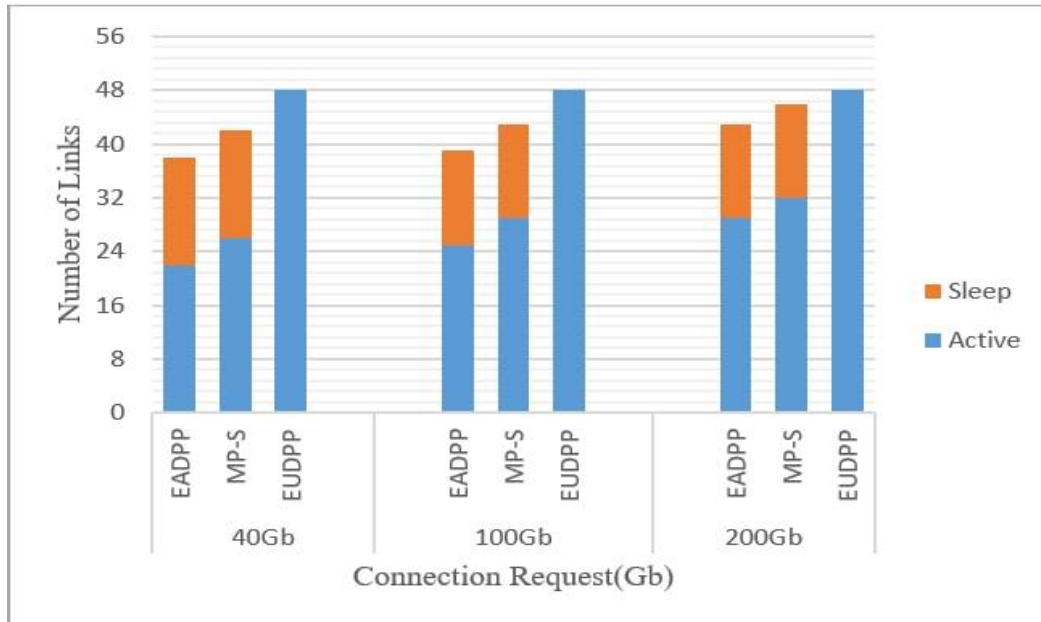


Figure 5.3: Total number of links whose devices are set active and sleep mode for a different connection request.

EADPP binds primary or working wavelengths in some links to decrease the idle, lightly loaded links energy consumption. Backup path links can be put into sleep mode until the occurrence of failure. The result shows a considerable improvement in EADPP compared with EUDPP in terms of the number of backup links in standby (sleep) mode for different traffic loads or various numbers

of connection requests. That means no sleep mode approaches are applied in EUDPP, i.e., 100% of the deployed links are utilized for the network flow.

The optimization result of the modified AA backbone network topology is depicted in Figure 5.4. As shown in Figure, when applying the proposed optimization model at a 40Gbit connection request (See Table 5.1, a traffic demand matrix), four bidirectional links are reduced from the existing network topology by using an energy-aware routing with link utilization and link disjoint path constraints. It is clearly shown that energy saving can be achieved by minimizing active network elements.

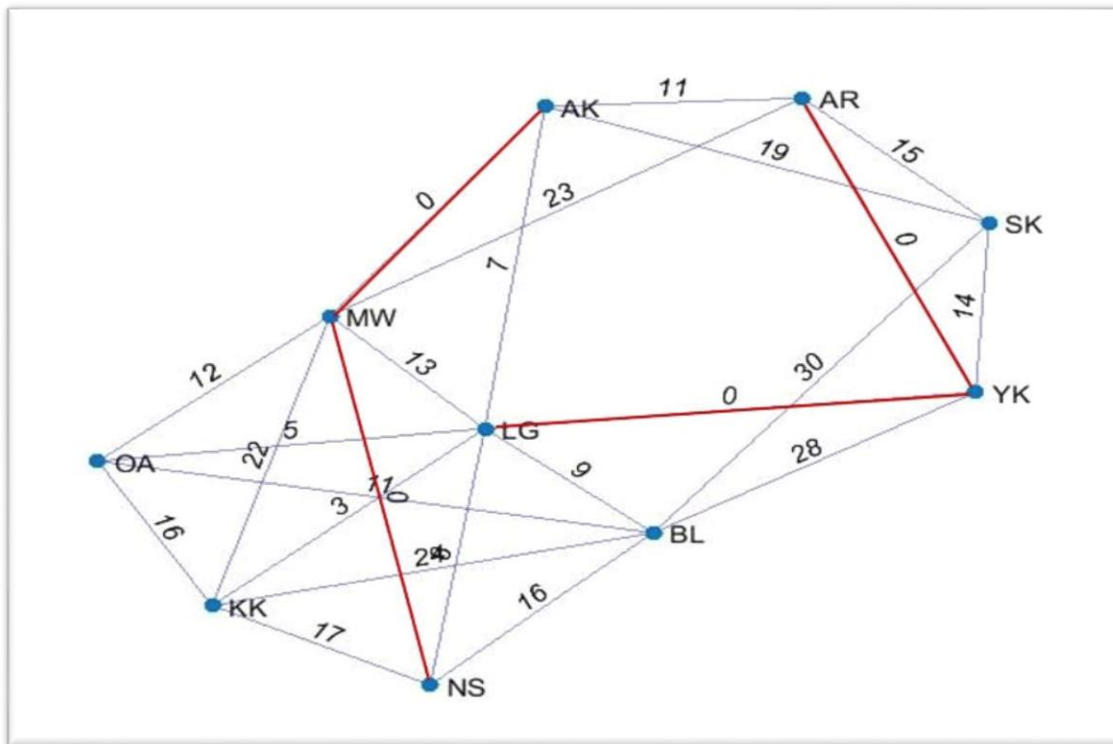


Figure 5.4: Optimization of AA Optical Backbone network topology with turn-off links.

The network topology and architecture, as well as the route traffic takes, have an impact on switching traffic from source to destination. By carefully optimizing network topology and enabling traffic flow to utilize the minimum amount of resources possible while also turning off network devices, significant savings can be obtained.



5.2.3 Trade-off: optimization result

This section presents the optimal result of a trade-off between energy consumption and the blocking probability. Based on the multi-objective optimization problem formulation discussed in chapter 4, apply the Pareto front principle to evaluate the trade-off between the two objectives (Energy consumption and blocking probability). The trade-off optimization result will show the effect of the energy-aware resilience approach on the network performance (i.e., blocking probability). Blocking probability is an essential metric for network performance evaluation since reducing energy consumption in some cases may cause a higher blocking probability.

For a given parameter α and a traffic matrix, a point of Pareto optimal value is found by solving the optimization model for different connection requests. In order to achieve the complete Pareto front optimal value, i.e., the lower bound for energy consumption and blocking probability, the α value was varied between 0 to 1.

The Pareto front of the optimization model is shown in Figure 5.5, which is the trade-off between energy consumption and blocking probability for a 40 Gbit traffic demand (connection request). For the considerations of universality and simplicity, normalized the energy consumption by the maximum energy consumption (the network's total energy consumption divided by the maximum energy consumption).

The graph of energy consumption versus blocking probability is shown in the Figure below, when the energy consumption minimizes, the blocking probability increases, which means considerable energy savings are achievable, but there is a significant increase in the network blocking probability.

From the result illustrated in Figure 5.5, the probability of a connection request being blocked increases as energy savings improve. The reason for this increase in blocking probability is decreasing available resources resulting from reduced network devices for minimizing power consumption and a rise in contention for resources as traffic demand between source-destination pairs grows.

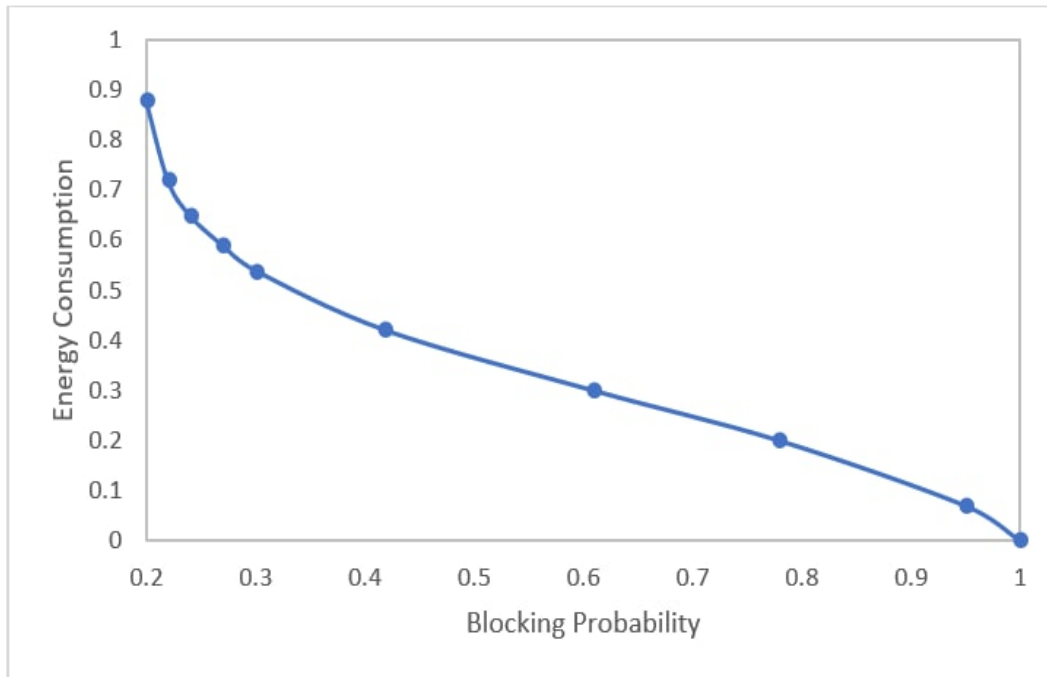


Figure 5.5: Energy consumption Vs. Blocking probability at 40 Gbit connection request.

Figure 5.5 indicates that significant energy savings of up to 60% are possible as a consequence of a large increase in the network blocking probability of up to 0.4. When the energy consumption of the network increases, which means all the available network resources are turned on, in this case, the blocked connection request decreases. On the other hand, when reduced energy consumption, many network resources are minimized, and also the blocking probability also increased. The figure also illustrates the different tradeoff results between these two objective functions, should an operator be ready to compromise on total network energy consumption. For example, with the energy consumption values of between 70% and 90%, there is a little significant impact on the blocking probability.

The optimal result confirms that energy efficiency and network performance parameters are conflicting objectives; this also ensures that an approach that accounts only for minimizes network energy consumption might lead to unacceptable network performance degradation. From the above result depicted in Figure 5.5, it is clearly shown that a reasonable compromise can be obtained to save energy by trading a small amount of blocking probability.



Chapter 6

Conclusion and Future Work

6.1 Conclusion

Due to the rise within the high-bandwidth applications over the Internet, the energy consumption of Information and communication technology (ICT) equipment is also increasing rapidly. Therefore, high redundancy network devices and high link utilization in today's large networks need to develop strategies to reduce energy consumption and provide unique opportunities for an energy-aware approach. By switching traffic onto fewer paths, one can free some links from carrying data traffic and put them to sleep for energy saving. This thesis presents an energy-efficient resilience strategy for survivable optical WDM networks design that exploits the energy-aware routing and sleep mode of devices supporting protection paths. The thesis aims to minimize the energy consumption of optical backbone networks with consideration of network survivability. To achieve this goal, proposed the EADPP approach and formulate the optimization problem in the MILP optimization model to minimize the energy consumption of active network devices under constraints of link utilization and link disjoint backup path for each connection request. This research work enhances network resilience, reduces energy consumption using optimization techniques, and significantly improves network resilience and energy efficiency in networks.

The optimal results show that energy savings are achieved by:

- Properly routing, aggregate the traffic flow, and turn off devices in unloaded network elements.
- Provisioned primary and secondary paths on separate links (a link disjoint paths) and put the backup or protection path devices into sleep mode.

Routing a connection request via two disjoint paths can be a tradeoff between reducing energy usage and enhancing network performance. Energy efficiency and network blocking probability are two conflicting objectives, to address the trade-off problem, this thesis proposed a multi-



objective MILP optimization model of a tradeoff between energy consumption and the blocking probability.

After evaluating the tradeoff optimization model, the result shows that it can achieve considerable energy savings in real networks with a minor impact on network performance.

6.2 Future Work

This thesis considers routing schemes to improve network survivability and energy efficiency considering a single failure scenario. Multiple failure survivability is determined to improve these routing schemes for real situations in networks. This energy-efficient design in networks with multiple failure survivability needs to be explored for the future direction.

Additionally, this thesis studies and analyze the tradeoff optimization problem between energy consumption and the blocking probability. Further investigation is needed to find the optimal value or acceptable tradeoff value in terms of different traffic demands or connection requests.



References

- [1] C. Lange and A. Gladisch, "Energy consumption of telecommunication networks - a network operator's view," OFC/NFOEC'09, Workshop on Energy Footprint of ICT: Forecast and Network Solutions, San Diego, CA, March 2009.
- [2] S. Lambert, W. Van-Heddeghem, W. Vereecken, B. Lannoo, D. Colle, et al., "Worldwide electricity consumption of communication networks," *Optics Express*, vol.20, issue.26, pp.513-524, 2012.
- [3] R. Leepila, "Routing Schemes for Survivable and Energy-Efficient Networks," PhD. Thesis, Department of Information and Communication Engineering, The University of Electro-Communications (2014).
- [4] C. Lange, D. Kosiankowski, R. Weidmann and A. Gladisch, "Energy consumption of telecommunication networks and related improvement options," *IEEE Journal of selected topics in Quantum Electronics*, 17(2), 285-295., 2011.
- [5] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti., "Energy Efficiency in the future internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE Communications Surveys and Tutorials*, vol.13, no.2, pp.223-244,2011.
- [6] F. Idzikowski et al., "A survey on energy-aware design and operation of core networks," *IEEE Commun. Surveys and Tuts.*, vol. 18, no. 2, pp.1453–1499, Second Quarter 2016.
- [7] G. Shen, J. Deng, and P. Ho, "Green backbone optical networks: The way forward," *Proc. ICICS*, pp. 1-5, 2011.mm
- [8] K. Sato, "Optical technologies that enable green networks," *IEEE 12th International Conference on Transparent Optical Networks, ICTON'10*, pp.1-4, June-July 2010.
- [9] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, "Energy Efficiency in Telecom Optical Networks," *IEEE Communications Surveys and Tutorials*, vol.12, no.4, pp. 441-458, Nov. 2010.
- [10] D. Xiaowen, "Green Optical Networks," Ph.D. Dissertation, School of Electronic and Electrical Engineering, The University of Leeds, Leeds, England,2012.
- [11] J. López Vizcaíno, "Energy-efficient design of optical transport networks," Ph.D. dissertation, Technical University of Dortmund, Munich, 2016.
- [12] M. Zhang, C. Yi, B. Liu, and B. Zhang, "GreenTE: Power-Aware Traffic Engineering." In *ICNP*, 2010.
- [13] A. Muhammad and et al., "Energy-efficient WDM network planning with dedicated protection resources in sleep mode," in *GLOBECOM proc.*, 2010.
- [14] C. Cavdar et al., "Energy-efficient design of survivable WDM networks with shared backup," in



-
- GLOBECOM, 2010.
- [15] B. Luo, W. Liu, A. Al-Anbuky, “Energy aware survivable routing approaches for next-generation networks design” M.Sc. Thesis, Auckland University of Technology, 2013.
- [16] S. Jalalinia and C. Cavdar, “Green and resilient design of telecom networks with shared backup resources,” *Optical Switching and Networking*, vol.23, pp.97–107, January 2017.
- [17] A. Jirattigalachote, C. Cavdar, P. Monti, L. Wosinska, and A. Tzanakaki, “Dynamic provisioning strategies for energy efficient WDM networks with dedicated path protection,” *Optical Switching and Networking*, vol. 8, no. 3, pp. 201–213, July 2011.
- [18] F. Musumeci and et al., “Energy-efficiency of protected IP-over-WDM networks with sleep-mode devices,” *J. High Speed Networks*, vol. 19, no. 1, pp. 19–32, 2013.
- [19] R. Ramaswami, K. Sivarajan and G. Sasaki, “*Optical Networks*, 3rd ed. USA: Morgan Kaufmann, ” 2010.
- [20] P. Wiatr, P. Monti, L. Wosinska, “Power Savings versus Network Performance in Dynamically Provisioned WDM Networks,” *IEEE Communications Magazine*, vol. 50, pp.48-55, May 2012.
- [21] J. M. Simmons “Network design in realistic All-Optical backbone networks,” *IEEE Communications Magazine*, vol. 44, no. 11, pp. 88-94, November 2006.
- [22] A. Bhandari and J. Malhotra, “A Review on Network Survivability in Optical Networks,” vol. 5, pp. 97-101, December 2015.
- [23] A. Hmaity, F. Musumeci, and M. Tornatore, “Power reduction strategies with differentiated quality of protection in IP-over-WDM networks,” *Annals of Telecommunications*, vol.73, no.1-2, pp.81–94, February 2018.
- [24] L. Wosinska *et al.*, “Network resilience in future optical networks,” in *Towards Digital Optical Networks*, vol. 5412 LNCS, 2009, pp. 253–284.
- [25] W. Kebede, “Constraint-Based Hybrid Resiliency Mechanisms for Better Resource Utilization and Service Performance Quality in ASON SLA,” Addis Ababa University, 2018.
- [26] J. Shen and Z. Mi, “Service-based survivability scheme in Intelligent Optical Networks,” *IEEE 12th International Conference on Communication Technology*, Nanjing, 2010, pp. 784-787.
- [27] D. A. Schupke, M. Jager and R. Hulsermann, “Comparison of resilience mechanisms for dynamic services in intelligent optical networks,” *Fourth International Workshop on Design of Reliable Communication Networks (DRCN) Proceedings.*, 2003, pp. 106-113.
- [28] A. Kavitha, “Performance of Optical Networks: a Short Survey,” *International Journal of Engineering Science and Technology (IJEST)*, Vol. 4 No.02, pp. 600-605, February 2012.
- [29] W. Wei, Z. Qingji, O. Young and L. David, “Differentiated Integrated QoS control in the optical



-
- Internet,” *IEEE Communications Magazine*, Vol. 42, No. 11, pp. S27-S34, 2004.
- [30] G. Karpagarajesh and M. Vijayaraj, “Blocking Probability in All-Optical WDM Network Using IMCA,” no. May, pp. 1068–1077, 2016.
- [31] K. Yassin, “QoS Performance Evaluation of RWA Algorithms under Different Resilience Mechanisms: in the Case of Ethio-Telecom Backbone Network,” Addis Ababa University, 2019.
- [32] W. Van Heddeghem, M. C. Parker, S. Lambert, W. Vereecken, B. Lannoo, D. Colle, M. Pickavet and P. Demeester, “Using an analytical power model to survey power saving approaches in backbone networks,” in *Networks and Optical Communications (NOC), 17th*, 2012, pp. 1-6.
- [33] Y. Belayneh, “Sleep mode operation of optical networks for energy consumption minimization: a case study of ethio telecom backbone optical transport network,” M.Sc.Thesis, Depart., Elect. &Comp. Eng., AAIT, Addis Abeba, Ethiopia, 2018.
- [34] P. Wiatr, P. Monti, L. Wosinska, “Green lightpath provisioning in transparent WDM networks: pros and cons,” in: Proc. of IEEE International Symposium on Advanced Networks and Telecommunication Systems, ANTS, 2010, Mumbai, India, December 2010.
- [35] S. I. Pouremami and B. Bakhshi, “On the trade-off between power-efficiency and blocking probability in fault-tolerant WDM networks,” *J. Netw. Comput. Appl.*, Vol. 58, no. 1084–8045, pp. 255–266, 2015.
- [36] E. Telecom, “Low Level Design for LOT-4 DWDM AA, Northern, Eastern, Somali Regions Backbone Transmission Project,” unpublished.
- [37] OptiX OSN 8800/6800/3800 V100R008C10 Hardware Description, Issue 03, Huawei Technologies Co., LTD, Shenzhen 518129, PRC, 2014.
- [38] W. Van Heddeghem et al., "Power consumption modeling in optical multilayer networks", *Photon. Netw. Commun.*, vol. 24, no. 2, pp. 86-102, Oct. 2012.
- [39] A. Teka, “Optimized Line Amplifier Placement for Energy Saving: a Case Study of ethio telecom Optical Backbone Network,” M.Sc. Thesis, Depart., Elect. & Comp. Eng., AAIT, Addis Abeba, Ethiopia, 2020.
- [40] A. Bianzino, J. L. Rougier, D. Rossi, C. Chaudet, “A Survey of Green Networking Research,” *IEEE Communications Surveys & Tutorials*, vol. 14, pp. 3-20, Dec. 2012.
- [41] Y. Ye, F. Jiménez Arribas, J. Elmighani, F. Idzikowski, J. López Vizcaíno, P. Monti, et al., "Heddeghem: Energy-efficient resilient optical networks: Challenges and tradeoffs", *IEEE Communications Magazine*, vol. 53, no. 2, pp. 144-150, 2015.
- [42] R. Bolla, R. Bruschi, A. Cianfrani, and M. Listanti, “Enabling backbone networks to sleep,” *IEEE Netw.*, vol. 25, no. 2, pp. 26-31, Mar./Apr. 2011.
- [43] C. Eyupoglu, M.A. Aydin, “Energy efficiency in backbone networks,” *Procedia-Soc. Behav.*



Sci., 195, pp. 1966-1970, 2015.

- [44] B. Addis, A. Capone, G. Carello, L. G. Gianoli, and B. Sansò, Energy management through optimized routing and device powering for greener communication networks. *Networking, IEEE/ACM Transactions on*, issue.99, pp.1-1, 2013.
- [45] E. Oki, *Linear Programming and Algorithms for Communication Networks: A practical guide to Network Design, Control, and Management*, CRC Press, 2016.
- [46] W. Dai, J. Zhang, and X. Sun, “On solving multi-commodity flow problems: An experimental evaluation,” *Chinese J. Aeronaut.*, no. January 2017.
- [47] P. Wiatr, “Energy Saving vs. Performance: Trade-offs in Optical Networks,” PhD dissertation, School of Information and Communication Technology, KTH Royal Institute of Technology, Stockholm, Sweden, May 2016.
- [48] W. Van Heddeghem, F. Idzikowski, “Equipment power consumption in Optical multilayer networks – source data,” Dept. Info. Tech., Ghent University Belgium, Report Number: IBCN-12-001-01, January 12th, 2012.

Energy-Aware Resilience Approach for Survivable Optical Network Design: a case study of Ethio Telecom

Birtukan Gezie
School of Electrical and Computer
Engineering
Addis Ababa University
Addis Ababa, Ethiopia
birtegez@gmail.com

Dr. Yalemzewd Negash
School of Electrical and Computer
Engineering
Addis Ababa University
Addis Ababa, Ethiopia
yalemzewdn@yahoo.com

Abstract— Today’s optical backbone telecommunication network infrastructures are deployed with redundant resources considering the backup resources for protection to be resilient against link failures and serving a tremendous amount of data transmission. Due to the rapidly increasing traffic demand and the deployed redundant resources, the energy consumption of telecommunication networks is increased. In this research, the energy-efficient resilience approach, which is Energy-Aware Dedicated Path Protection (EADPP) for survivable optical Wavelength division multiplexing (WDM) networks, is investigated; considering the sleep mode and energy-aware routing strategies is taken into account for the energy consumption minimization method with 1:1 dedicated path protection (DPP). The Mixed Integer Linear Programming (MILP) model is proposed and formulated to minimize the energy consumption of active network elements while putting idle and redundant backup resources to sleep mode, which takes link utilization and a link disjoint backup path together with other constraints. The proposed model’s evaluation is implemented using Matlab toolbox, taking Ethio telecom Addis Ababa optical backbone network topology as a case study. The result is compared to the energy-unaware model and the other power consumption minimization model. Furthermore, using the multi-objective MILP optimization model, this research investigated the trade-off between energy consumption and blocking probability and found optimal trade-off problems. The optimal solution indicates that it is possible to save a significant amount of energy while only having a little influence on network performance.

Keywords— Energy-aware, Energy efficient, Resilience, Survivable WDM network, Dedicated Path Protection, QoS, MILP.

I. INTRODUCTION

According to the global connectivity via massive networks and explosive growth of communication technology, the high bit-rate services (like video-streaming, cloud computing, etc.) and the information exchange through the Internet have been highly increased [1]. It implies that bandwidth-hungry applications will be expanded. To keep up with the continuous growth of data traffic, new network technologies and structures were required. As a result, the volume of traffic on broadband telecom networks is increasing, as are network capacity expansions, both of which significantly increase the operational expenditure (OpEx) and greenhouse gas emissions. Energy efficiency does not improve with newly designed network equipment; it is predicted that energy consumption will be one of the main constraints for network operators [2].

To avoid an increase in telecom network energy consumption, traffic must be transported via the network

using more energy-efficient solutions at reasonable costs. Wavelength division multiplexing (WDM)-based optical communication networks provide massive transmission capacity. That is used to the networks can carry a vast amount of data which is expected to solve several challenges in the next-generation Internet network infrastructure [3]. Optical WDM networks have extremely high-capacity links and nodes, and a single point of failure in the network can result in a loss of connection, the interruption of a large number of services [2], and a reduction in the Quality of Service (QoS) offered to the end-user. From the perspective of the service provider, this is a major issue. To address this issue, different protection mechanisms or backup resources for survivability have been developed for WDM networks to enable the rerouting of the affected traffic upon a failure. In backbone network design, ensuring resiliency against network failures is critical [4].

Network Resilience (sometimes called survivability) is defined as the ability of a network to recover from a failure or to provide uninterrupted service in the presence of failure [5]. Based on their recovery path or link provisioning time, survivability mechanisms can be classified into two broad groups: restoration (reactive) and protection (proactive).

This research work considers an optical WDM network with 1:1 dedicated path protection to enable resilience against single-link failure. Primary (working) paths must be provisioned and protected by dedicated link-disjoint backup (protection) paths, ensuring that each connection request is protected against a single link failure.

The contribution of the backbone network to total network power consumption is increasing rapidly in line with traffic growth [6]. Optical backbone networks Energy consumption is increasing because of two main reasons: the exponential growth of bandwidth demands and also increases the availability to ensure the protection of high-capacity optical networks [7] [8].

Optical networks energy efficiency and new energy-aware solutions can be achieved in the design solutions and optimization techniques. This research investigated the energy-efficient resilience approach for the energy consumption minimization method with 1:1 dedicated path protection (DPP), which focuses on proposed Energy-aware dedicated path protection (EADPP), considering the Ethio telecom Addis Ababa optical backbone network topology.

The contributions of this research are: formulate a Mixed integer linear programming (MILP) model for EADPP to interpret the goal of minimizing the energy consumption of active network devices while putting idle and redundant backup devices to sleep mode under constraints of link

utilization and a link disjoint backup path for each request. This research also proposes a multi-objective MILP model to find the optimal trade-off between power consumption and blocking probability.

The remaining part of the research work is organized as follows. Section II discusses an overview of relevant literature. Section III presents the research's system model, including the power consumption model and the MILP problem formulation of the proposed energy-aware model. Section IV evaluates the proposed approach, and the detailed results of the research are discussed. Finally, conclusions are drawn based on the previously mentioned sections, and possible future works are discussed in section V.

II. RELATED WORK

Some of the existing literature for Energy-Aware approaches focusing on Resilience may come in place to reduce the power consumed with current protection schemes. Most of these strategies intend to save energy by concentrating backup paths in separate links, and devices on these links can be set into sleep mode without being constrained by the presence of working paths.

The authors in [9] have presented an energy-efficient planning strategy for survivable WDM networks and proposed ILP formulation. They recommend that the network protection device be put to sleep mode. It was assumed that these devices could be immediately turned on upon occurrence of failure. The author achieved 25% of power-saving that devices for network protection are set to sleep mode. Similarly, the authors in [10] investigated the energy-efficient design of survivable WDM networks using shared backup resources considering both energy efficiency and network survivability. The paper focused on energy-efficient survivable network design where backup resources are shared for efficient capacity consumption. ILP model for energy-efficient shared backup protection is proposed to minimize both capital and operational expenditures and enable the sleep mode operation for the links associated only with the backup paths. And also can be achieved up to 40% energy savings compared to the energy-unaware shared backup protection approach. Both the research works on the above only considered energy-saving without considering the network performance.

Energy efficiency in protected WDM networks has also been studied under dynamic traffic conditions [8]. The paper focused on the power consumption of survivable WDM networks where the traffic is rerouted upon a failure using a predetermined and already reserved secondary path and used 1:1 dedicated path protection (DPP). The authors proposed different energy-aware dedicated path algorithms, i.e., EA-DPP, EA-DPP-DifEA-DPP-MixS, and discussed the trade-off between energy-saving and blocking probability. Finally, the proposed sleep-aware algorithms are compared with another energy-aware connection provisioning algorithm; the power consumption reduction of up to 25% can be achieved by setting protection resources in a sleep mode.

Research paper [11] studied the Energy-aware survivable Routing approach for Next Generation Network design. The authors proposed three energy-aware survivable routing algorithms: EABP 1+1, EABP 1:1, and EASBP, which considered energy reduction and take network survivability. They aimed to tackle the trade-off problem between energy efficiency and network survivability and developed an ILP

formulation for the three energy-aware models. Finally, the authors simulated the models using two network topologies and compared the performance of three routing algorithms. EABP 1:1 is the most energy-efficient model and could save 90% of energy costs. EASBP could provide the best approach to tackle the trade-off problem between energy efficiency and network survivability.

The authors in [12] proposed MILP models for obtaining optimal solutions under various objectives and analyzed the trade-off between capacity and power consumption of various survivability schemes. Power minimization hurts sharing capability in SBP and capacity consumption in both DPP and SBP due to the packing of primary paths. Energy-aware shared path protection (EASPP), a novel energy-efficient method presented by the authors, addresses the trade-off caused by conflicting green and resilient network planning objectives. The author tested the performance of the EASPP algorithm and observed that if power optimization is done without taking care of capacity consumption. The above two researchers considered only capacity consumption on the network performance metrics.

III. SYSTEM MODEL

A. Network Model

The network considered in this research is an optical backbone WDM network. The physical network topology modeled Graph $G(N, E)$, where N is set nodes and E is set of links. Each link $(x, y) \in E$ contains C capacity and W wavelength channels with the same bandwidth.

The network uses the 1:1 dedicated path protection (1:1 DPP) scheme, where another backup path protects each primary path. As a trade-off between energy consumption and network resiliency, each connection request (demands) two disjoint (primary and backup) paths from source node s to destination node d . The backup path is used to reroute the request if a link failure on the primary (active) path. So energy-aware routing with disjoint backup paths can ensure the network is resilient to single link failure. The following assumptions are made:

- 1) *Each connection request has two link disjoint paths and can only be transported via an active primary path. It uses the backup path only if the active working path fails.*
- 2) *Each link device can be set into sleep mode independently. A link can be sleep if there is no traffic on it.*

B. Power Consumption Model

A power model or correct data for devices' power consumption values is required to compute the total power consumption of the network and an approach to reduce this consumption. The overall network power consumption can be calculated as the sum of the power consumption of the network devices or components. In previous studies, different power consumption models, which almost are similar, have been used for optical network segments that follow the same pattern as those applied for the general telecommunication network.

In this research, apply the power model used in [8] [9]. The amount of power consumed by the network devices depends on their operational modes. This model assumes three power modes for optical devices: active, sleep, and off, summarized in Table 1.

TABLE I. POWER CONSUMPTION IN DIFFERENT MODES [8] [9].

Mode	Functionality	Power Consumption
Off	Null	None
Sleep	Prompt switching to active mode	Negligible
Active	Full	Fixed power + Proportional Power

A device is in active mode if at least a working light path is passing through it. In sleep mode, if only backup lightpaths use it, during this mode, each device can be activated instantly in the case of a failure within the network. If there is no light path going through a device, it will be in off mode; in this case, devices do not consume any power. The overall or total power consumed by the optical WDM network is, thus, given by the power consumed by the active devices installed in links and nodes [8] [9].

In this research, network devices in sleep mode are assumed to consume a negligible amount of energy. Under this assumption, an optical WDM network's overall energy consumption can be calculated as the sum of the energy consumed by active devices. As a result, decreasing the number of devices in active mode is comparable to minimizing energy usage. This problem can be tackled in two parts: maximizing the number of network devices that can be potentially put into sleep mode and off mode. The idea of an energy-aware resilience lies behind separating primary and secondary paths and maximizing the resources that can be sleep mode.

Energy Consuming Devices

Amplifiers: Optical amplifiers are the devices used in optical networks to amplify the degraded signal when the signal power falls below a specified threshold.

Transceivers: are the devices used in optical networks to terminate the light paths at each end. It converts the electrical signal from a switch or router to an optical signal.

Transponders: The devices used for service processing in the optical fiber are used to send and receive the signals in the optical fiber.

Optical Cross Connection- The devices in this category are used for cross-connecting services of lower or higher granularity from a specific source port to a particular destination port. An OXC switch is used to switch high-speed optical signals in an optical network.

C. Energy-Aware Resilience approach

This section discusses the energy-efficient strategies for developing the proposed energy-aware approaches in this research. The energy efficiency of survivable optical backbone networks can be improved by using various techniques. The solution consists of planning or operating the optical WDM network to minimize power consumption instead of reducing the resource installation or utilization [9] [13] [14]. Additional improvement can be achieved by enabling a sleep mode state where network resources enter a low-power state during inactivity [9] [13]. Another approach is adopting proportional energy mechanisms, where the device architecture is designed to make energy consumption proportional to the actual load [15].

In order to reduce the energy consumption of optical WDM networks, energy-aware routing strategies have been developed, and sleep mode of operation has been proposed to be used in network equipment [11].

In this research work, the proposed approach within the energy-saving aspect integrates both the energy-aware routing and sleeping mode strategies. To enhance energy saving within the 1:1 DPP scheme obtained by provisioning a link disjoint working and protection paths and setting protection resources in sleep mode.

Energy-aware routing aims at aggregating traffic flows over a subset of the network devices and links, allowing other links and interconnection devices to be switched off [17]. The energy-aware routing with 1:1 dedicated path protection (DPP) is an energy-aware survivable routing strategy that aims to route a primary path, using already provisioned working resources, and routing a secondary path using already provided protection resources [8]

In order to save energy, energy-aware routing with the 1:1 DPP approach applies two ways.

1. Tries to route the connection requests using the minimum number of network devices and Switching off redundant links.
2. Provision primary and backup paths on separate links, then put sleep mode for backup path devices.

D. Problem Formulation

This section will discuss the mathematical problem formulation of the energy-aware resilience mechanisms that will be evaluated. This research proposes MILP formulations for energy-efficient survivable optical networks with 1:1 DPP to protect against single-link failures and formulated as multi-commodity flow (MCF) with different commodities or constraints. The proposed MILP solution finds a link disjoint primary and backup routes for each connection request to minimize the network's energy consumption. The mathematical problem of the EADPP is formulated considering a network topology $G(N, E)$ with $|N|$ a number of nodes and $|E|$ a number of links. The optimization problem is formulated as an MCF model consisting of input parameters, objective function, and constraints.

Notation

- (s, d) : The source and destination nodes of a connection request.
- (x, y) and (m, n) : The links in the physical network topology used by primary and backup path routes, respectively.

Given parameters

- $G(N, E)$: Physical network topology consisting of set N nodes and E of links.
- W : Maximum number of wavelengths supported on each link.
- C_{xy} : Capacity of each link
- D : Set of connection requests or demands.
- r : A request r from source s to destination d .

- d_r : traffic demand of request r .
- λ_r : denotes the traffic in a number of lightpath requests r between any source-destination pair to set up paths allocated on wavelength w .
- M : Constant value used in the Big-M constraints (i.e., greater than twice the maximum node capacities) for the MILP formulation.
- ϵ_t : Energy consumption of a transmitter in a node.
- ϵ_r : Energy consumption of a receiver in a node.
- ϵ_s : Energy consumption of switching devices (i.e., optical switches and wavelength converter) in a node.
- ϵ_a : Energy consumption of an inline amplifier.
- \emptyset_n : Wavelength traffic independent (idle power) energy consumption in node n by the active devices.
- α : the adjustment parameter that trades off between the objectives of the optimization model.

Variables

The model includes the following decision variables.

- p_{xy} : Number of resources used by primary paths on the link (x, y) .
- b_{mn} : Number of resources used by backup paths on the link (m, n) .
- p_{xy}^r : Number of lightpath requests r from s to d passes through a primary physical link (x, y) .
- b_{mn}^r : Number of lightpath requests r from s to d passes through a backup wavelength on the physical link (m, n) when the physical link (x, y) fails.
- lp_{xy} : Binary variable is 1 if a resource on the link (x, y) is used by a primary flow of a connection request, or if a link (x, y) is powered on.
- lp_n : Binary variable is 1 if node $n \in N$ is used by any incoming or outgoing primary flows of a connection request or if node n is powered on.
- s_{xy} : Binary variable is 1 a resource on the link (x, y) is in sleeping state for backup protection, it indicates whether a link (x, y) is in sleeping mode or not.
- s_n : Binary variable is 1 a resource on node n is in sleeping state for backup protection, it indicates whether a node n is in sleeping mode or not.
- E_{total} : The total energy consumption of active network devices.
- A_r : Binary variable is 1 if a request r is successfully provisioned.
- T_L : Link maximum utilization threshold; $0 \leq T_L \leq 1$.

MILP Problem Formulation for EADPP

As shown below, the optimization problem can be formulated as a MILP problem with constraints with the above input parameters and decision variables.

Objective:

$$\begin{aligned} \text{Minimize } E_{\text{total}} &= \sum_{n \in N} \emptyset_n \cdot lp_n + \sum_{(x,y) \in E} (\epsilon_t + \epsilon_r) \cdot p_{xy} \\ &+ \sum_{(x,y) \in E} \epsilon_s p_{xy} + \sum_{(x,y) \in E} \epsilon_a \cdot lp_{xy} \end{aligned} \quad (1)$$

With the given input parameters and decision variables stated above, the objective function for the MILP formulation given in Equation 1 is used to minimize the total energy consumption of active network devices.

Constraints:

$$\sum_{x \in N} p_{xk}^r - \sum_{y \in N} p_{ky}^r = \begin{cases} \lambda_r, & k = d \\ -\lambda_r, & k = s, \forall k, r \in D \\ 0, & k \neq s, d \end{cases} \quad (2)$$

$$\sum_{m \in N} b_{mk}^r - \sum_{n \in N} b_{kn}^r = \begin{cases} \lambda_r, & k = d \\ -\lambda_r, & k = s, \forall k \in N, \forall r \in D \\ 0, & k \neq s, d \end{cases} \quad (3)$$

Constraints (2) and (3) are flow conservation constraints for routing λ_{sd} a number of connection requests from source s to destination d node for primary and backup paths, respectively. These equations maintain traffic flow at the source node, destination, and intermediate nodes of the network.

$$p_{xy}^r + b_{mn}^r \leq 1, \quad \forall r \in D, \quad \forall (m = x, n = y) \in E \quad (4)$$

$$p_{xy}^r, b_{mn}^r = \{0, 1\}$$

$$p_{xy} = \sum_{r \in D} p_{xy}^r, \quad \forall (x, y) \in E \quad (5)$$

$$b_{mn} = \sum_{r \in D} b_{mn}^r, \quad \forall (m, n) \in E \quad (6)$$

$$p_{xy} + b_{mn} \leq W, \quad \forall (x, y) \in E, \quad \forall (m, n) \in E \quad (7)$$

Constraint (4) guarantees link disjointness of a failure in primary from the corresponding backup path, which assures that if a link (x, y) fails, the connection from s to d cannot be the route through a link (x, y) . Constraints (5) and (6) define a number of wavelengths employed by primary paths on the link (x, y) and backup wavelengths that require to be reserved on the link (m, n) , respectively. This Equation calculates the total traffic on a given link represented by the total flow of all demands passing through that link. Constraint (7) defines the maximum amount of resources (wavelengths) assigned to the traffic flow, i.e., the total number of lightpaths traverse on the link (x, y) and link (m, n) for all source-destination pair connection requests on primary and backup paths.

$$\sum_{r \in D} (p_{xy}^r + b_{mn}^r) d_r \leq T_L C_{xy} W, \quad \forall (m = x, n = y) \in E \quad (8)$$

Eqn. (8) ensures maximum link utilization for a congestion reduction constraint, which means the total flow on the link (x, y) of the active and backup paths cannot exceed $T_L C_{xy} W$. If there is traffic on it, the link is in use, and the backup path

should reserve d_r bandwidth for request r . This constraint also prevents routing a demand through a sleeping link.

$$M \cdot lp_{xy} \geq p_{xy}, \quad \forall (x, y) \in E \quad (9)$$

$$M \cdot lp_n \geq p_n, \quad n \in N \quad (10)$$

$$lp_{xy} + s_{xy} \leq 1, \quad \forall (x, y) \in E \quad (11)$$

$$lp_n + s_n \leq 1, \quad \forall n \in N \quad (12)$$

$$b_{xy} - M p_{xy} \leq M s_{xy}, \quad \forall (x, y) \in E \quad (13)$$

Equations (9) and (10) are constraints that define the value of decision variables to determine whether a link or node, respectively, are used by any primary path. Such constraints force devices supporting primary light paths to be active. Devices not supporting any light path are turned off. Constraints (11) and (12) define that a link and node, respectively, are used in a primary path or switched into the sleeping mode or not. It means link (x, y) and node n cannot work and sleep. Constraint (13) sets link (x, y) in sleeping mode only when this node is not used as primary by any connection request. The devices in links and nodes can be put in sleep mode only if used exclusively for protection purposes.

The constraints (8), (11) - (13) are additional constraints for this Thesis that added for the general formulation for the energy-aware survivable routing with the DPP approach.

Trade-off Optimization Problem

In this section, the trade-off optimization problem is formulated as a multi-objective MILP optimization model to minimize the joint total network energy consumption and the blocking probability of connection requests via optimally routing a link disjoint working and backup paths. To develop the multi-objective MILP model, use the scalarization technique (α), and add one constraint to the above EADPP optimization model constraints.

Objective:

$$\text{Minimize } \alpha \cdot E_{\text{total}} + (1 - \alpha)BP \quad (14)$$

Constraints:

$$BP = \left(|D| - \sum_{\forall r} A_r \right) \quad (15)$$

$$\sum_{w=1}^W \lambda_r = A_r, \quad \forall r \in D \quad (16)$$

The objective function for the MILP formulation given in Equation (14) above has two parts. The first part is used to minimize the energy consumption of active network devices. The second part is used to minimize the number of blocked connection requests.

Equation (15) is the blocking probability that calculating the difference between the total number of connection demands or requests $|D|$ and the total number of successfully provisioned connection requests. In this Equation, α is the scalarization parameter that makes a trade-off between these objectives.

Scalarizing a multi-objective optimization problem is an a priori methodology, which implies formulating a single-objective optimization problem such optimum solutions to the single-objective optimization problem are Pareto optimal solutions to the multi-objective optimization problem [16]. Instead of a single solution that optimizes all criteria simultaneously, a set of trade-off solutions can only be improved in one criterion by deteriorating another criterion simultaneously. These solutions are called Pareto optimal. Pareto optimal solutions of real-valued optimization problems usually form a manifold (i.e., collection of points comprising a particular set) within the objective space referred to as a Pareto front.

Constraint (16) ensures that the total number of connection requests r from node s to node d are successfully provisioned and allocated on a wavelength.

IV. OPTIMIZATION RESULT AND DISCUSSION

This section shows the results obtained for the proposed energy-aware approach and gives the proposed model's optimization using the Matlab optimization toolbox. Ethio-telecom, such as Addis Ababa (AA) optical backbone network topology shown in Figure 5.1, is considered as a reference topology. The AA network topology consists of 10 nodes and 48 unidirectional links. Each link supports 40 wavelengths, and each wavelength supports up to 40Gbps.

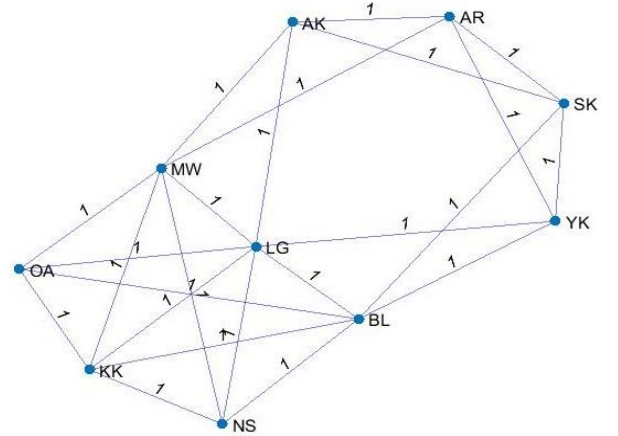


Fig. 1. AA Optical Backbone network topology

The energy consumption of the deployed network element depends on the configuration of the specified site. The optical network devices' power consumption values are chosen by averaging the data provided in [18]. The power drained by transceivers, ϵ_t and ϵ_r equal to 7W, respectively, and the Energy consumption of switching devices is 6.4 W.

A. Energy Consumption

The Energy-saving scenario for AA optical backbone network is assessed using the given model. One of the performance metrics used to evaluate the proposed energy-aware model is energy consumption. The detailed result obtained for the proposed energy-aware model (EADPP), with compared to another energy-saving approach, i.e., minimum power with devices in sleep mode (MP-S), as well as the energy-unaware (EUDPP) is discussed below.

Figure 2. shows the total energy consumption of the Energy-aware model (EADPP) with energy unaware and the

power minimization model with sleep mode option applied to only backup devices (MP-S), according to different connection requests (traffic demands) in the AA optical backbone network.

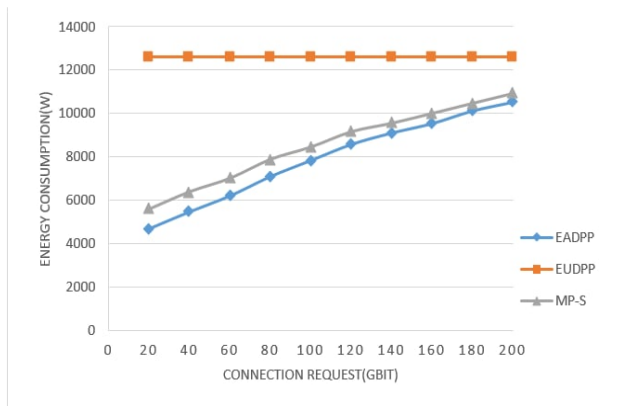


Fig. 2. Total Energy Consumption Vs. Connection Request for AA backbone network

The above Figure shows that the Energy unaware model consumes more power than the other two energy-aware models. In the EUDPP case, many resources are reserved for each connection request, and the redundant idle resources are considered active or fully powered on. The EUDPP is applying the multi-commodity flow (MCF) algorithm, i.e., traditional telecommunication strategy, that is, the power consumption is independent of the traffic load.

To achieve energy-saving, the optimization of the proposed energy-aware model minimizes the number of active network devices by putting backup resources into sleep mode and sleeping some links (lightly loaded links), shifting the traffic carried by those links to the remaining links. It can achieve a visible reduction in total network energy consumption, especially when the network traffic load is low. Because when low network traffic load (small connection request), there are many idle and redundant resources in the network and can be directly switched to sleep mode. Since when the redundant backup (protection) devices are set into sleep mode, energy consumption is consumed only for devices on the working paths. When a connection request increases, the value of Energy consumption of the Energy-aware model will increase.

The result obtained shows that, by putting protection devices into sleep mode and considering energy efficiency in the routing phase, the proposed energy-aware model EADPP outperforms EUDPP & MP-S in terms of total energy consumption. It can achieve energy saving up to 35% compared to EUDPP and 5-10% compared with MP-S. For a larger number of connection requests or high network traffic load, EADPP behaves close to MP-S. Because at a high load, all network resources need to be utilized, which reduces packing primary paths.

B. Link Usage

Fig. 3. illustrates the number of links used in the network (active and sleep links) based on network load. As expected, the previously presented energy consumption results from efficient utilization of network devices already powered on. When a traffic load or connection request increases, many links are active, and thus more energy is consumed.

In order to achieve energy-saving, the model sleeps some links and shifts the traffic carried by those links to the remaining links. The number of links operating in sleep mode is proportional to the amount of power saving obtained.

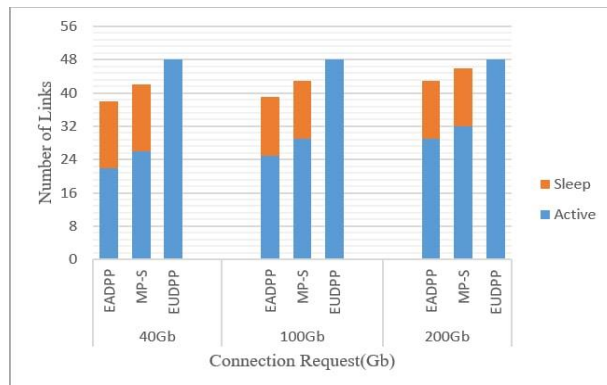


Fig. 3. Total number of links whose devices are set active and sleep mode for a different connection request

EADPP binds primary or working wavelengths in some links to decrease the idle, lightly loaded links energy consumption. Backup path links can be put into sleep mode until the occurrence of failure. The result shows a considerable improvement in EADPP compared with EUDPP regarding the number of backup links in standby (sleep) mode for different traffic loads or various numbers of connection requests. That means no sleep mode approaches are applied in EUDPP, i.e., 100% of the deployed links are utilized for the network flow.

The optimization result of the modified AA backbone network topology is depicted in Fig. 4. As shown in Figure, when applying the proposed optimization model at a 40Gbit connection request (a traffic demand matrix), four bidirectional links are reduced from the existing network topology by using an energy-aware routing with link utilization and link disjoint path constraints. It is clearly shown that energy saving can be achieved by minimizing active network elements.

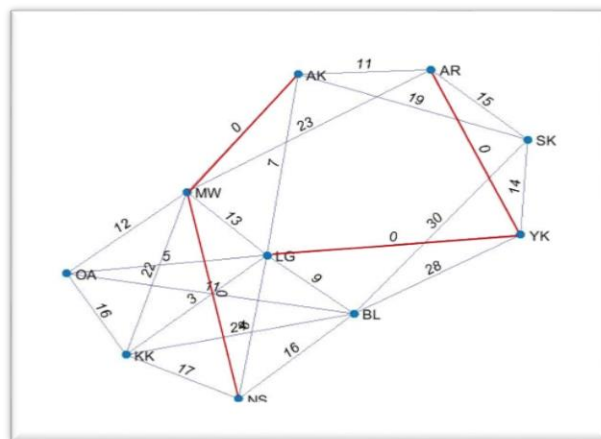


Fig. 4. Optimization of AA Optical Backbone network topology with turn-off links

C. Trade-off: Optimization Result

This section presents the optimal result of a trade-off between energy consumption and the blocking probability.

Based on the multi-objective optimization problem formulation discussed in section III, apply the Pareto front principle to evaluate the trade-off between the two objectives (Energy consumption and blocking probability). Blocking probability is an essential metric for network performance evaluation.

For a given parameter α and a traffic matrix, a point of Pareto optimal value is found by solving the optimization model for different connection requests. In order to achieve the complete Pareto front optimal value, i.e., the lower bound for energy consumption and blocking probability, the α value was varied between 0 to 1.

The Pareto front of the optimization model is shown in Figure 4, which is the trade-off between energy consumption and blocking probability. For the considerations of universality and simplicity, normalized the energy consumption by the maximum energy consumption.

As shown in the Figure below, when the energy consumption minimizes, the blocking probability increases, which means considerable energy savings are achievable, but there is a significant increase in the network blocking probability.

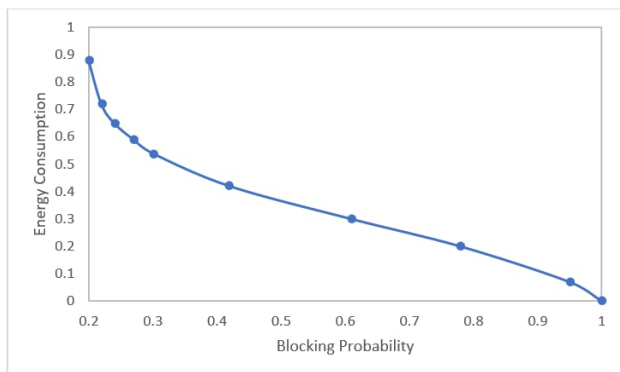


Fig. 5. Energy Consumption Vs. Blocking Probability at 40 Gbit connection request

Fig. 5 indicates that significant energy savings of up to 60% are possible as the consequence of a large increase in the network blocking probability of up to 0.4. When the energy consumption of the network increases, which means all the available network resources are turned on, in this case, the blocked connection request decreases. On the other hand, when reduced energy consumption, many network resources are minimized, and also the blocking probability also increased. the figure also illustrates the different tradeoff results between these two objective functions. For example, with the energy consumption values of between 70% and 90%, there is a little significant impact on the blocking probability.

The optimal result confirms that energy efficiency and network performance parameters are conflicting objectives; this also ensures that an approach that accounts only for minimizing network energy consumption might lead to unacceptable network performance degradation. From the above result depicted in Figure 4, it is clearly shown that a reasonable compromise can be obtained to save energy by trading a small amount of blocking probability.

V. CONCLUSION

This research presents an energy-efficient resilience strategy for survivable optical WDM network design that applies the energy-aware routing and exploits the sleep mode of devices supporting protection paths. The research work aims to minimize the energy consumption of optical backbone networks with consideration of network survivability. To achieve this goal, proposed the EADPP approach and formulated the optimization problem in the MILP optimization model to minimize the energy consumption of active network devices under constraints of link utilization and link disjoint backup path for each connection request. This research work enhances network resilience, reduces energy consumption using optimization techniques, and significantly improves network resilience and energy efficiency.

Routing a connection request via two disjoint paths can be a trade-off between reducing energy usage and enhancing network performance. Energy efficiency and network blocking probability are two conflicting objectives. To address the trade-off problem, this research proposed a multi-objective MILP optimization model of a trade-off between energy consumption and the blocking probability. After evaluating the trade-off optimization model, the result shows that it can achieve considerable energy savings with a minor impact on network performance.

This research considers routing schemes to improve network survivability and energy efficiency considering a single failure scenario. The energy-efficient design in networks with multiple failure survivability needs to be explored for the future direction. Additionally, further investigation is needed to find the optimal value or acceptable tradeoff value in terms of different traffic demands.

REFERENCES

- [1] R. Leepila, "Routing Schemes for Survivable and Energy-Efficient Networks," PhD. Thesis, Department of Information and Communication Engineering, The University of Electro-Communications (2014).
- [2] C. Lange, D. Kosiankowski, R. Weidmann and A. Gladisch, "Energy consumption of telecommunication networks and related improvement options," *IEEE Journal of selected topics in Quantum Electronics*, 17(2), 285-295., 2011.
- [3] F. Idzikowski et al., "A survey on energy-aware design and operation of core networks," *IEEE Commun. Surveys and Tuts.*, vol. 18, no. 2, pp.1453–1499, Second Quarter 2016.
- [4] A. Hmaity, F. Musumeci, and M. Tornatore, "Power reduction strategies with differentiated quality of protection in IP-over-WDM networks," *Annals of Telecommunications*, vol.73, no.1-2, pp.81–94, February 2018.
- [5] L. Wosinska et al., "Network resilience in future optical networks," in *Towards Digital Optical Networks*, vol. 5412 LNCS, 2009, pp. 253–284.
- [6] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, "Energy Efficiency in Telecom Optical Networks," *IEEE Communications Surveys and Tutorials*, vol.12, no.4, pp. 441-458, Nov. 2010.
- [7] D. Xiaowen, "Green Optical Networks," Ph.D. Dissertation, School of Electronic and Electrical Engineering, The University of Leeds, Leeds, England, 2012.
- [8] A. Jirattigalachote, C. Cavdar, P. Monti, L. Wosinska, and A. Tzanakaki, "Dynamic provisioning strategies for energy efficient WDM networks with dedicated path protection," *Optical Switching and Networking*, vol. 8, no. 3, pp. 201–213, July 2011.
- [9] A. Muhammad and et al., "Energy-efficient WDM network planning with dedicated protection resources in sleep mode," in *GLOBECOM* proc., 2010.
- [10] C. Cavdar et al., "Energy-efficient design of survivable WDM networks with shared backup," in *GLOBECOM*, 2010.

- [11] B. Luo, W. Liu, A. Al-Anbuky, "Energy aware survivable routing approaches for next-generation networks design" M.Sc. Thesis, Auckland University of Technology, 2013.
- [12] S. Jalalinia and C. Cavdar, "Green and resilient design of telecom networks with shared backup resources," *Optical Switching and Networking*, vol.23, pp.97–107, January 2017.
- [13] K. Yassin, "QoS Performance Evaluation of RWA Algorithms under Different Resilience Mechanisms: in the Case of Ethio-Telecom Backbone Network," Addis Ababa University, 2019.
- [14] Y. Belayneh, "Sleep mode operation of optical networks for energy consumption minimization: a case study of ethio telecom backbone optical transport network," M.Sc.Thesis, Depar., Elect. &Comp. Eng., AAIT, Addis Abeba, Ethiopia, 2018.
- [15] C. Eyupoglu, M.A. Aydin, "Energy efficiency in backbone networks," *Procedia-Soc. Behav. Sci.*, 195, pp. 1966-1970, 2015.
- [16] S. I. Pouremami and B. Bakhshi, "On the trade-off between power-efficiency and blocking probability in fault-tolerant WDM networks," *J. Netw. Comput. Appl.*, Vol. 58, no. 1084–8045, pp. 255–266, 2015.
- [17] B. Addis, A. Capone, G. Carello, L. G. Gianoli, and B. Sansò, "Energy management through optimized routing and device powering for greener communication networks. " *Networking, IEEE/ACM Transactions on*, issue.99, pp.1-1, 2013.
- [18] W. Van Heddeghem, F. Idzikowski, "Equipment power consumption in Optical multilayer networks ," Dept. Info. Tech., Ghent University Belgium, Report Number: IBCN-12-001-01, January 12th, 2012.