ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
ADDIS ABABA INSTITUTE OF TECHNOLOGY
ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

Sleep Mode Operation of Optical Networks for Power Consumption Minimization: a Case Study of Ethio Telecom Backbone Optical Transport Network

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 Masters of Science in Telecommunication Network Engineering

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November, 2018
Addis Ababa, Ethiopia

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Declaration

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

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Abstract

Due to the growth in data traffic volume and diversification of applications that use telecommunication network infrastructure more power consuming telecommunication network equipments have been deployed. This scenario, although efforts are made to minimize the power consumption of the deployed equipments, has led to an increase in the power consumption of the sector. When it comes to backbone networks this increase in power consumption is more dependent on the traffic level, which is the aggregate traffic from all access segments, and on the number of subscribers on the access side. In the future it is expected that one of the bottlenecks in the development of the telecommunication sector will be its power consumption. In order to overcome this problem, stake holders in the sector are striving to come up with ways to minimize this power consumption.

In this thesis, the sleep mode operational strategy which enables some components in the network to operate in sleep or low power consumption state after rerouting traffic on the remaining components, is assessed. After investigation of different algorithms proposed under this strategy, an approach which takes the Physical Layer Impairment (PLI), power loss/attenuation, together with other constraints is proposed. An evaluation of the approach is carried out on an optimization platform and a simulation environment and results analyzed taking two Ethio Telecom backbone Optical Transport Network (OTN) segments as a case study. These optimizations & simulations help to analyze impacts on Quality of Service (QoS) of applying this approach in addition to its main goal of power consumption minimization. Results reveal that up to 51% and 44% of power saving can be achieved at maximum link utilization thresholds of 70% and 50% for AA backbone and N-E backbone segments respectively. In addition, the evaluations show the trade-off between power saving and QoS using different parameters.

Key words: Attenuation, Consumption, Energy, Power, QoS, Sleep mode, Utilization.

Aknowledgement

I would first like to thank my thesis advisor Dr. Yalemzewd Negash for his endless support and encouragement during the entire course. He consistently allowed this paper to be my own work, but guided me in the right direction whenever he thought I needed it. I am also thankful to have an advisor who cared so much not only about my work but also my future in the academic track. I would also like to thank all the instructors who have been part of this program.

I wish to express my sincere thanks to Mr. Yiheys Takele, transmission section manager of engineering department at ethio telecom, and his team for the support and willingness to provide me with the inputs necessary for this thesis and their encouragement through the past two and half years. I am indebted to them.

I would also like to acknowledge Mr. Agegnehu Tesfaye and Mr. Biniam Tadesse who were really a good hand for me in the course of my class and this thesis with their valuable encouragements and comments. In addition I would like to thank members of my family, friends and colleagues who were with me throughout my study time.

Finally, I want to express my very profound gratitude to my wife, Helen, for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of doing this thesis. This accomplishment would not have been possible without her. Thank you so much and glad to have you.

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Acronyms

AMPL	A Mathematical Programming Language
ASON	Automatically Switched Optical Network
BER	Bit Error Rate
CR-LDP	Constraint-based Routing Label Distribution Protocol
DPP	Dedicated Path Protection
EA-AR	Energy Aware- Adaptive Routing
EA-TE	Energy Aware – Traffic Engineering
EDFA	Erbium Doped Fiber Amplifier
GHG	Green House Gas
GLPK	GNU Linear Programming Kit
GMPL	GNU Mathematical Programming Language
GMPLS	Generalized Multi Packet Label Switching
GNU	Gnu's Not Unix
ICT	Information Communication Technology
ILP	Integer Linear Programming
IP	Internet Protocol
LED	Light Emitting Diode
LSA	Link State Advertisement
LSP	Label Switched Path
MCF	Multi-Commodity Flow
MEMS	Micro Electro-Mechanical Systems
MIP	Mixed Integer Programming
MPLS	Multi Packet Label Switching
MTBF	Mean Time Before Failure
MTTR	Mean Time to Repair

O/E/O	Optical-Electrical-Optical conversion
OLA	Optical Line Amplifier
OSPF	Open Shortest Path First
OXC	Optical Cross-Connect
PA	Power Aware
PA-RWA	Power Aware - Routing and Wavelength Assignment
PATE	Power Aware Traffic Engineering
PATE-a	Power Aware Traffic Engineering with attenuation
PLI	Physical Layer Impairment
QoS	Quality of Service
RSVP-TE	Resource Reservation Protocol- Traffic Engineering
RWA	Routing and Wavelength Assignment
SD	Source-Destination
SOA	Semiconductor Optical Amplifier
TE	Traffic Engineering
TE-LSA	Traffic Engineering Link State Advertisement
TOTEM	TOolbox for Traffic Engineering methods
WDM	Wavelength Division Multiplexing
XML	Extensible Markup Language

Chapter 1

Introduction

Starting from the beginning of this millennium the power consumption of telecommunication networks and their segments is increasing and is expected to keep increasing in the future due to mainly the increase in traffic demand. In [1] it is shown that the overall energy consumption of telecommunication network segments increases as traffic increases with the highest energy consumption growth rates seen in the data centers and IP backbone networks. Of these power consumption values customer premises equipments consume significantly higher energy values than those found at the operator premises. Concerning the network sections at the operator premises, highest energy consumption shares are observed in the fixed and mobile access networks. In addition to these parts, it is also predicted that the power consumption in the core network will show a high increment in line with the growth in traffic.

In a related work, [2] shows that the energy consumption in wired access networks is dependent on the number of connected subscribers and increases with the increase in the later as contrasted to that of backbone networks which is more proportional to the traffic volume. Although the backbone network segment consists of small number of devices consuming high power, it is significantly affected by the increased traffic levels when traversed by increasingly larger traffic volumes. This will be a trend of backbone networks in the future which can be easily deduced from the increased demand from customer side currently. As a general indicator of the energy consumption in telecommunication networks and its trend, Fig.1.1 is used by [3].

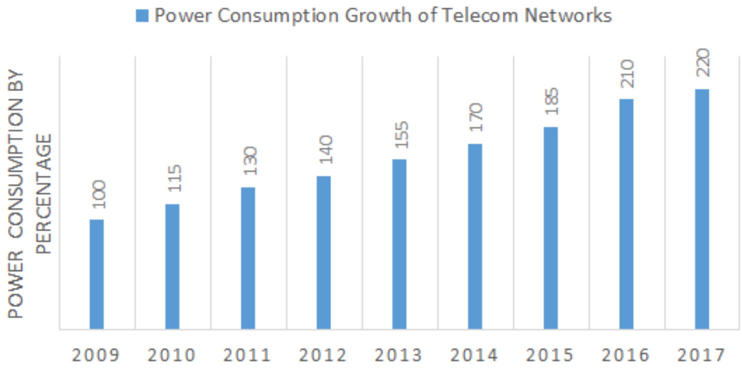

Figure 1.1: Energy consumption forecast of telecommunication networks [3]

Although the trend in power consumption of telecommunication networks shows a significant increase as seen above, current communication networks are still energy inefficient for two main reasons:

1. Networks are designed and deployed with an over provisioned capacity in order to meet high traffic demands and occasional traffic bursts, but do not consider power-saving mode during low traffic/ off-peak periods.
2. The network elements are always powered on wether they are carrying traffic demand or not in order to maintain network connectivity [4].

Due to this overprovisioning and energy unaware operation of network elements which in turn leads to an increase in OPerational EXpense (OPEX) and emissions of pollutants directly from the network elements or sources of energy which are used to power them. Thus the power consumption of telecommunication networks is already raising questions and developement of energy efficient telecom solutions is needed[3]. Generally as a solution strategy to this problem two main research directions are being followed by stakeholders. These are:

1. Usage of renewable energy sources such as solar and wind
2. Investigation of power consumption minimization approaches

Of these two research directions telecom researchers, equipment vendors and service providers are widely engaged in the second one which enables them devise ways that can minimize the power consumption of equipments, components and networks as a whole. These approaches are further classified into different categories depending on the perspective taken by the authors. For instance, [5] classifies the approaches as component, transmission, network and application level and [6] as re-engineering, dynamic adaptation and sleep-modes.

From the perspective of service provider's network level, the approaches are classified into energy aware network design and energy aware network operation approaches. In the design approach there are strategies such as network architecture modification, traffic grooming and topology optimization which can be considered during the design stage of a service provider's network segment. In the operational approach strategies such as sleep mode operation, energy aware routing, energy aware resilience and dynamic operation are found which can be implemented during the operational stage of a network segment. Fig.1.2 shows the summary of classification of energy efficiency improvement approaches at network level.

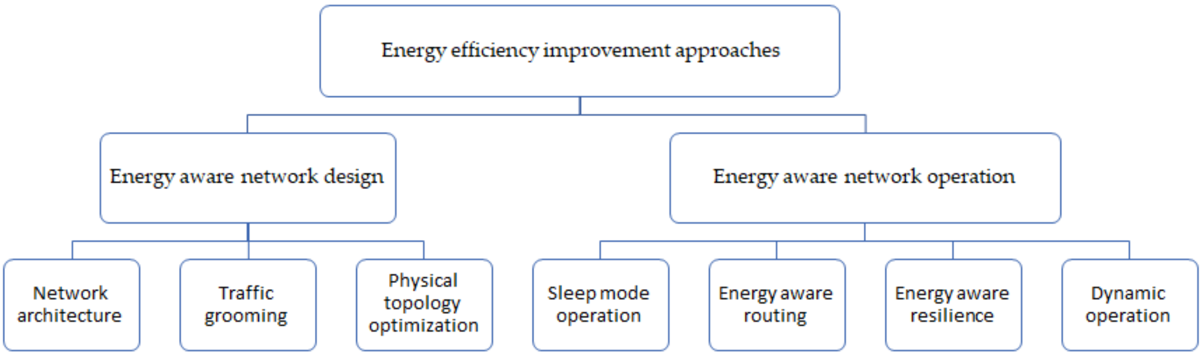

Figure 1.2: Energy efficiency improvement approaches

Sleep mode operation is currently one of the approaches that is used and considered in research works widely. Aside from improving the energy-efficiency, the introduction of sleep-based power saving approaches can affect the network performance. These effects may result in increased delay in the network traffic due to the introduction of longer paths to reroute traffic or a decrease in recieved signal power below acceptable levels which will in turn cause packet drop. Thus it is important to investigate the possible negative impacts of the application of sleep mode approaches on the network performance as a whole and on the component characteristics [7].

1.1 Motivation

Today's optical networks are designed and operated to carry the maximum demand traffic in the most reliable way without considerations of power consumption or energy efficiency [8]. This means that a network is built up of many redundant links and over-provisioned link bandwidth to handle link failures and worst case or burst traffic scenarios. While these redundant links and bandwidth greatly increase the network reliability, they also greatly reduce the energy efficiency as all network devices are powered ON at full capacity every time consuming energy but highly under-utilized most of the time. Rule of thumb states that today's backbone links use at most 40% of their capacity to carry traffic demands [9]. While the average link utilization is low most of the time, network power consumption,stays constant, wasting so much energy during off-peak periods if there are no power aware mechanisms implemented. The case for ethio telecom also shows the same trend. Fig. 1.3 shows the link utilization scenario for two of the gateway router interfaces of ethio telecom showing that the actual traffic on the links varies with time of the day and is also utilizing a small part of the deployed capacity.

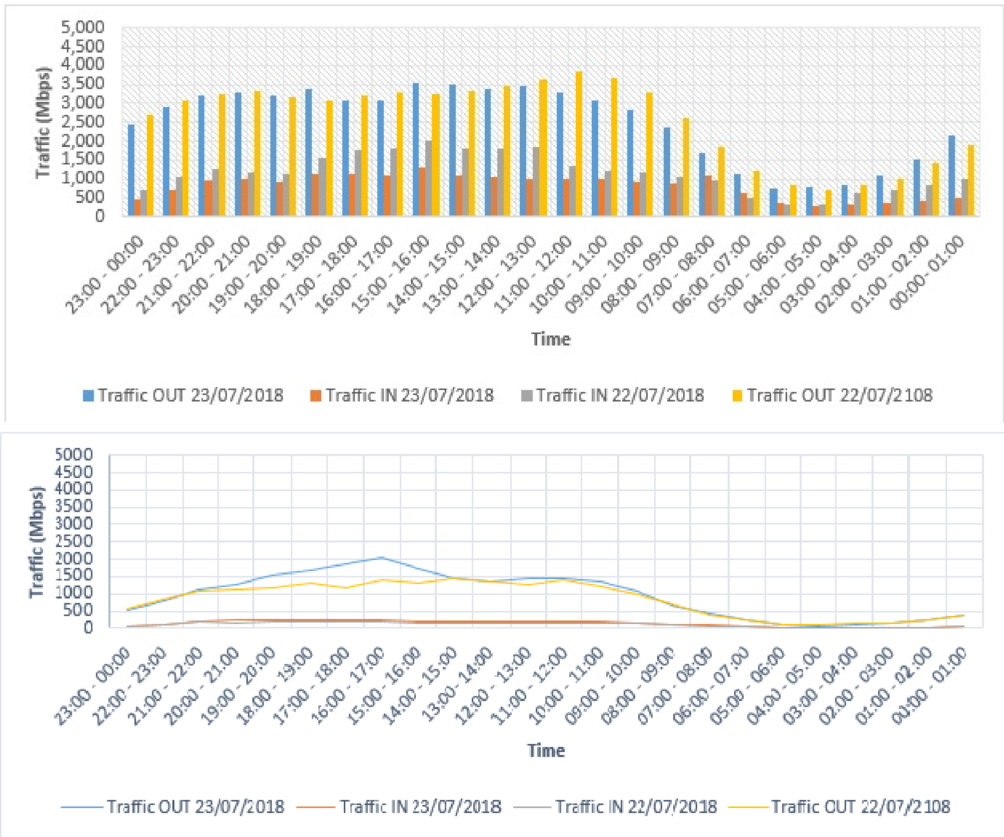

Figure 1.3: BD-MK-BR-B and BL-MW-A traffic data [55]

The features of high path redundancy using protection/restoration paths and low link utilization provide unique opportunities for Power Aware Traffic Engineering (PATE). When there are more number of paths between the same Source-Destination (SD) pair, and the traffic volume on each path is low, the traffic can be moved to a fewer number of paths so that the other paths do not carry any traffic thus the links in those paths and the accompanied end components such as line cards can be put to sleep for power saving. Hence based on this driving force behind the deployment and utilization of current networks, the scope of this thesis work is on energy efficient operation of optical networks via sleep mode, which is based on sleep mode mechanism that reduces network power consumption while still maintaining network performance at desired levels using different constraints such as link utilization and power loss/ attenuation.

1.2 Problem Statement

In its general sense this thesis tries to answer the following problem statement:
"How can a sleep mode operational strategy be utilized for power consumption minimization in optical networks taking into consideration the PLI constraint power loss/ attenuation, traffic burstiness and link utilization in order to balance the trade-off between power saving and performance of the network?"

1.3 Objectives and contribution

The main objective of this thesis is to propose a sleep mode operational approach that takes the physical layer impairment power loss/attenuation together with other constraints into consideration for optical networks and analyze its impact on network performance during implementation. The analysis of this approach on the operation of a real network will be assessed taking ethio telecom's backbone OTN segments as a case study.

The thesis has also the following specific objectives:

- Analysis of the power consumption of optical networks. This analysis covers power consumption of the total segment, per node power consumption and per component power consumption. The analysis takes into consideration the OTN equipments deployed at ethio telecom's backbone network segments.

- Modeling of the power consumption of optical networks.
- Review of algorithms under sleep mode operation for various QoS performance metrics.
- Propose a sleep mode operational approach which takes into consideration QoS in optical networks in terms of power loss/ attenuation, link utilization and traffic burstiness as constraints.

1.4 Methodology

In order to achieve the stated objectives, this thesis follows the methodology stated below.

- Ethio telecom backbone optical transport network power consumption data collection and analysis.
- Proposing a sleep mode operational approach that takes the physical layer constraint power loss/attenuation, traffic burstiness and link utilization together with other constraints into consideration for optical networks and perform mathematical optimization and simulation of the proposed model using GNU Linear Programming Kit (GLPK) and TOolbox for Traffic Engineering Methods (TOTEM) toolbox. This helps to evaluate in advance the impact on network performance of the application of the model. Shortest path generation for input to the optimization model will be done using Matlab.

1.5 Organization of the thesis

The rest of this thesis work is organized as follows. Chapter 2 gives background information on optical networking basics, building blocks of optical network systems, components in an optical network system and their features, some operational issues in optical networking, Yen's K-shortest path algorithm, basics of Traffic Engineering (TE) and basics of linear programming and Multi Commodity Flow (MCF). Chapter 3 discusses the power consumption modeling and energy efficiency evaluation issue in optical systems and analyses the power consumption of the systems under case study, Addis Ababa and North-East ethio telecom backbone OTN circles, gives an overview of power consumption in ICT sector, specifically in optical network segments and approaches that are used to minimize power consumption in optical networks, gives general overview on sleep mode operational approach in optical networks, introduces algorithms that are used for the implementation of the sleep mode operation in optical networks and evaluates their impact on network performance using parameters such as link length, link utilization and delay. Chapter 4 introduces the problem formulation for this thesis stating all the constraints applied. A proposed implementation strategy is also covered for the model. Chapter 5 evaluates the proposed approach based on power saving scenarios for various constraints to see the network performance with the help of the given network topology and traffic demand profiles. Finally, conclusion and future works are presented in Chapter 6.

Chapter 2

Fundamentals of Optical Networking and Linear Programming

2.1 General Overview

Optical network is a system that uses the optical fiber as a medium of transmission. One fiber can multiplex and carry several optical signals over very long distances using Wavelength Divison Multiplexing (WDM). Optical transmission provides numerous benefits as compared to other transmission systems. These include huge bandwidth, low signal attenuation and immunity to electromagnetic interference, long distance transmission span, among others. In addition to the above benefits, optical signals can also be handled directly in the optical domain. They can be passively split or combined without the need of electronic processing. An optical signal can also be switched in the optical domain, e.g., by Optical Cross Connects (OXCs). In this way signals can be transmitted transparently between source and destination nodes without Optical/Electrical/Optical (O/E/O) conversion [7].

Although the optical network system has numerous advantages, it has also impairments that are the results of light properties, fiber cable material properties, interaction of light with optical fiber material and construction or deployment of optical fibers. The use of optical technologies can significantly reduce the network power consumption compared to the case in which switching is done in the electronic domain, as the need of energy demanding O/E/O conversions required to switch data in the electronic layer can be minimized or even removed [10]. The energy efficiency of optical networks can also be further improved by using power saving techniques. These techniques include traffic grooming, sleep mode operation and energy aware design and placement of optical network components.

2.1.1 Network model

The complete model of an optical system can be better seen as a multi-layer model which consists of the Wavelength Division Multiplexing (WDM) and Internet protocol (IP) layers with the consideration that the control plane is a Generalized Multi Packet Label Switching (GMPLS) control plane. This model gives an overview of the whole system from a high level perspective as shown in Fig.2.1.

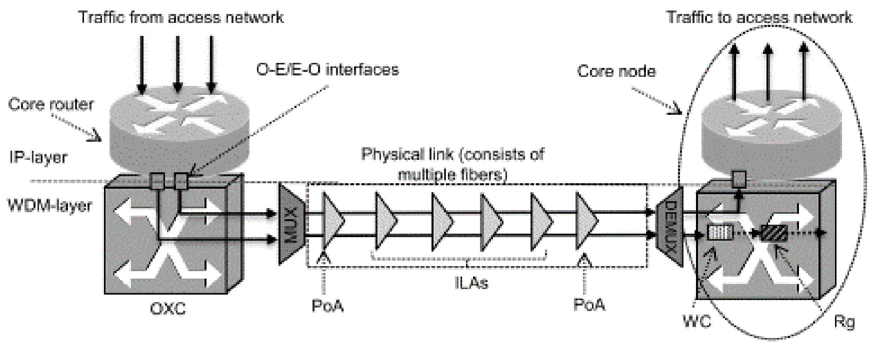

Figure 2.1: Model of an IP-over-WDM network [11]

The high capacity offered by optical systems is achieved using the WDM technology, where multiple optical signals that are going to use a single wavelength are multiplexed into a single fiber. Each optical signal is generated by an optical transmitter and received by a receiver [11]. Both the transmitter and the receiver are located in a transponder or line card. The add/drop functionality of optical signals is carried out by OXCs. An OXC has the ability to dynamically change its configuration. It can also act as a pass through for optical signals which need not be added or dropped. While the optical signal travels from the transmitter to the receiver it experiences a degradation in its transmitted power due to attenuation. In order to overcome the attenuation, two amplifiers called pre-amplifier and post amplifier/booster are used at the ends of each fiber. The pre & post amplifiers together with the multiplexer/ de-multiplexer are often referred to as WDM terminals, which provide the interface between fibers and OXCs. The optical signal traversing a fiber needs to be amplified every Lkms by Optical Line Amplifiers (OLAs). Dynamic Gain Equalizers (DGEs) are placed at some OLAs to compensate for any channel power tilt introduced by the OLAs, optical filters, or the Raman effect inside the transmission fiber [12]. In addition, if the signals travel for longer distances, usually greater than 1200KMs, without add or drop, re-generators are used which are used to accomplish the 3R functions, Reamplifying, Reshaping and Retiming in the electrical domain.

The optical WDM channel originating and terminating in the transponders and traversing two or more OXCs is called a lightpath. A lightpath may span multiple fiber links. Each intermediate node traversed by the lightpath provides an optical bypass facility in which there will be no add or drop functionality but a transparent bypass of traffic [11]. The light path can be assigned a unique wavelength on all physical links that it traverses or wavelength converters can be used at intermediate nodes to switch between available wavelength. The assignment of wavelength and choice of the set of physical links that a lightpath traverses is referred to as a Routing and Wavelength Assignment (RWA) problem.

2.1.2 Optical network operational issues

While considering optical network systems, although their capacity is high to support bandwidth consuming traffic using WDM and other enabling technologies, there are operational issues that make their deployment and reliable operation difficult. From the perspective of this thesis the most influential issues are physical layer impairments and energy efficiency and awareness which are discussed briefly below.

1. **Physical Layer Impairments (PLI)**
   Until recently the physical layer impairments in optical transmission systems were not given much attention. This is mainly due to the fact that optical transmission gives high bandwidth advantage over other technologies that diverts the attention from the constraints. But the actual performance of the system may be unacceptable due to the optical signal degradation, which is particularly harmful in high-rate and long-distance transmission systems such as wide area backbone networks. Indeed, as optical signals traverse the optical fiber links and also propagate through passive and/or

active optical components, they encounter many impairments that affect different optical network properties. For this reason, the incorporation of PLIs in optical network planning and operation has recently received increasing attention [13].

The few works that are based on network optimization methods make use of PLI models that estimate only static impairments, which do not involve actual network state information [14]. In this thesis one of the PLI parameters in optical networks, power loss/attenuation, is considered. Power loss/attenuation is defined as the optical loss that is accumulated from source to destination along fiber links. Attenuation is given as the loss encountered per unit of distance traversed by the signal and is taken as a constant value which is mainly a property of the fiber type used in the network. This value varies from 0.2db/km to 0.3db/km. An average value of 0.25db/km is usually used which gives a near to exact value for most types of optical fiber cables deployed now a days.

2. **Energy Efficiency and Awareness**

   As stated in the previous chapter, one of the most important problems facing the development of telecommunication networks currently is the problem of increasing power consumption and the associated problem of Green House Gas (GHG) emission. Usually networks are designed and operated with out consideration of power consumpption minimzation. But currently there are numerous activities carried out all around the globe aiming at both goals in green networking stated in the previous chapter; the reduction of power consumption and the replacement of existing energy sources with renewable ones. Among these activities, there are new initiatives, such as the Green Touch started by scientists of Alcatel-Lucent Bell Labs and the Green Communications initiated by ITU, which aim at the development of the energy efficient communication devices and networks [15].

   In the context of optical networking, the minimization of power consumption and hence the maximization of the energy efficiency of components as well as the entire network can be achieved through power aware design and operation schemes of these network segments and the accompanying components [16].

2.2 Physical building blocks

A typical optical network system consists of mainly three components as shown in Fig. 2.1. These components are the OXCs, Optical Amplifiers which can be used as pre/post amplifiers or line amplifiers and Transponders which are used for transmission and reception of optical signals and could also employ the O/E/O conversion.

2.2.1 Optical transmission/reception

Transmitters

The most commonly used optical transmitters are semiconductor devices of which the main ones are LEDs and laser diodes. The difference between the two categories of devices is that LEDs produce incoherent light whereas laser diodes produce coherent light. Currently used optical transmitters using these devices are compact, efficient and reliable.

An LED can be seen as a forward-biased p-n junction, which emits light through spontaneous emission. The emitted light is incoherent with a relatively wide spectral width of 30–60nm. LED light transmission is also inefficient, with only about 1% of input power, being converted into launched power which will be transmitted through the optical fiber. Communications LEDs are most commonly made from Indium gallium arsenide phosphide (InGaAsP) or gallium arsenide (GaAs). The large spectrum width of LEDs is subject to higher fiber dispersion, which affects their bit rate-distance product. LEDs are suitable primarily for local-area-network applications with bit rates of 10–100Mbit/s and transmission distances of a few kilometers.

A semiconductor laser emits light through stimulated emission rather than spontaneous emission, which results in high output power, around 100mW as well as other benefits related to the nature of coherent light. The output of a laser is relatively directional, allowing high coupling efficiency into a single-mode fiber. The narrow spectral width also allows for high bit rates since it reduces the effect of chromatic dispersion. Furthermore, laser diodes are often directly modulated, that is the light output is controlled by a current applied directly to the device. For very high data rates or very long distance links, a laser source may be operated continuous wave, and the light modulated by an external device, an optical modulator. External modulation increases the achievable link distance by eliminating laser chirp, which broadens the linewidth of directly modulated lasers, increasing the chromatic dispersion in the fiber. For very high bandwidth efficiency, coherent modulation can be used to vary the phase of the light in addition to the amplitude.

Receivers

The main component of an optical receiver is a photo-detector which converts light signals into electric signals using the photo-electric effect. The primary photo-detectors for telecommunications are made from Indium gallium arsenide. The photo-detector is typically a semiconductor-based photo-diode. There are several types of photo-diodes including p-n photo-diodes, p-i-n photo-diodes, and avalanche photo-diodes. Metal-semiconductor-metal (MSM) photo-detectors are also used due to their suitability for circuit integration in re-generators and wavelength-division multiplexers.

Further signal processing such as clock recovery from data (CDR) performed by a phase-locked loop may also be applied before the data is passed on. Coherent receivers use a local oscillator laser in combination with a pair of hybrid couplers and four photo-detectors per polarization, followed by high speed ADCs and digital signal processing to recover data modulated with QPSK, QAM, or OFDM.

2.2.2 Optical switching

In optical networks, there are three main types of optical switching techniques: Optical Circuit Switching (OCS), Optical Packet Switching (OPS) and Optical Burst Switching (OBS). The first two are based on legacy circuit switching and packet switching techniques. Recently, OBS is proposed as an option that combines the advantages of OCS and OPS to overcome their limitations [17]. This section briefly discusses the advantages and drawbacks of the three techniques.

1. *Optical Circuit Switching*

   This technique is the first optical switching technique used in legacy optical networks. In an OCS based optical network, a dedicated wavelength on each link is used to establish physical connections between pairs of SD nodes through switching nodes [18]. Therefore, the established paths are composed of sequences of physical links between the source and destination. the switching of an incoming data to the appropriate outgoing link uses three phases namely circuit establishment, data transfer and circuit disconnection.

OCS is suitable for large data transmissions that need long connection holding times and therefore is widely adopted in core networks. A key challenge in the practical implementation of OCS based optical networks is the development of efficient algorithms and protocols for establishing light-paths [19]. OCS techniques have also some drawbacks with a major issue being each wavelength must be dedicated between sources and destinations (if no wavelength conversion is used), and cannot allow grooming or statistical multiplexing, which results in low channel usage efficiency. Another issue is that for burst traffic, the setup time of a light-paths can be longer than the burst duration. This results in low bandwidth utilization.

2. *Optical Packet Switching*

   OPS techniques are initially based on packet switching techniques used in computer networks. In this technique, traffic data is divided and assembled in the payload with a preceding header that contains the destination information. The intermediate nodes function as packet routers, based on the header information, to decide where packets should be forwarded.

   But there are two main obstacles that made difficult the implementation of this technique. These are the need for all-optical packet header processing and the lack of optical RAM. Therefore, hybrid OPS approaches, employing O/E/O conversion have been proposed, with a relatively complex approach where the packet header is processed in the electrical domain [20].

3. *Optical Burst Switching*

   OBS is proposed to overcome the limitations of OCS and OPS. In OBS, the switching granularity is at the burst level, rather than the wavelength level in OCS and the packet level in OPS. OBS provides statistical multiplexing and only the wavelength of the control packet (sent ahead of the burst to align switches and reserve wavelengths and other resources) needs O/E/O conversion at intermediate nodes [21].

2.2.3 Optical amplification

As stated earlier optical fiber transmission is a high speed wired communication technique. But while enabling this high speed transmission its function is highly affected by signal degradation which is referred to as attenuation. This attenuation decreases the signal power as it traverses through the fiber along the light-path from source to destination. One possible suggestion to overcome this effect is the introduction of signal re-generators which basically depend on O/E/O conversion. While this can be feasible when transmitting a single low capacity optical channel, it quickly becomes unfeasible when transmitting large number of channels as each channel requires separate re-generator, resulting in a highly expensive, power-hungry and bulky re-generator stations which led to the introduction of optical amplifiers to overcome the effect of attenuation. An ideal optical amplifier is designed to directly amplify any input optical signal in the optical domain. It can amplify all WDM channels together, and is generally transparent to the number of channels, their bit-rate, protocol, and modulation format. Hence a number of re-generators can be replaced with a single optical amplifier. Furthermore, the transparency of the optical amplifier means that the link can be upgraded without the need to replace the amplifier. The comparison between the two approaches is shown in Fig.2.2.

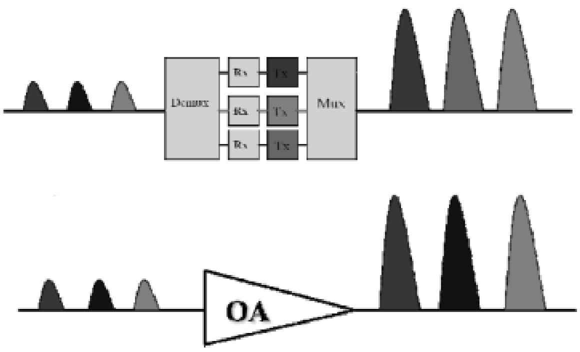

Figure 2.2: Comparison between regeneration and optical amplification [23]

The main optical amplifier technologies in use currently are Erbium Doped Fiber Amplifiers (EDFAs), Raman amplifiers, and Semiconductor Optical Amplifiers (SOAs).

An EDFA amplifier mainly consists of an erbium doped fiber, which is a conventional Silica fiber doped with Erbium. When the Erbium is illuminated with light energy at a suitable wavelength (either 980nm or 1480nm) it is excited to a long lifetime intermediate state, following which it decays back to the ground state by emitting light within the 1525-1565 nm band. If light energy already exists within the 1525-1565nm band, for example due to a signal channel passing through the erbium doped fiber, then this stimulates the decay process (so called stimulated emission), resulting in additional light energy. Thus, if a pump wavelength and a signal wavelength are simultaneously propagating through an erbium doped fiber, energy transfer will occur via the Erbium from the pump wavelength to the signal wavelength, resulting in signal amplification [22].

In its most basic form the EDFA consist of a length of erbium doped fiber (typically 10-30m), a pump laser, and a component for combining the signal and pump wavelength so that they can propagate simultaneously through the erbium doped fiber. In principle EDFA's can be designed such that pump energy propagates in the same direction as the signal (forward pumping), the opposite direction to the signal (backward pumping), or both direction together. The pump energy may either by 980nm pump energy, 1480nm pump energy, or a combination of both. Practically, the most common EDFA configuration is the forward pumping configuration using 980nm pump energy, as shown in Fig. 2.3 [22].

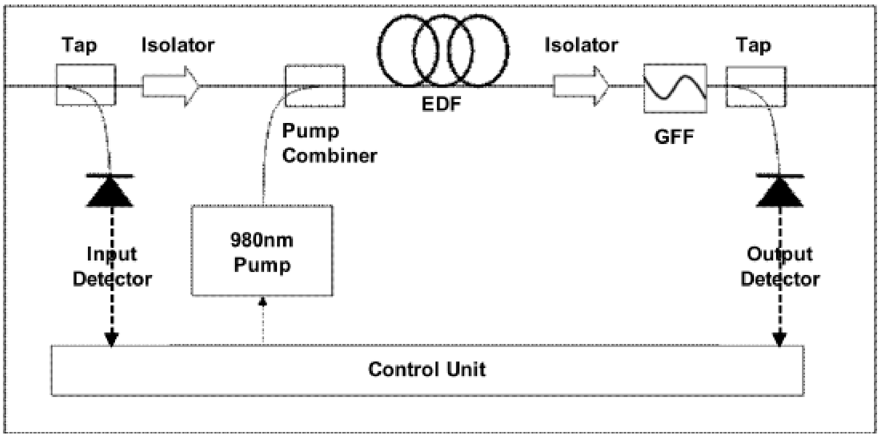

Figure 2.3: Typical single stage EDFA [22]

In Raman amplifier, the signal is amplified due to Stimulated Raman scattering (SRS). This scattering phenomena is a process in which light is scattered by molecules from a lower wavelength to a higher wavelength. When sufficiently high pump power is present at a lower wavelength, stimulated scattering can occur in which a signal with a higher wavelength is amplified by Raman scattering from the pump light. SRS is a nonlinear interaction between the signal (higher wavelength; e.g. 1550 nm) and the pump (lower wavelength; e.g. 1450 nm) and can take place within any optical fiber. In most fibers however the efficiency of the SRS process is low, with high pump power being needed to obtain a useful amplified signal which limits the usage of Raman amplifiers [23].

SOAs are amplifiers which use a semiconductor to provide the gain medium. They operate in a similar manner to standard semiconductor lasers, and are packaged in small semiconductor packages. Unlike other optical amplifiers SOAs are pumped electronically and a separate pump laser is not required [23]. Despite their small size and potentially low cost due to mass production, SOAs suffer from a number of drawbacks which make them unsuitable for most practical applications. These and other drawbacks make the SOAs largely unsuitable for multichannel WDM applications.

2.3 QoS parameters

QoS is the ability of a network to provide better service to the selected network traffic over various technologies. QoS also refers to traffic control and resource management mechanisms that seek to either differentiate performance based on application or service provider requirements [24]. QoS parameters in optical networks that are mostly used include packet loss, Bit Error Rate (BER), delay, bandwidth utilization, fault tolerance, recovery time, reliability, and response time. The current increase in the use of applications and service from user side resulted in many types of quality problems to be observed from the network side. As one of the segments of a telecommunication network, optical networks also suffer from these QoS problems. Although optical fibers have higher bandwidth, they also suffer from impairments that affect the QoS parameters of the network which should be given proper measures to resolve in order to optimize the utilization of bandwidth fully.

BER measurement is one of the prime considerations in determining signal quality [25]. BER is analogous to signal to noise ratio in an analog system. In networks, there is the possibility of transmitted packets fail to reach their destination, resulting in packet loss. Packet loss is the failure of one or more transmitted packets to arrive at their destination. This event can cause noticeable effects in all types of digital communications. There are so many reasons for the occurrence of packet loss such as signal degradation, packet corruption, faulty networking hardware, faulty network drivers, distance between the transmitter and receiver and so on. Packet loss is one of the major factors which affect the QoS in networks.

Network delay is a vital and integral characteristic of a network. Delay of a network relates as to how long it takes for a bit of data traveling across one endpoint to another measured in fractions of seconds usually in milliseconds. Delay differs depending on the location of the specific pair of communicating nodes. Thus, usually both the maximum and average delay are reported. Delay is also divided into processing delay, queuing delay, transmission delay and propagation delay. When a packet is sent from one node to another, the following delays occur: (1) transmission delay (time required to send all bits of packet into the wire), (2) propagation delay (the time taken by the packet to travel through the wire), (3) processing delay (the time taken to handle the packet in the network system), and (4) queuing delay (the time taken to buffer the packet before it can be sent). In order to achieve 100% throughput, processing delay should be reduced. To find delay in the network, propagation delay and queuing delay are only considered, but the processing delay is ignored because of its negligible values [26].

Network reliability is another QoS parameter which refers to the reliability of the overall network to provide communication in the event of failure of a component or components in the network. Reliability is a technique that determines how long a particular component is functioning without malfunctioning. It does not relate to the time it takes for its repair and back to restoration. Survivability, the ability of a network to withstand and recover from failures, is one of the most important requirements of networks [27].

2.4 Yen's K-shortest path algorithm

Yen's algorithm is an algorithm that computes K-shortest loop-less paths for a source in a given graph. The algorithm considers graphs with non-negative edge costs. It employs any shortest path algorithm to find the best path, then proceeds to find $K-1$ deviations of the best path. The algorithm usually uses Dijkstra's algorithm to find the shortest path. In this thesis also the implementation of the algorithm in Matlab to find k-shortest paths using Dijkstra's algorithm is used to find the shortest paths for each SD pair [57].

The steps in the algorithm can be broken down into two main parts, determining the first k-shortest path A_k and then determining all other k-shortest paths. It is assumed that the container A will hold the k-shortest path, whereas the container B, will hold the potential k-shortest paths. Fig. 2.4 shows the pseudo-code for Yen's k-shortest path algorithm.

Definitions:

- Consider a directed graph with N vertices $v_1, v_2, \ldots, v_N$.
- Let v_1 be the source and v_N be the destination for the k-shortest path computation.
- Let d_{ij} be the cost of the edge (v_i, v_j). Let M be the number of edges.
- Let A^k be the k^{th} shortest path, $k = 1, 2, \ldots, K$ from v_1 to v_N.
- Let v_i^k be the i^{th} node on the k^{th} shortest path.
- Let A_i^k, be a deviation from A^{k-1} at the i^{th} node on A^{k-1}. A_i^k follows the same path as A^{k-1} until the i^{th} node of A^{k-1}. Then its $i^{th}+1$ node is different from any path A^j $j = 1, 2, \ldots, k-1$ which also follows the same path as A^{k-1} until the i^{th} node of A^{k-1}.
- The root R_i^k of A_i^k is the subpath of A_i^k that coincides with A^{k-1} until the i^{th} node of A^{k-1}.
- The spur S_i^k of A_i^k is the subpath of A_i^k starting at the i^{th} node of A_i^k and ending at the end node v_N.

Algorithm:

1. Initialize heap B.
2. Determine A^1 as the shortest path using Dijkstra's algorithm.
3. Iterate $K-1$ times to determine A^i, $i = 2, 3, \ldots, K$.
   - Find all deviations of A^{i-1} and add each one to heap B.
   - Extract the minimum cost path from heap B as A^i.

Figure 2.4: Pseudo code for Yen's K-shortest path algorithm [57]

2.5 Basics of linear programming

Linear Programming (LP) is a mathematical optimization method which takes various linear inequalities and equalities to meet some constraints and determines the best obtainable result for the objective function under those conditions. An LP consists of maximizing or minimizing a linear objective function subject to a set of linear constraints over real variables constrained to be non-negative. In general, an LP problem that maximizes an objective function is represented by the following formula:

$$
\begin{aligned}
&\text{Maximize} \\
&\quad c_1x_1 + c_2x_2 + ... + c_nx_n \\
&\text{Constraints} \\
&\quad a_{11}x_1 + a_{12}x_2 + ... + a_{1n}x_n \leq b_1 \\
&\quad a_{21}x_1 + a_{22}x_2 + ... + a_{2n}x_n \leq b_2 \\
&\quad ... \\
&\quad a_{m1}x_1 + a_{m2}x_2 + ... + a_{mn}x_n \leq b_m \\
&\quad x_1 \geq 0 \\
&\quad x_2 \geq 0 \\
&\quad ... \\
&\quad x_n \geq 0
\end{aligned}
\tag{2.1}
$$

The expression for minimization can also be given as:

$$
\begin{aligned}
&\text{Minimize} \\
&\quad c_1x_1 + c_2x_2 + ... + c_nx_n \\
&\text{Constraints} \\
&\quad a_{11}x_1 + a_{12}x_2 + ... + a_{1n}x_n \geq b_1 \\
&\quad a_{21}x_1 + a_{22}x_2 + ... + a_{2n}x_n \geq b_2 \\
&\quad ... \\
&\quad a_{m1}x_1 + a_{m2}x_2 + ... + a_{mn}x_n \geq bm \\
&\quad x_1 \geq 0 \\
&\quad x_2 \geq 0 \\
&\quad ... \\
&\quad x_n \geq 0
\end{aligned}
\tag{2.2}
$$

Fig.2.5 shows terminology for an LP problem with two decision variables. A boundary is a constraint that expresses the upper or lower bound of an inequality or equality which encloses the feasible region. A corner point is an intersection of the boundaries. In an LP problem, if the problem has an optimum solution and at least one corner point of the feasible region exists, an optimum solution is one of the corner points. Therefore, the optimum solution can be found by checking each value of the objective function associated with every

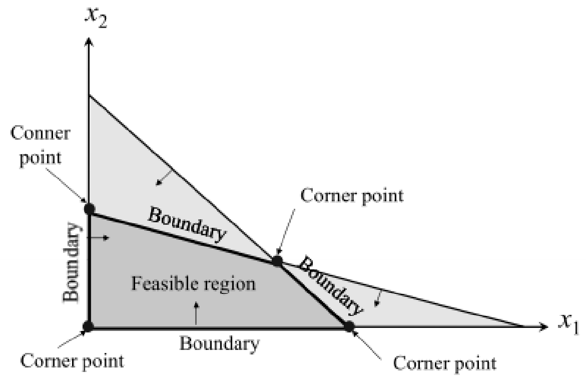

Figure 2.5: Nomenclature in Linear Programming Problem [28]

corner point.

Simplex method

If the number of decision variables and the number of constraints becomes large, the complexity of obtaining all the corner points and their corresponding values of the objective function is significant. This makes the computation times so long that the solution cannot be obtained in a practical time. To overcome this issue, a more efficient way of finding the optimum solution for an LP problem, called the simplex method, was invented which uses the idea that at least one of the corner points is the optimum solution. One corner point is selected as a starting point. Then walk along the boundary lines along the paths on which the value of the objection function does not decrease in case of maximization objective and along paths on which the value of the objection function does not increase in case of minimization objective. If a path that improves the value of the objective function at a certain corner point is not found, the corner point is the optimum solution [28].

The steps followed by the simplex algorithm in solving LP problems are as follows: [28]
Step 1. Set up the initial table.
Step 2. Apply the optimality test which checks if the objective row has no negative entries in the labeled columns, then the indicated solution is optimal. Stop computation if the optimality criterion is satisfied.
Step 3. Find the pivotal column by determining the column with the most negative entry in the objective row. If there are several possible pivotal columns, choose any one.
Step 4. Find the pivotal row. This is done by forming the 0-ratios, the ratios formed by dividing the entries of the rightmost column (except for the objective row) by the corre-

sponding entries of the pivotal columns using only those entries in the pivotal column that are positive. The pivotal row is the row for which the minimum ratio occurs. If two or more 0-ratios are the same, choose one of the possible rows. If none of the entries in the pivotal column above the objective row is positive, the problem has no finite optimum. We stop our computation in this case.

Step 5. Obtain a new table by pivoting. Then return to **Step** 2.

2.5.1 Integer Linear Programming (ILP)

ILP is a sub-category of linear programming where some or all of the decision variables take integer values. If some variables in LP need to be integer, then the LP problem becomes a Mixed Integer Linear Programming (MILP) problem defined in standard form as:

$$\begin{aligned} &\text{minimize} \quad c^T x \\ &\text{subject to} \quad Ax \leq b, x_i \geq 0 \end{aligned} \tag{2.3}$$

$$\text{with } A \in \mathbb{R}^{pxn}$$

$$x_i \in \mathbb{Z}, i \in \{1, 2, ...n\}$$

Where

$$x^T = \begin{bmatrix} x_1 & x_2 & x_3 & \dots & x_n \end{bmatrix}$$

$$b^T = \begin{bmatrix} b_1 & b_2 & b_3 & \dots & b_m \end{bmatrix}$$

$$c^T = \begin{bmatrix} c_1 & c_2 & c_3 & \dots & c_n \end{bmatrix}$$

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{m1} & x_{m2} & x_{m3} & \dots & x_{mn} \end{bmatrix}$$

The last row is called the integrality condition of the MILP which marks the difference between LP and MILP. It states, that some (or all) of the variables in the solution vector must be integer values. Some of these variables can also be restricted to be either 0 or 1, which makes them binary variables.

MILP is used to solve many practical optimization problems, such as economic problems, supply problems and control problems. A special application of MILP is the optimization of network flow. Most of the research on the optimization of routing and wavelength assignment in optical networks is based on MILP [29],[30].

In general cases MILP problems are NP-hard. For these category of problems, linear relaxation is a possible way to get feasible solutions. The linear relaxation ignores the integer constraints and threats 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].

A branch and bound algorithm

Given an integer programming problem, the first step in the branch and bound approach is to ignore the integral restrictions and solve the corresponding linear programming problem. If this problem does not have an integral optimal solution, new constraints are generated to cut off this optimal non integral solution. But here, instead of expanding the original problem by the addition of a single constraint, a branch of two distinct problems are created, each coming about by the addition of a new constraint to the original set of constraints.

These two new constraints are generated from the non-integral optimal solution to the original problem as follows. Select a variable, say X_j, that assumes a non-integral value in this optimal solution. Suppose $x_j = b_i$ in this solution. Then the two new problems are created by adding to the original constraint set for one problem the constraint and for the other the constraint. Note that the original non-integral optimal solution is not a feasible solution to either new problem, but that any integral feasible solution to the original problem would be a solution to one of these new problems. However, there are now two IP problems to deal with, and the integral optimal solution to the original problem could be contained in either problem. We continue, considering the two new problems just as before. For each, we initially ignore the integral restrictions, solve, and, if the problem has a non-integral optimal solution, we again branch from that problem, formulating two new problems using the above method.

Cutting plane method

The cutting plane method has been the most powerful improvement of the branch and bound algorithm in the past. To speed up the branch and bound algorithm, it is crucial to reduce the number of problems to solve, and cutting planes were found to be a powerful tool to do so. By introducing additional constraints, called cuts, to the LP relaxations dynamically, domains of the search tree that contain only fractional solutions are cut off. That means that the number of variables to branch on is reduced. Normally, many cutting planes are added already before branching for the first time, right after solving the root relaxation.

These additional constraints considerably reduce the search tree size. However, also during the process of exploring the search tree, new cuts can be added to the sub-problems to cut off branches, in cases when a cut possibility only became visible at a certain sub-problem. One of the most popular cutting plane algorithms used in GLPK is Gomory's cutting plane algorithm. In addition to this algorithm, GLPK uses algorithms such as MIR cuts, Cover cuts and Clique cuts.

2.5.2 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 with the most fundamental being minimum cost flow problem models, which deal with a single commodity over a network. In these kinds of models a single demand flows in a given network path from source to destination. This restricts the use of resources or links for a single flow which affects their efficient use. Multi-commodity flow problems arise when several commodities use the same underlying network. The commodities can be classified based on their physical characteristics or their source and destination pair. Different commodities have different sources and destinations, and commodities have separate mass balance constraints at each node. However, the sharing of the common underlying network resources and capacities binds the different commodities together.

In fact, the essential issue addressed by the multi-commodity flow problem is the allocation of the capacity of each arc to the individual commodities in a way that minimizes overall flow costs. In a communication network, nodes represent source and destination stations for traffic and arcs represent transmission links and their capacities. Traffic between different pairs of nodes define distinct commodities; the supply and demand for each commodity is the number of messages to be sent between the origin and destination nodes of that commodity.

The optimal MCF formulation takes the form:

$$Minimize \quad \sum_{l \in L} D_l(f_l) \tag{2.4}$$

Subject to flow conservation constraints and any additional special constraints such as those used in this thesis including link utilization, power consumption and others where f_l denotes the total flow on link l, and L is the set of links in the network. The link cost function D_l is typically chosen to be a convex monotonically increasing function. As a result, this formulation tends to spread the traffic and keep the link flows away from link capacity, thereby resulting in efficient utilization in link capacities and minimizing blocking of incoming requests which may be in the form of bursts [32].

2.5.3 GLPK and GNU Mathematical Programming Language (GMPL)

Modeling languages were created to simplify the task of manually solving mathematical programming problems which is difficult and time consuming if not possible. The assumption behind modeling languages is the recognition that many mathematical programming problems can be expressed in a computer language whose syntax is close to the standard presentation of these problems. These languages typically provide a number of data types such as arrays and sets, as well as computer-language equivalents to algebraic notations. An optimization problem is specified by an objective function that can be maximized or minimized and constraints over some decision variables. A solution to the problem is an assignment of values to the variables that satisfies the constraints and optimizes the value of the objective function.

GLPK is an open-source package which is used to solve LP, MILP and other related problems. GLPK supports GMPL. The GLPK package includes the following main components:

- primal and dual simplex methods
- primal and dual interior-point method
- branch-and-cut method
- translator for GMPL

- Application Program Interface (API)
- stand-alone LP/MILP solver

GMPL is a modeling language used for describing linear mathematical programming models. Model and data can be in one or separate files. The latter feature allows having arbitrary number of different data sections to be used with the same model section. In a process called translation, a program called the model translator analyzes the model description and translates it into internal data structures, which may be then used either for generating mathematical programming problem instance or directly by a program called the solver to obtain numeric solution of the problem.

In GMPL a model is described in terms of sets, parameters, variables, constraints, and objectives, which are known as model objects. Each model object is provided with a symbolic name which uniquely identifies the object and is intended for referencing purposes. It is sometimes desirable to write a model which, at various points, may require different data for each problem instance to be solved using that model. For this reason, in GMPL the model description consists of two parts: the model section and the data section. The model section is a main part of the model description that contains declarations of model objects and is common for all problems based on the corresponding model. The data section is an optional part of the model description that contains data specific for a particular problem instance.

2.6 Traffic Engineering (TE)

Broadly speaking traffic engineering covers all network related concepts, such as network traffic measurement, analysis, modeling, characterization, simulation and control. The techniques of traffic engineering are applicable to all kinds of network segments. The forecasting of network usage and investment in the right parts and resources in the network is essential in cost-efficient network business. Carefully designed network planning also helps utilizing TE methods and it improves the network efficiency because network optimization becomes an easier task with the application of TE.

Like the other network segments, the optical network segment also applies TE in different operational blocks. The main TE techniques are applied in:

- Routing:- Current optical networks which have GMPLS control plane mechanism use Open Shortest Path First- Traffic Engineering (OSPF-TE) for routing [34]. This protocol is used for the auto discovery of topology and advertisement of resource states such as bandwidth and protection type. The main features introduced by the TE extension are:
  - Advertisement of link protection type
  - Implementation of derived links for improved scalability
  - Accepting and advertising links with no IP address-link ID
  - Incoming and outgoing interface ID
  - Route discovery for back-up that is different from the primary path [31]
- Signaling:- The main protocol used is Resource ResreVation Protocol- Traffic Engineering (RSVP-TE) [47]. This protocol is used for the establishment of traffic-engineered Label Switched Paths (LSPs). The major enhancements are:
  - Label exchange to include non-packet networks
  - Establishment of bidirectional LSPs
  - Signaling for the establishment of a back-up path
  - Expediting label assignment via suggested labels
  - Waveband switching support [31]

2.7 TOTEM toolbox

TOTEM is an open source toolbox which supports a range of TE algorithms. The kernel of the toolbox is a repository of TE methods and is grouped into four main categories namely IP, MPLS, BGP and Generic algorithms. Besides this kernel, the topology manager contains all the topological data. This module is the reference access point to topology representations in the toolbox. The configuration manager configures the global toolbox parameters and the different algorithms. Finally, the web-service interface module provides the standard interface for interoperability with existing external tools. The TOTEM toolbox architecture is shown in Fig.2.6.

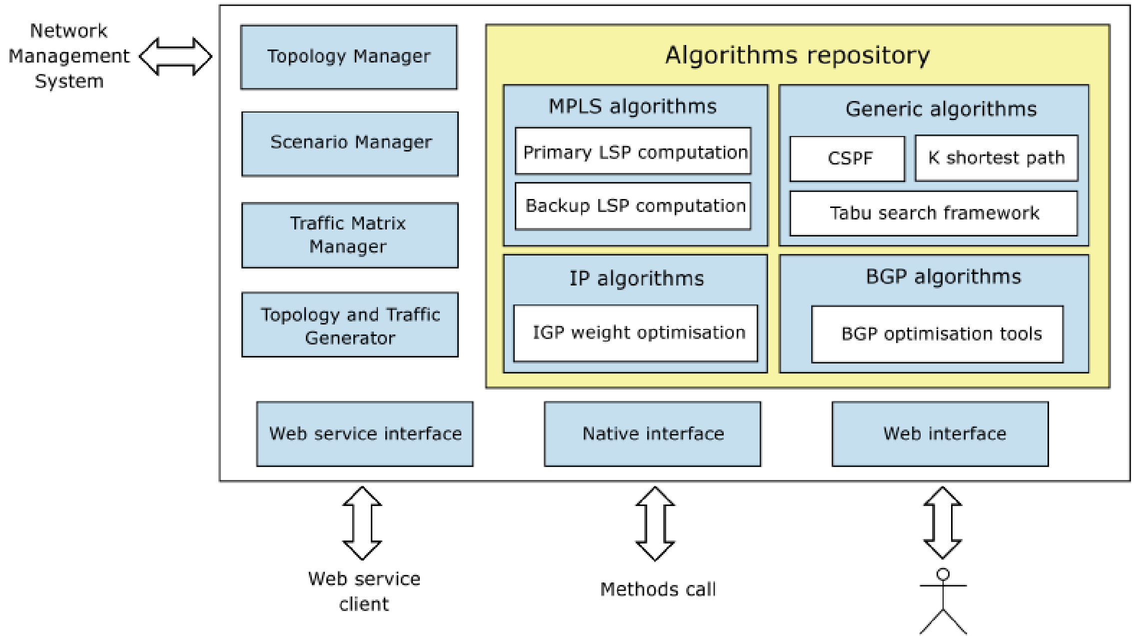

Figure 2.6: TOTEM Architecture [33]

The design of TOTEM allows two utilization modes; on-line deployment in operational networks and as off-line tool for simulation purposes. The toolbox also has the capability to integrate third party algorithms that are developed using Java, AMPL or other languages that are supported by the toolbox. It provides topology information (nodes, links, LSPs,) to the algorithm to be integrated. It also provides a scenario execution service. This service parses an XML file describing a scenario and then calls the appropriate algorithm to execute the scenario.

Chapter 3

Power Consumption Minimization in Optical Networks

3.1 General overview

Among the power-consuming sectors, the ICT sector is rapidly becoming a big player. Recent studies have shown that the ICT impact on global power consumption ranges from 2% to 10% [35]. The three main areas of power consumption in the ICT sector are: telecommunication networks, data-centers, and mobile terminals. In line with the growing usage of data intensive applications such as social media and content sharing platforms and the increasing number of devices from user side, the total telecom network traffic is growing. Traffic is currently growing at about 40% per year and therefore is doubling approximately every 2 years [36]. Accordingly, the power consumption of telecommunication networks is also growing rapidly. According to [35], telecommunication networks currently consume around 37% of the total ICT sector power consumption.

Due to the increasing network usage which leads to further deployment of network infrastructures, the GHG emission by the ICT sector is also increasing significantly. Global e-Sustainability Initiative (GeSI) estimated that network infrastructures will emit about 350 million tons of CO_2 in 2020. As illustrated in Fig. 3.1, the CO_2 emissions of telecommunications devices (e.g. routers, switches) are estimated to increase from 12–22% in 2020 compared to 2002 [37].

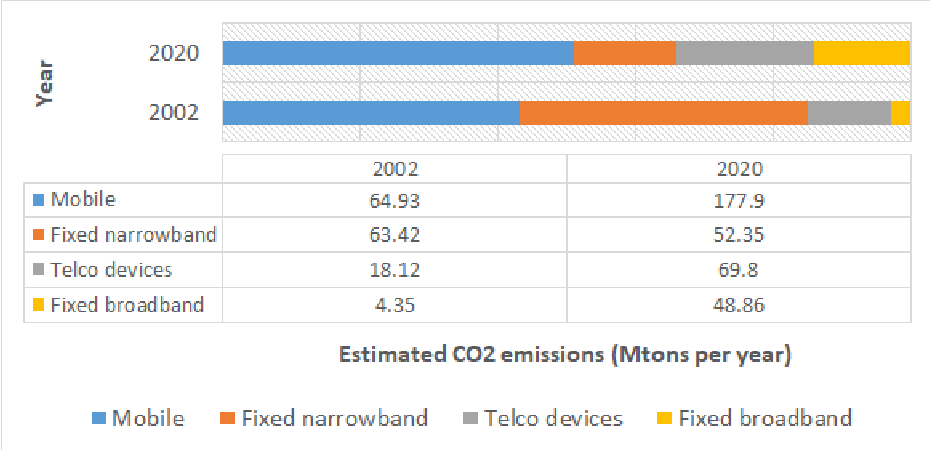

Figure 3.1: GeSI estimation on GHG emission [37]

This increase in power consumption of the telecommunication sector which in turn leads to an increase in operator OPEX is currently attracting the attention of stake holders for its solution. Hence significant academic and industrial research effort has been focused recently on reducing the power consumption of communication networks. Results show that considerable amount of power can be saved through the use of renewable energy sources such as wind and solar energy sources and the development/deployment of new architectures, protocols, and algorithms operating on telecommunication equipment hardware, software and network.

3.2 Power consumption modeling in optical networks

When a power consumption and an approach to minimize this consumption is considered, a correct power consumption data or a power consumption model is needed. The availability of this data enables the making of decisions that will help to apply power consumption minimization approaches on ICT sectors. This data is also important for equipment vendors, service providers and researchers to devise solutions that will enable the reduction of the power consumption of a specific equipment, the segment under question or the entire network in general.

Although this is the case, the power consumption of a specific component differs among vendors or models. These differences make the results obtained for power saving for different equipments in the same segment to vary significantly. In addition, maximum power consumption values are sometimes used, which can differ substantially from power consumption under typical operating conditions [49]. In addition to these issues, getting the exact power consumption models used by equipment manufacturers is difficult as this information is usually confidential which leads to variation of power saving values using same equipment due to the different models used to model their power consumption.

Different works give different power consumption models which from the authors' perspective satisfy the system under consideration. For instance, in [12] a model is given for optical multi-layer networks, subdividing the network in to four layers: IP/MPLS layer, Ethernet layer, OTN layer and WDM layer. The model considers the OPEX value for each layer and equipment found in each layer. This model enables the computation of power saving potential depending on the layer under consideration rather than considering specific components.

In [50] a power consumption model considering IP router ports, transponders and optical amplifiers is proposed in order to compare the power saving potential of static optical bypass over non-bypassed design in an IP over WDM network. The paper considers an energy-oriented model for the IP over WDM network incorporating the physical layer issues such as energy consumption of each component and the layout of optical amplifiers in the design. These and other related works try to model or estimate the power consumption of components or the network segment in general so that by applying a proposed algorithm or approach the power saving obtained can be easily seen. Although the works consider different segments in telecommunication networks, they can also be applied to optical network segments with modifications related to the segment.

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

In [49] the power consumption of the optical core network segment is divided into four layers; IP/MPLS, Ethernet, OTN and WDM. For each layer power consumption of each component involved is taken from data sheets. The total power P_{core} is thus given as the sum of the power consumption in the constituting layers.

$$\begin{aligned} P_{core} &= P_{ip} + P_{ethernet} + P_{otn} + P_{wdm} \\ Where & \\ P_{wdm} &= P_{oxc} + P_{amplifier} + P_{tsp} + P_{reg} \end{aligned} \tag{3.1}$$

The power consumption for each layer and component is also given as a function of the average IP demand, a power efficiency value for that layer, and the hop count for each layer.

When the OTN power consumption values are considered, they are mainly based on confidential information and are approximations. The power consumption values are based on the typical power consumption of a maximum configured system, including the power overhead of the chassis and any required control and switch fabric cards. The power consumption values used for the OTN line cards in [49] are given in table 3.1.

Table 3.1: OTN line card power consumption values (values in bracket indicate projected values at the time of the paper's preparation)[49]

Type	Power Consumption (W)
OTN 1Gbps port	7W
OTN 2.5Gbps port	15W
OTN 10Gbps port	34W
OTN 40Gbps port	160W
OTN 100Gbps port	(360W)
OTN 400Gbps port	(1236W)
OTN 1Tbps port	(2794W)

The approach used in [53] uses an analytical power model to determine the power consumption and power saving potential of an IP over WDM optical system. The analytical model gives the total power $P_{backbone}$ in an IP-over-WDM network as the sum of the power consumption of the constituting layers:

$$P_{backbone} = P_{ip} + P_{wdm}$$
$$Where \tag{3.2}$$
$$P_{wdm} = P_{oxc} + P_{amplifier} + P_{tsp} + P_{reg}$$

This model is similar to that stated in [49] with the exclusion of the OTN and Ethernet layers. The power consumption of each component is given as

$$P_x = \eta_{eo} \times \eta_{pr} \times N_d \times D_c(\frac{P_x}{C_x} \times H) \tag{3.3}$$

The external overhead factor η_{eo} accounts for the power consumption of external cooling and facility overheads. The protection factor η_{pr} accounts for traffic protection. The combined factor $N_d \times D_c$ gives the total amount of traffic in the network as a product of the number of demands and the average required capacity per demand . The power rating factor $\frac{P_x}{C_x}$ expresses the average power per capacity for a given component. Finally, the hop count H is the average number of hops between processing elements in the respective layer.

A Similar work, [54], provides a bottom-up model which does not consider the network architecture and demands. The model uses a proportional power consumption profile and gives the power consumption of a component at a given time t as

$$P(t) = P_{idle} + EC(t) \tag{3.4}$$

Where P_{idle} is the idle state power consumption of a component when $C(t)$ is zero, $C(t)$ the load/throughput at time t and E is a proportionality constant know as incremental energy per bit given as

$$E = (P_{max} - P_{idle})/C_{max} \tag{3.5}$$

As stated earlier, the drawback of this model is, although it follows a proportional power consumption profile, it does not explicitly consider the change in demand that occurs at a given time t. The paper considers each service and assigns part of the available capacity for each considered service.

The works mentioned above consider the power consumption modeling of optical networks from different perspectives. This thesis considers a power consumption model similar to that stated in [54] with an inclusion of a term that considers the traffic/demand change as a traffic burstiness coefficient. Given in equation 3.4 is the proportional power consumption model used in [54]. As seen in the equation, the model considers the idle power consumed when a given component is operating in sleep mode or is carrying no traffic, an incremental energy consumption per bit value and load/throughput at time t to calculate the power consumption of a component at a given time t. Here the given model has no explicit consideration on the actual demand value for the network as the demand varies with time. To consider this demand equation 3.4 and equation 3.5 are merged and given as:

$$P(t) = P_{idle} + (P_{max} - P_{idle})C(t)/C_{max} \tag{3.6}$$

With $C(t)/C_{max}$ being defined as traffic burstiness coefficient, $\beta(t)$. This coefficient indicates the traffic demand the network is experiencing at a given time with respect to the maximum demand. The coefficient $\beta(t)$ is in the range $0 < \beta(t) \leq 1$. Thus equation 3.7 is given as:

$$P(t) = P_{idle}(1 - \beta(t)) + P_{max}\beta(t) \tag{3.7}$$

Here the value of P_{max} for each component can be found from the data sheet of the selected model. As the value of P_{idle} is difficult to find on data-sheets a value of 90% of the maximum power consumption is considered for each component taking a value which is related to those indicated in [51], [52].

3.3 ET backbone power consumption scenario

The power consumption values for each component is an essential part of any power consumption analysis task. This section gives the power consumption values of the components used in Ethio Telecom's Addis Ababa and North-East backbone optical transport networks. The networks consist of two types of equipments; OSN 8800 V100R008C00 and OSN 6800 V100R008C00 [55]. The total power consumption of a given equipment is the sum of the power consumption of the components found in the equipment. The equipments can be configured as Optical Terminal Multiplexer (OTM), Optical Add Drop Multiplexer (OADM), OLA or OADM/OTM. The components found in each equipment are categorized into six categories. These are:

- OADM- These components are used for optical add/drop functionality and Multiplexing/ De-multiplexing functions. In addition, the components that are used for fiber related processes are categorized under this category.

- Tributary Modules- The components under this category are used for supportive tasks of the equipment under consideration. These tasks include clock synchronization, system communication and control and power management tasks.
- Optical Amplification (OA)- The components in this category are solely used for amplification purposes which is used for the amplification of the degraded signal using different amplification methods. These components can be used as pre/post amplifiers with line cards or as stand-alone optical line amplifiers.
- Optical Transponder Units (OTU)- These are used for service processing. The service processing is carried out from client side to line side or vice-versa. O/E/O conversion is also carried out by these components. Signal regeneration is also accomplished by these components which can be realized by the back-to-back configuration of two transponder units.
- Cross Connection- The components in this category are used for cross connecting services of lower or higher granularity from a specific source port to a specific destination port.
- Optical Transceivers

Typical configuration of OADM and OLA sites consists of the components shown in Tables 4.2 and 4.3 respectively.

Table 3.2: OADM site component power consumption [56]

No.	Category	Board Type	Typical PC(W)	Maximum PC(W)
1	OADM	Fiber Interface Board	0.2	0.3
2	OADM	Interleaver 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	13.0
5	OADM	40-channel Demultiplexing Board	10.0	13.0
6	Tributary module	Interface Board of Alarm & Timing	0.3	0.3

Continued on next page

Table 3.2 – *Continued from previous page*

No.	Category	Board Type	Typical PC(W)	Maximum PC(W)
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
14	OA	C-BAND Optical Booster Unit(MAX -1dBm IN and 16dBm OUT, Gain 17dB)	10.0	12.0
15	OA	C-BAND Optical Amplifier Unit(MAX 0dBm IN and 20dBm OUT, Gain 20 to 31dB)	12.0	15.0
16	OA	C-BAND Optical Amplifier Unit(MAX 4dBm IN and 20dBm OUT, Gain 16 to 23dB)	12.0	15.0
17	OTU	8 x Any-rate Ports Service Processing Board	23.0	25.0
18	OTU	40GE Tributary Service Processing Board	58.0	64.0

Continued on next page

Table 3.2 – *Continued from previous page*

No.	Category	Board Type	Typical PC(W)	Maximum PC(W)
19	OTU	40Gbit/s Line Service Processing Board	99.0	103.0
20	CX	High Cross-connection, System Control and Clock Processing Board	$340 - 7.4 \times (32 - n)$	$374 - 8.1 \times (32 - n)$

"n" is equal to the total number of tributary, line, and Photonics Integrated Device (PID) boards housed in a sub rack.

- If a sub rack is configured with VC-3 or VC-12 cross-connections, "n" is equal to 0.
- If a sub rack is not configured with any VC-3 or VC-12 cross-connections, "n" is equal to 1.

Table 3.3: OLA site component power consumption [56]

No.	Category	Board Type	Typical PC(W)	Maximum PC(W)
1	OADM	Fiber Interface Board	0.2	0.3
2	Tributary module	Power Interface Unit	3.0	3.6
3	Tributary module	Bidirectional optical supervisory channel and timing transmission unit	17.5	19.5
4	Tributary module	System Auxiliary Interface Board	9.0	13.0
5	Tributary module	System Control and Communication Board	23.0	25.1
6	OA	C-BAND Optical Amplifier Unit(MAX 0dBm IN and 20dBm OUT, Gain 20 to 31dB)	12.0	15.0

Continued on next page

Table 3.3 – *Continued from previous page*

No.	Category	Board Type	Typical PC(W)	Maximum PC(W)
7	OA	C-BAND Backward Raman and Erbium Doped Fiber Hybrid Optical Amplifier Unit(MAX 1dBm LINE IN and MAX 20dBm OUT, Gain 19 to 33dB for G.652)	?	?

3.4 Power consumption minimization approaches in optical networks

Currently optical networks are deployed considering the worst case scenario of traffic demand including burst traffic which usually is not the case. In addition, there are resources deployed for ensuring reliability of the service such as protection and restoration resources which only kick-in when there is a fault in the network but idle otherwise. Thus this creates a large gap between the actual usage of network resources and the deployed capacity. The main idea of Power Aware (PA) network design and operation is to minimize this gap between the utilization of the network and the offered capacity. Optical networks can use different approaches to minimze their power consumption hence increase their energy efficiency. These approaches are classified into different categories depending on the point of view taken by the authors. In [38], power consumption reduction approaches are broken down into three levels depending on the area of application namely circuit level, equipment level and network level. Another work,[39], classifies the approaches as re-engineering, dynamic adaptations, and sleep or standby mode.

[40] classifies the approaches into four categories:

- Re-engineering: The aim of this approach is to use more energy-efficient hardware components for network architectures, especially through reducing the internal complexity of elements.

- Interface proxying: This approach entails switching off of an inactive end device to the sleep/standby state and delegating the processing of its background traffic either locally to the low-energy processor on-board of the same device, or to an external entity.
- Power-proportional or Adaptive Link Rate (ALR): In this approach, the Ethernet link capacity is adapted with its local current flow load.
- Sleep-scheduling: This approach consists in switching off some un-utilized network components (node or link) to preserve the energy consumed for keeping them awake during inactive periods.

In [41], a general survey of works focusing on green networking research in wired networks is provided. The authors used the employed energy-aware strategy to classify existing efforts into adaptive link rate, interface proxying, energy-aware application and energy-aware infrastructure categories. The energy-aware application category proposes modifications in user-level applications or kernel-level network stack according to the varying load imposed by applications. The energy-aware infrastructure comprises approaches using collaborative decision with a wider knowledge of the entire system state to improve the amount of energy saving. Especially, some general sleep-scheduling based routing protocols up to year 2011 are enumerated in this category.

A recent survey on techniques and solutions dealt to improve the energy efficiency of computing and network resources is provided in [42]. The paper categorizes the existing approaches by node level and network level. In the node level, re-engineering, shutdown and adaptive link rate techniques are identified. In the network level, some coordinated techniques including energy-efficient network protocols, clean-state approaches and energy-aware frame- works are considered.

A related work,[43] classifies the approaches used for power saving in telecommunication core networks as follows.

1. Power-efficient architectures
2. Power-efficient devices

3. EA network design
4. Adaptation in high-low demand hours
5. Reduction of transmitted data

3.5 Sleep mode operational approach

As stated in the previous section, there are many approaches in which telecommunication networks or specifically the optical network segment can be designed or operated at in order to minimize power consumption. Although these approaches are mainly targeted in minimizing power consumption of the designated network segment or entire network, some also take QoS constraints into consideration with different parameters to evaluate the change in performance on the network that would occur due to the application of the approach. One of these approaches is sleep mode operation of optical system components. An optical system can operate in sleep mode in two scenarios, if it is totally unused or the traffic flowing through it remains under a given threshold, with residual traffic rerouting, in order to avoid traffic disruptions [44]. In the up-state, devices are operational and use their maximum power consumption, whereas in down-state they are un-powered and unused. The intermediate state is an idle-state in which the device is non-operational but semi-powered, hence it does not transmit any traffic but can go to the operational or up state with in a short time period.

When sleep mode operations are considered for optical networks two main issues arise that need careful assessment. The first one is the strategy that should be followed to select the sleeping links/nodes. This strategy should be carefully devised not to affect the existing or newly arriving traffic demands. The second one is the routing strategy that will be followed in order to reroute existing traffic from the links/nodes that are candidates for sleep mode operation. This strategy should also be carefully assessed in order to avoid packet drop and in the worst case traffic interruption during execution.

3.6 Comparison of algorithms in sleep mode operation of optical networks

While devising a method to implement a sleep mode operational approach, numerous aspects of its impact on the network performance apart from power saving should be considered. These can be given as constraints that are incorporated in the algorithm or model in order to keep the QoS of the network segment under consideration in an acceptable range or level depending on the given metric. Thus based on these constraints and other considerations, sleep mode operational approach algorithms can be compared. The main criteria used for this comparison and their description is given in Table 3.4. These criteria are discussed in detail in [43].

3.7 Algorithms in sleep mode operation of optical networks

There are numerous algorithms or approaches taken by authors to implement sleep mode operation in optical networks. Although the main aim of these approaches is power consumption minimization, some of them also consider QoS aspects of the network segment under consideration. Some of the algorithms or approaches in this area are discussed below.

One of the notable works in this area is [44]. This work focuses on the power consumption minimization problem of a wide area optical transport network. The specific problem of PA-RWA is addressed considering a transparent multi-fiber optical network in which bundles of optical fiber cables are used. It considers power consumption minimization by switching off fiber links and hence OLAs. An ILP formulation is provided for the static light path establishment problem and heuristics are proposed to solve the problem for dynamic light path establishment. To solve the routing and wavelength assignment problems, the authors propose different algorithms. Their proposal is compared with a number of already known RWA algorithms showing that it is able to reduce the power consumption of the network by about 20-30%, depending on the amount of traffic treated. As a measure of QoS for the proposed heuristics, the blocking probability is evaluated.

In [45] the power consumption of a transparent WDM optical network is evaluated, with constraints on protection requirements and traffic variability. The paper provides a

Table 3.4: Evaluation criteria for EA-ARs [43]

No.	Criterion	Description
1	Physical layer constraints	The incorporation of classical physical layer constraints found in optical transport deployments such as number of wavelengths used
2	Constraints on installed devices	Checks whether the existing installed devices can be used for execution of the algorithm or additional devices are needed.
3	Impact on QoS	Consider its impact on the QoS of the network using different metrics
4	Computation time	The algorithmic computation time required in order to produce results
5	Triggering events	Considers the events that trigger network reconfiguration
6	Operation	Identifies whether the algorithm is implemented in centralized or distributed architectures.
7	Network knowledge	The input information that is used by the algorithm in order to gather information about the state of the network
8	Protection consideration	Whether the algorithm considers protection mechanisms and resources or not
9	Reconfiguration cost	Consideration of the reconfiguration cost between two consecutive time periods
10	Future traffic assumption	The incorporation of future traffic variations or demands in the algorithm
11	Control mechanism	What control mechanisms, new or existing, are used by the algorithm

power consumption model for both nodes and links, and an ILP formulation of the power consumption minimization problem. Moreover, a heuristic algorithm is applied to the considered network scenario to reduce the power consumption of optical links. When traffic load decreases, the algorithm tries to switch off optical links according to several heuristic criteria that take into account the power consumption parameter of links, some topological consideration and the congestion of each fiber. By performing such an optimization, an energy saving of about 35% can be obtained. The work considered power consumption values for devices both from data sheets and/or research papers.

Another work [46] tries to assess the trade-off between power saving and network performance. To achieve this objective an approach known as Weighted Power-Aware Lightpath Routing is proposed and evaluated using two core networks and considering blocking probability as a criterion for QoS evaluation. The study assumes a transparent WDM network where nodes are equipped with OXCs and fiber links consist of OLAs, depending on the fiber link length. Connection requests are provisioned all-optically from source to destination. Based on these assumptions, the power required to provision one connection request is the sum of the power consumption of the transponders, the power needed to optically switch the signal at intermediate OXCs and the power consumed by the OLAs along each fiber link in the path and the total network power consumption, at any given time, is the sum of the power consumed by all the connection requests currently provisioned in the network. Results show that power savings of up to 50% are achievable, but at the expense of a significant increase in the network blocking probability which indicates that an approach that accounts only for the minimization of the network power consumption might lead to unacceptable performance degradation. With an adjustment on the power-weighting factor used in the paper a trade-off between power saving and blocking probability can be obtained with up to 30% power saving with an acceptable blocking probability value.

In addition to proposing approaches or algorithms based on the existing protocols, some works also consider modifying the available protocols to consider power saving. In [48] the authors propose enhancements embedded in GMPLS based protocols enabling power control in optical devices, and then analyzed the impact of controlling the daily power consumption of optical switching equipment in the network. In current signaling protocols, the bit "A" in the ADMIN STATUS object of RSVP-TE path/resv messages, is dedicated to administratively setting-up or taking down a specific LSP [47]. The network administrator can set the bit “A” to trigger specific actions to be taken locally at each network node crossed by the LSP. While “A” is set to 0, during normal network operation, the network device is powered and fully operational. By setting bit “A” to 1, a change to an un-operational and switched-off device state can be triggered; this is usually done in case of failures. The authors propose to extend the signaling protocol to dynamically allow the management of a device’s power state. To represent the power states a new bit “S”, is proposed. Thus when $A = 0$, S is used to discriminate whether the devices are up or idle. Conversely, if $A = 1$, S discriminates between down state and damaged.

The authors also proposed a mathematical formulation for the estimation of the power consumption when the proposed device power management is implemented considering two traffic scenarios - no protection and 1:1 protection. Daily traffic variations were used for the comparison and the daily network power requirements estimated when the different traffic-aware strategies were implemented; savings were calculated by comparing such consumption with a case in which no power management was performed. Results showed that the standalone link-sleep mode leads to a power saving of up to 3.5%, while device power management obtains up to 17% savings. Moreover, if both of these strategies were implemented jointly, power savings increased up to 20% [48].

Chapter 4

Problem Formulation

So far the power consumption minimization approaches in optical networks are discussed. The approach used in this thesis, sleep mode operational approach, is discussed in detail and different algorithms used in this approach are compared from power consumption point of view and impact on network QoS using different parameters. This chapter discusses the proposed sleep mode operational model in this thesis, Power Aware Traffic Engineering with attenuation (PATE-a). It gives the input parameters, decision variables, objective function and constraints used and their analysis. Finally an implementation strategy is proposed that uses the GMPLS Graceful shutdown feature which uses re-routing of traffic before sleep mode operation of links in order to ensure uninterrupted traffic flow.

4.1 Power consumption minimization areas

As can be seen from the power consumption data of the components in each site and each configuration in Section 3.3, generally three main component categories consume high amount of power and are potential candidates for sleep mode strategy for power consumption minimization. These are transponders, cross-connect units and optical amplifiers. Although cross-connect units consume high power, it is usually impractical and has a profound effect on QoS and other network wide metrics to switch off or operate in sleep mode these components as they carry traffic most of the time. This is also in part due to the fact that optical cross-connect units now-a-days can switch to upto 9 directions whose simultaneous shutting down is a very rare case. Thus the main components on which sleep mode operational strategy can be implemented on are the transponders and optical amplifiers. Fig.4.1 gives the optical transport system model used in this thesis.

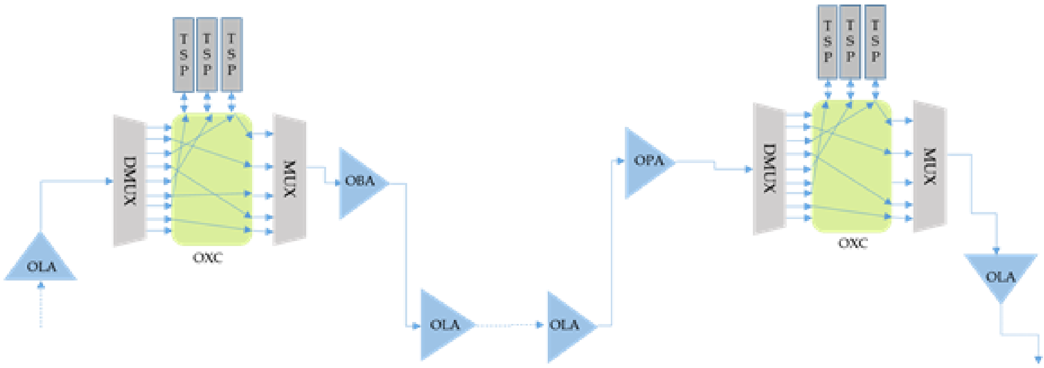

Figure 4.1: Optical Transport System Model

Depending on the choice of the component that is going to operate in sleep mode, the sleep mode operational areas are divided into two. These are:

1. Node sleep mode: This area entails the sleep mode operation of transponders or line cards and leads to a total sleep mode of a node when all the outgoing and incoming links are operating in sleep mode.
2. Link sleep mode: This area is concerned with the sleep mode operation of optical amplifier components so that the links associated with these amplifier components will also operate in sleep mode.

The algorithms and mathematical formulations used in sleep mode operations also use these areas of power consumption minimization as their main areas of concern and formulation.

4.2 Mathematical Formulation

4.2.1 PATE-a Model

The general PATE-a model problem uses input information such as network topology and traffic demand for each traffic SD pair. Based on the input data, this model can be formulated to calculate the link utilization to find the energy efficient routing path by applying a threshold level on the link utilization for each link which differs it from classical flow routing models that are solely concerned with traffic flow optimization through links. Results of the optimization help to analyze which links are highly utilized and least utilized, so that finally re-route the traffic on the chosen energy efficient routing path obtained from the model and sleep links that are not used for routing traffic demand.

The PATE-a problem is formulated as a MCF model which consists of input parameters, objective function and constraints. Then the model is implemented using AMPL which is used to generate an ILP model. Once the model is formulated, the problem is solved using GLPK solver. The network can be modeled as a directed graph $G = (V, E)$, where V is the set of nodes and E is the set of directional links. In this model it is assumed that all line cards have single ports (i.e., Tx/Rx pair) thus a line-card can be put to sleep if both ports are asleep. In addition, it is assumed that all line cards and amplifiers consume a sleep mode power of 90% of their maximum consumption as there are no specific values for the sleep mode power consumption of components stated in the manufacturer data-sheets [51], [52]. The objective is to maximize the number of links and line cards that will operate in sleep mode so that the total power consumption of the network will be minimized while keeping the performance of the network at acceptable levels.

4.2.2 PATE-a Mathematical Model

As stated above the PATE-a problem can be approached mathematically based on the MCF model. To formulate the model, first the input parameters and decision variables are defined. Tables 4.1 and 4.2 give the input parameters and variables of the model respectively.

Table 4.1: Mathematical model input parameters

Input Parameter	**Description**
Nodes	Number of nodes V in $G(V,E)$
Links	Number of edges E in $G(V,E)$
NumberofPaths	Number of k shortest paths
Pair	Bi-directional link for each SD pair
LinkThresholdLevel	Maximum threshold for link utilization
Capacity	The capacity of each link E in $G(V,E)$
Demand	The traffic demand between source and destination nodes V in $G(V,E)$
BurstinessCoefficient	The traffic burstiness level for each demand between source and destination node V in $G(V,E)$
Paths	Binary, 1 if the n^{th} path contains link E in $G(V,E)$, 0 otherwise
CardPower	The typical power consumption of a line card at 25^0C
CardSleepingPower	The sleeping mode power consumption of a line card
AmpPower	The typical power consumption of an amplifier card at 25^0C
AmpSleepingPower	The sleeping mode power consumption of an amplifier card
AmplifierGain	Typical gain of a given amplifier
Distance	The physical link length of each link E in $G(V,E)$ in KM
NumAmplifiers	The number of amplifiers in a given link E in $G(V,E)$
TransmitPower	The transmitted power from the line card's T_x port in dB
ReceiverSensitivity	The minimum power in dB that the R_x port of a line card can detect
LinkLossPerKM	The optical fiber link loss in dB/KM

Table 4.2: Decision variables for the mathematical model

Variable	**Description**
TrafficFlowPerLink	The traffic flow per link E in $G(V,E)$
TrafficSplitRatio	Ratio of Traffic Demand between source and destination pair routed through the n^{th} Path
Utilization	The utilization of link E in $G(V,E)$
PowerState	Binary, 1 if a component (i.e., card/node or link) is sleeping, 0 otherwise
PathDistance	The physical length of a path in KM
PathLoss	The fiber power loss in a given path as a function of its PathDistance and LinkLossPerKM
PathGain	The power gain of each path as a function of PathAmpNum and AmplifierGain
PathAmpNum	Number of amplifiers in a path
PathLinkNum	Number of links in a path
PathLossConstraint	Path loss as a function of PathGain and PathLoss
CardConsumption	Power consumption of a card ≥ 0
LinkConsumption	Power consumption of a link ≥ 0
TotalNetworkEnergy	The total energy consumption of the sleep mode operating components in the network ≥ 0
NetworkPowerSaving	The saving obtained from sleep mode operation of components ≥ 0
LinkMaxUtilization	The maximum utilization of a given link E in $G(V,E) \geq 0$
SleepingLinkNum	Number of sleeping links ≥ 0

4.2.3 Problem Formulation

Input Parameters

- $G(V,E)$; topology where $|V|$=Nodes & $|E|$=Links
- $|V|$ = Number of Nodes
- $|E|$ = Number of Links
- K = Path Number
- B = Pair of links
- C_e = Maximum capacity of link
- T_L = Utilization threshold
- D= Traffic demand between source and destination
- β= Traffic burstiness coefficient
- R = Paths
- E_{mn} = Typical power consumption of a line card
- E_{sn} = Power consumption of a line card in sleep mode
- E_{ma} = Typical power consumption of an amplifier
- E_{sa} = Power consumption of an amplifier in sleep mode
- G_a = Amplifier Gain
- L_d = The physical link length for a given link E
- N_a = Number of amplifiers in link E
- P = Maximum transmitted signal power
- S = Receiver sensitivity of a line card receiving port
- α_e = attenuation coefficient in dB/KM

Decision Variables

- x_n = binary, $x_n = 1$ when n is in sleep mode; 0 otherwise
- $f_e^{s,d}$ = Traffic flow per link between source and destination using link e
- $r_p^{s,d}$ = Ratio of demand from s to d flowing through path p
- u_e = Utilization of link
- d_p = The physical distance of path p
- l_p = The path power loss for path p
- a_p = The number of amplifiers in path p
- g_p= The total power gain of path p
- e_p = The total number of links in path p
- p_{lc} = The power loss constraint for path p
- c_c = Network wide line card power consumption ≥ 0
- p_c = Network wide link power consumption ≥ 0
- p_t = Total network wide power consumption of sleep mode operating components ≥ 0
- p_s = Total network wide power saving of sleep mode operating components ≥ 0
- e_{um} = Link maximum utilization; $0 \leq e_{um} \leq 1.0$
- e_s = Number of sleeping links ≥ 0

With the given input parameters and decision variables above the optimization problem can be formulated as ILP problem as shown below with constraints.
$Maximize:$

$$\sum_{e=1}^{E} x(e) \times E_{sa} \times (N_a(e) + 2) + \sum_{e=1}^{E} x(e) \times E_{sn} \tag{4.1}$$

$Subject\ to:$

$$f_e{}^{s,d} = \sum_{p=1}^{K} R_p{}^{s,d}(e) * D^{s,d} * r_p{}^{s,d} * \beta \tag{4.2}$$

$$\sum_{p=1}^{K} r_p{}^{s,d} = 1 \tag{4.3}$$

$$x(e) = x[B](e), e \in |E| \tag{4.4}$$

$$u_e = \sum_{s=1}^{|V|}\sum_{d=1}^{|V|} f_e{}^{s,d}/C_e, e \in |E| \tag{4.5}$$

$$u_e \leqslant T_e, e \in |E| \tag{4.6}$$

$$x_e + u_e \leqslant 1, e \in |E| \tag{4.7}$$

$$P - ((\sum_{e=1}^{E} R_p{}^{s,t}(e) * L_d(e)) * \alpha_e) - (G_a(a_p{}^{s,t} + 2) + (\ e_p{}^{s,t} - 1) * 2 * G_a) \geqslant S \tag{4.8}$$

As can be seen from the problem formulation above, the mathematical formulation considers not only the power saving in the network but also QoS constraints such as link utilization and received power. In this model the binary variable x_n, that denotes the power state of components is used which makes the formulation a MIP problem.

With the given input parameters stated in table 4.1 and decision variables in table 4.2, the objective function given in equation 4.1 maximizes the sleeping mode power consumption of both links and line cards. The power consumption of each link is calculated as the sum of working/sleeping power consumption of each Pre/Post and line amplifier.

The traffic flow per link for each link $e \in E$ and traffic demand between source s and destination d is given in equation 4.2. It is dependent on the Paths parameter which shows whether the given link e is used to route the demand D from s to d, the traffic demand for SD pair, the traffic split ratio and traffic burstiness coefficient. The parameter Paths is used to determine pre-defined K-shortest paths from the given network topology using different metrics. These K-shortest paths can be computed beforehand using the network topology as the change in traffic demand do not affect the topology and can be used for the rest of the model execution unless a major change on the topology is carried out in which case the paths should be re-calculated. The usage of these pre-calculated K-shortest paths helps to greatly minimize the execution time of the optimization problem in that it would only use the given shortest paths rather than going through the topology and search for suitable paths for routing. In the given model the K-shortest paths are pre-calculated using Matlab script of Yen's K-shortest path algorithm and given as an input parameter to the model. For the case of finding the K-shortest paths in Matlab three metrics are used in this approach; power loss/attenuation, link power consumption and hop count.

The other input used in constraint equation 4.2 is the traffic burstiness coefficient, β. This parameter gives the estimated increase in traffic demand from source to destination which is experienced in optical networks during peak usage hours or special occasions. This coefficient ensures this burst in traffic is considered in the model so as to ensure while there is an increase in traffic the execution of the model does not lead to congestion of the network. It is set with in a range $0 < \beta \leq 1$ taking the maximum requested link capacity from client side of the network.

Another important variable is considered in equation 4.2, demand split ratio r. This variable allows the model to split traffic demand between different paths so that multi-path routing feature which is supported by current backbone equipments can be exploited. Once the demand is split between the selected paths each part will be transmitted via the assigned path. Here the model also ensures the sum of the split ratios should not be greater than 100% or 1 in equation 4.3.

The parameter B indicates the bi-directionality of each link as the given link e in the topology is a unidirectional link. This parameter is used to show that every node or line card has an incoming and outgoing link which operate in conjunction. Thus when a particular link is put to sleep mode its corresponding pair will also operate in sleep mode i.e., there will be no outgoing traffic if there is no incoming traffic and vice-versa. Equation 4.4 ensures this constraint is implemented in the model.

Equations 4.5 to 4.7 are concerned with one of the QoS parameters in optical networks namely component utilization. The utilization of each link is calculated as a ratio of the traffic flow per link given in equation 4.2 and the capacity of the link C_e. This value should be less than the maximum threshold level for link utilization given as input for the model. This threshold level varies from network to network depending on the operator requirements thus in this model different threshold values are considered with a range $0 < T_e \leq 1$ and the impact on power saving is shown. After the threshold criterion is fulfilled, equation 4.7 gives the criteria for sleeping a given link. Accordingly, a link can be put to sleep only if there is no traffic on it, and when it is ON, it does not carry traffic more than its capacity.

Equation 4.8 ensures the application of another QoS constraint, path loss constraint, in the model. It forces the selected paths for demand routing to have a path loss constraint which is greater than the receiver sensitivity, the minimum amount of received power a line card receiver port detects. If the value of the received power is less than the receiver sensitivity value, no signal will be detected and hence traffic will be lost. Different vendors have different values for receiver sensitivity for their equipments.

In addition to this the power saving obtained and the number of links operating in sleep mode is given in 4.9 and 4.10 respectively.

$$p_s = (\sum_{e=1}^{|E|} E_{mn}(e) + \sum_{e=1}^{|E|} N_a(e) * E_{ma}) - (((\sum_{e=1}^{|E|} (1 - x(e)) * N_a(e) * E_{ma}) + (\sum_{e=1}^{|E|} x(e) * N_a e) * E_{sa}) \\ +(\sum_{e=1}^{|E|} (1 - x(e) * ((1 - \beta) * E_{sa} + E_{ma} * \beta))) + (\sum_{e=1}^{|E|} x(e) * E_{sn})) \tag{4.9}$$

$$e_s = \sum_{e=1}^{|E|} x(e) \tag{4.10}$$

The optimization code written in AMPL is provided with the DVD disk accompanying this thesis.

The given model is formulated using AMPL and it is solved using GLPK solver. As stated in Section 2.5, the problem is of type MIP which makes it NP-Hard and getting optimized result in real time for large network scenarios is difficult. Here the simulation scenarios are divided into two sections which are described in detail in Section 5.1. After the model is optimized using GLPK solver, a simulation and comparison of link utilization is made with pure MCF model by implementing the model in TOTEM toolbox.

4.3 Implementation Strategy

The proposed implementation of this model uses existing features of the GMPLS control plane such as OSPF-TE, RSVP-TE and GMPLS Graceful shutdown in order to reduce the execution time and increase its efficiency. The use of these existing features for the implementation of the model also helps to have compatibility, ease of computation and ensure the uninterrupted routing of demands before the sleep mode operation of links. Thus it is considered that the networks on which this model is going to be deployed have integrated functionality of the GMPLS control plane namely OSPF-TE, RSVP-TE and GMPLS Graceful shutdown. A central controller can be used to deploy the model which is used to collect information of the current network topology, traffic demand and link congestion levels which are given as input from external sources or from OSPF-TE and RSVP-TE messages. The shortest paths can also be pre-computed and given as an input to the model.

The inter-connection of the controller with the existing GMPLS control plane can be accomplished through standard interfaces such as the North Bound Interface or via proprietary interfaces. This central controller thus can run the model using these and other related input parameters and computes the optimal flow assignment and the links and cards that can be put to sleep. This result can be then distributed to each network element via existing protocols such as OSPF LSAs.

The following main steps are carried out while implementing the model.

- **Collection of Input Information**
  The controller collects network topology and traffic matrix from external input database or OSPF LSAs. Once the topology is given as an input, for any changes in the network topology information the controller can use OSPF LSAs for update to collect all the link state information and compile the up-to-date network topology. The controller also collects link load information from nodes and computes the traffic change in demand as a burstiness coefficient locally. The link load information is part of the TE-LSA defined in RFC3630 [31]. In addition to the basic messages flooded as LSAs, OSPF-TE also reports a link's maximum bandwidth and unreserved bandwidth, and the difference between them is the link load. This information can also be obtained from a TOTEM toolbox configured to operate in an online mode. A node sends out TE-LSA when there is a significant change in its bandwidth usage which can be used by the proposed model to see if the threshold level for link utilization is satisfied.

- **Distribution of Model Results**
  With the network topology , traffic demand and other input parameters, the controller solves the PATE-a model to get which links and line cards can be operated in sleep mode together with the traffic flow per link, and distributes this information to the network nodes via the OSPF-TE attribute [31]. Once the nodes are flooded with the information the usual procedure of confirmation message exchange can be carried out to show that the nodes are ready to implement the changes.

- **Execution of the Model**
  The results of the PATE-a model give the paths that traffic should be routed on. If a path happens to be the shortest path according to OSPF-TE, the traffic is simply transmitted as native IP packets; otherwise an LSP is set up, by either the CR-LDP or RSVP-TE, to implement the non-shortest path to carry traffic. In the case that the

traffic between an SD pair takes multiple paths in the PATE-a solution, the traffic split ratio among the multiple paths will also be part of the solution. After the reception of the results and the availability of the paths for the new flows are confirmed, the next step is to execute the GMPLS Graceful shutdown feature which is mainly used for scheduled maintenance in GMPLS enabled optical networks. A PathErr message with the error code "Local Maintenance on TE Link required Flag" (if the affected network element is a link) or the error code "Local node maintenance required" (if the affected network element is the node) is sent before the links or node are taken out of service. When a (Label Edge Node) LEN receives the message, it performs a make-before-break on the LSP path to move the LSPs away from the links/nodes whose IP addresses are indicated in the PathErr message and reroute them. Affected link/node resources are flagged in the TE database so that others will signal LSPs using the affected resources only as a last resort. The main steps of GMPLS Graceful shutdown execution are shown below.

- Initiating node communication
- Reroute path computation
- New set-up request is sent along the new computed path before tearing-down the connection from the old one
- IF the new connection can be established, the old one is torn down,
- ELSE an RSVP-PATH message is sent along the old path indicating that the reroute cannot be performed.

The use of this GMPLS Graceful shutdown feature to reroute traffic ensures that there will be no interruption in traffic as it first reroutes the existing traffic before shutting down the proposed links.

Chapter 5

Optimization and Simulation Results for PATE-a Model

In Chapter 4 the mathematical model formulation for the proposed sleep mode operational model in this thesis is given and the input parameters, decision variables and constraints are discussed in detail. This chapter gives the optimization and simulation of the proposed model using GLPK and TOTEM toolbox. The results show the amount of power saving obtained by the implementation of the model and the impact of this implementation on QoS parameters such as link congestion. The mathematical optimization of the model in Section 4.2 is carried out using AMPL that is implemented in GLPK optimizer to mainly show the power saving and link sleep mode operation in the given network scenarios. In addition, the given AMPL code is evaluated by integrating within the TOTEM toolbox to show the link utilization and flow scenarios and the result is compared with the MCF model that has a main purpose of routing traffic without the consideration of power saving.

5.1 Experimental Topology and Network Configurations

The case study of this thesis uses two real network topologies; Addis Ababa (AA) backbone OTN and North-East (N-E) backbone OTN networks deployed by ethio telecom covering the capital city Addis Ababa and Northern & Eastern parts of the country. Both topologies have an ASON feature which has a control plane technology, GMPLS, enabled. Table 5.1 shows the number of nodes and links for each topology considered. In addition

Table 5.1: Network topologies for case study

Network	Nodes	Links	Demands	Type	Power consumption
AA Backbone OTN	10	38	15	Semi-mesh	12.375KW
N-E Backbone OTN	42	194	164	Ring	53.787KW

the table also shows the total power consumed by sleep mode operating components, line cards/transponders and amplifiers. As for the number of nodes in the topologies, only OTM, OADM or OTM+OADM nodes are considered and OLA nodes are given as input for the model to calculate the link power consumption and sleeping link power saving. The need for considering these two networks separately is two fold. The first one is that as the type of the networks is different; i.e., semi-mesh and ring, it will help to show the impact of the network type on the implementation of the model and the second one is as the AA backbone network has no amplifiers due to the short distance between nodes the evaluation of the model using power consumption criteria for shortest path selection is impossible. The networks consist of two types of equipments; OSN 8800 V100R008C00 and OSN 6800 V100R008C00 whose card configurations and power consumption of components are given in Section 3.3. Concerning the service between the nodes, there are totally 179 services configured. Fig. 5.1 shows the network topology for AA backbone and N-E backbone OTN.

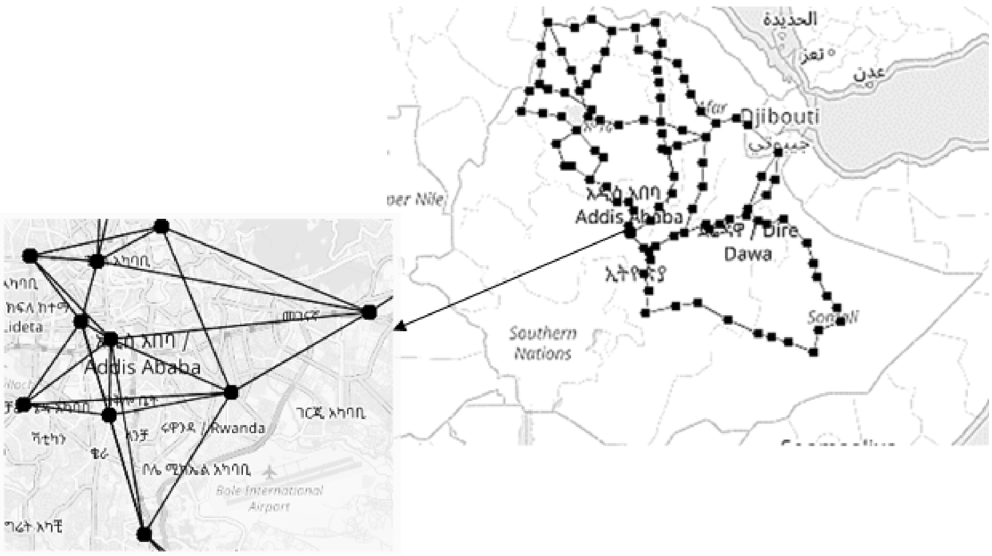

Figure 5.1: AA and N-E backbone OTN topology [55]

In addition to the network topology, traffic demand profiles and link capacities; other input parameters that are stated in Section 4.2 are also given as input to the model. In order to compute the parameter Paths, Yen's K-shortest path algorithm implementation is used in Matlab [57]. The implementation of this algorithm gives the K-shortest paths with K being given as an input so that a balance between computation time and optimal result is maintained. The K-shortest Path is computed by considering power loss/attenuation for AA backbone OTN whereas power loss/attenuation and link power consumption are used for N-E backbone OTN. For comparison purpose the legacy shortest path computation metrics, hop count, is also used.

Each line card in the considered equipment models is connected to a single pair of links; therefore, a line card can be put to sleep when there is no traffic on both directional links connected to the line card. This is achieved with the help of the bi-directional pair constraint used in the model. This makes sure that the links are put to sleep in pairs. After carrying out the optimization task of the model, the total power saving for each network is obtained. In addition, the solution also gives which paths to use for each traffic demand between source and destination pair and how to split traffic among these paths based on the actual traffic demand considered in the traffic demand profiles.

For the optimization task the proposed proportional power profile is considered which is discussed in detail in Section 3.2. For the comparison of the amount of power saving obtained with the proportional power consumption profile, the ON/OFF power consumption profile which considers no power in sleep mode and maximum power consumption while operating is also used for optimization purpose.

The scenario of link utilization as per the given threshold level is also considered. The model's AMPL code is integrated into TOTEM toolbox to see the comparison in utilization for the case of legacy routing flow optimization algorithms that only consider link utilization/congestion as constraint and the proposed model which also considers power saving while performing traffic flow optimization tasks.

5.2 AA backbone OTN

5.2.1 Power Saving

The power saving scenario for AA backbone OTN is evaluated using the given model by considering two parameters for K-shortest path selection; power loss/attenuation and hop count. When considering power loss as a parameter, the algorithm selects shortest paths based on the total loss of the path with a path having the smallest loss being selected first. The number of pre-computed shortest paths K used is 5. Here to calculate the path loss a path loss coefficient of $0.25dB/KM$ is used. The power saving obtained using power loss/attenuation as a metric to calculate the K-shortest paths and using proportional power consumption profile is shown in Fig. 5.2.

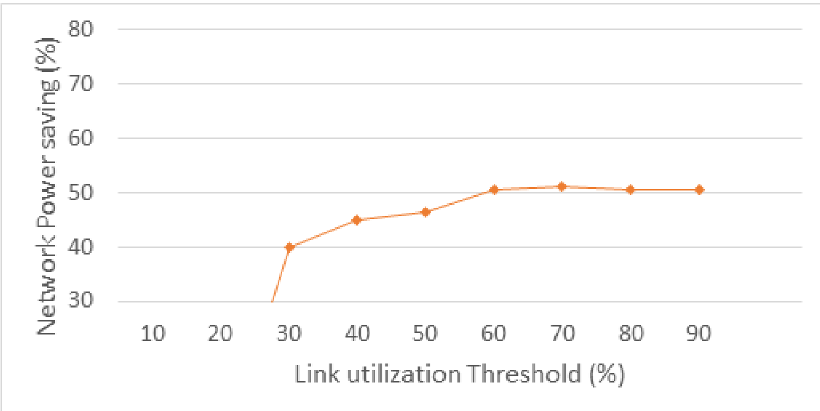

Figure 5.2: Power saving for AA backbone OTN using power loss/attenuation metric

As can be seen from Fig.5.2, a power saving of up to 51% can be obtained for AA backbone using power loss/attenuation as a metric to select shortest paths. The routing of traffic demands to ensure power saving is achieved as per the model with the consideration of power loss/attenuation in order to ensure that paths with high path power loss are not included which will result in a better QoS. The result also shows that for link utilization of less than 30% it is infeasible to apply the current model for power saving. This shows that the current level of traffic needs upto 30% of the total deployed link capacity so that sleeping links or cards for a lesser threshold level will result in a congestion level that is unacceptable and results in traffic drop.

The percentage of power saving attains its maximum at 70% link utilization which is an optimal point for compromising between power saving and link utilization. The remaining capacity can be used for protection implementation scenarios or to route burst traffic that may appear in addition to that considered in the model.

In order to achieve this power saving the algorithm 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.5.3 shows the number of links operating in sleep mode in order to save power for different link utilization threshold scenarios of AA backbone OTN.

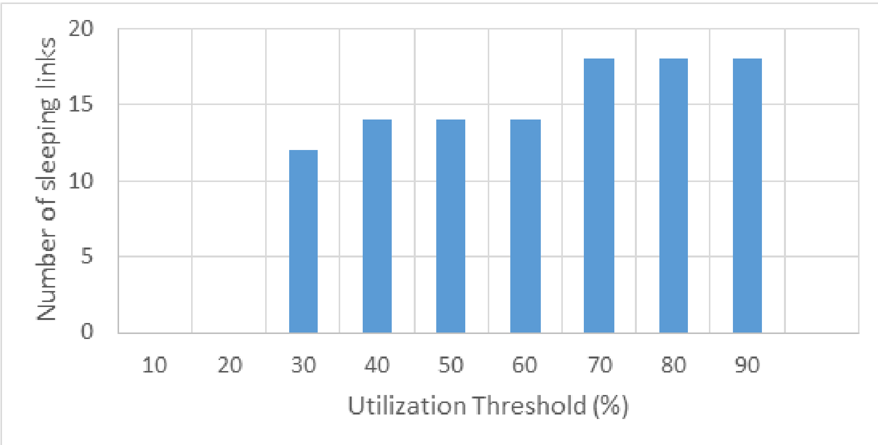

Figure 5.3: Number of sleeping links for AA backbone OTN

As can be seen from Fig. 5.3, the percentage of links operating in sleep mode for the maximum saving obtained at 70% link utilization threshold is 47%. This indicates that, according to the assumption that each bidirectional link is generated and terminated at a single line card, the same amount of line cards can also be operated in sleep mode. The result also shows that beyond the 70% link utilization threshold level there is no change on the number of links operating in sleep mode which reflects the result in power saving that shows an insignificant change beyond the stated threshold level.

For comparing the previous results obtained using power loss/attenuation as a metric in the model, hop count which is used by most algorithms as a metric for computing shortest paths is used. The power saving and the number of sleeping links obtained with this scenario is given in Fig.5.4 and 5.5 respectively.

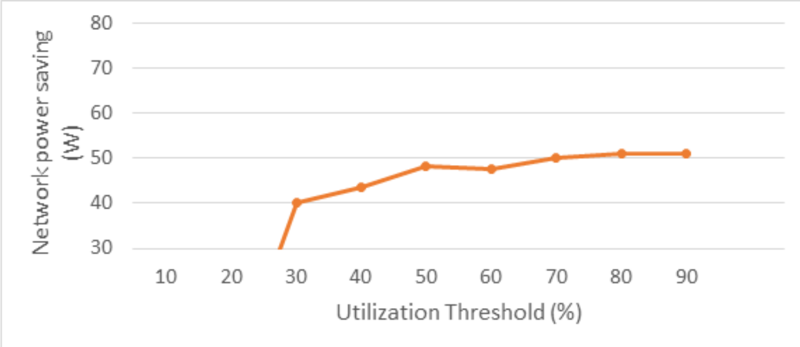

Figure 5.4: Power saving for AA backbone OTN using hop count metric

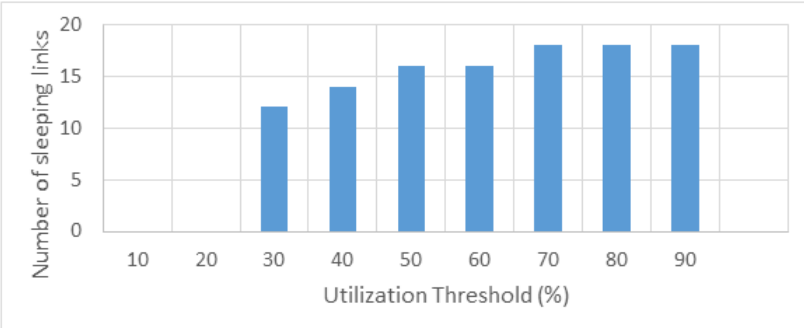

Figure 5.5: Number of sleeping links for hop count metric

The results show that the hop count metric gives a maximum power saving at 80% link utilization which is a 10% increase in the congestion of the network links but the saving obtained only shows an increase of 1% which shows the approach using power loss/attenuation to select shortest paths is more optimal in compromising between power saving and link utilization threshold as compared to hop count metric. The number of sleeping links somehow shows similar scenario in both conditions. The comparison in power saving between the two conditions is summarized in Fig. 5.6.

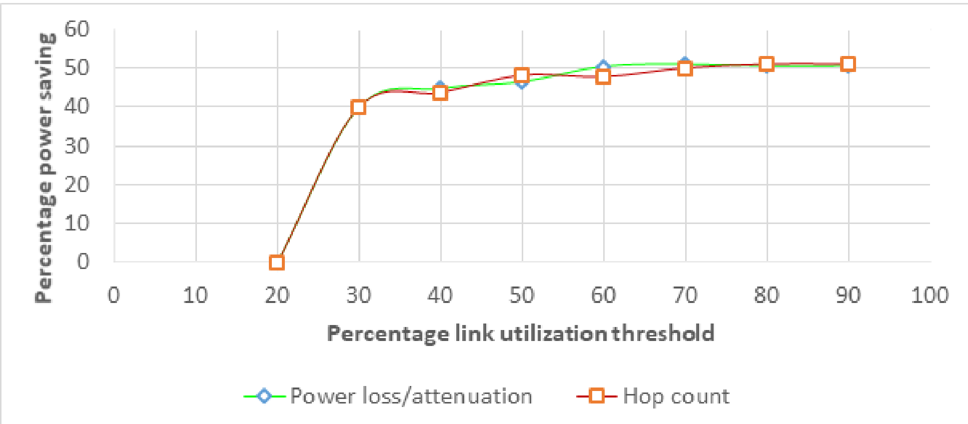

Figure 5.6: Comparison of scenarios on power saving

So far the optimization of the proposed model is carried out using traffic proportional power profiles for component power consumption. But as the information about the power consumption profile used by each equipment vendor is confidential and is difficult to get the exact profile of a given component, to get a complete picture of the scenarios, an optimization is carried out using an ON/OFF power consumption profile for the components. An approach similar to that followed for proportional power consumption profile is followed here also. Fig.5.7 shows the power saving obtained for components operating in ON/OFF power consumption profile for different link utilization threshold values.

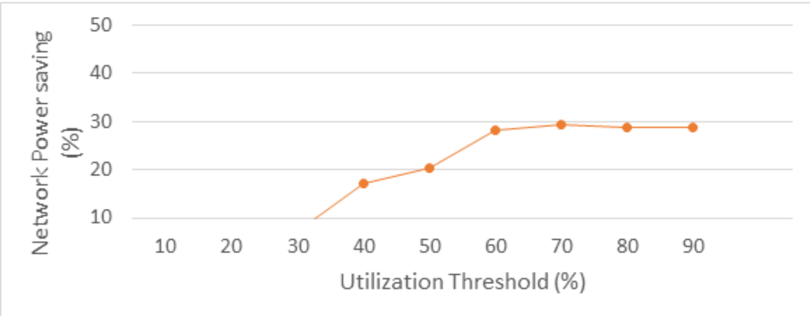

Figure 5.7: Network power saving for ON/OFF power consumption profile using power loss/attenuation metric

The result obtained shows that the power saving obtained follows the same trend as that of the proportional power consumption profile but with the saving being decreased and the maximum saving obtained is around 29% which occurs mainly due to the operation of the components being operated in ON/OFF profile which makes them consume high power while they are operational independent of the carried traffic. Similar scenario is also observed for the case of the number of sleeping links. Fig. 5.8 and 5.9 show the comparison for the two approaches for shortest path selection using ON/OFF power consumption profile.

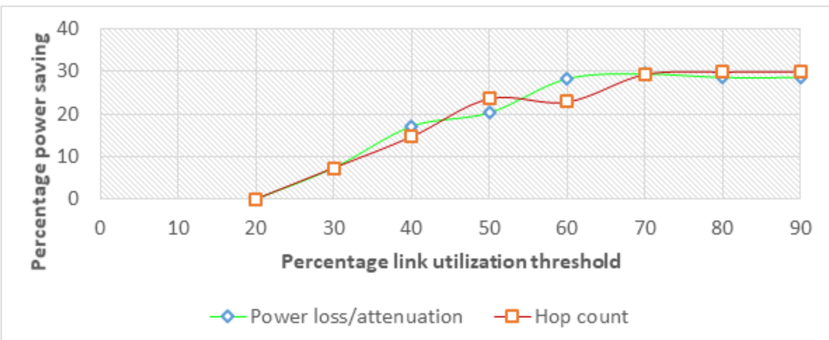

Figure 5.8: Results for ON/OFF energy profile-power saving

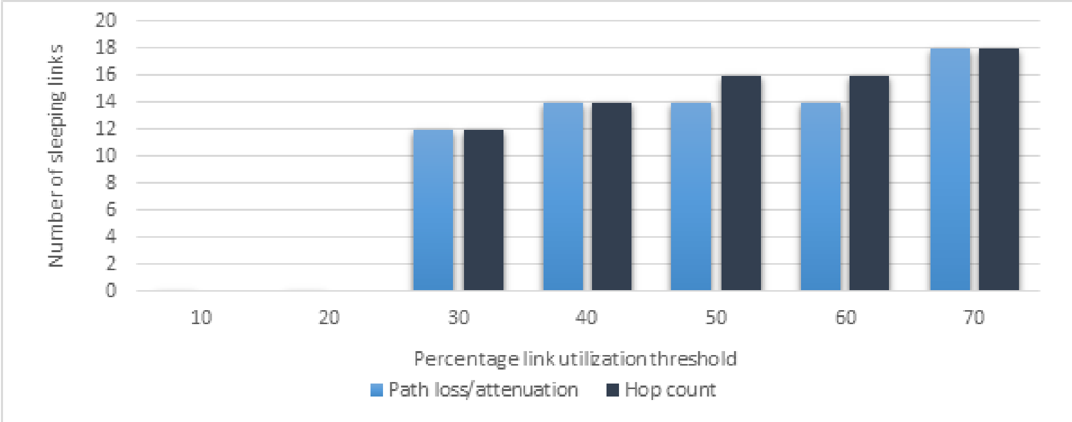

Figure 5.9: Results for ON/OFF energy profile-number of sleeping links

5.2.2 Traffic burstiness

One of the features that characterizes optical backbone networks is an occasional burst of traffic demand that arises during peak hours or special occasions that force clients to increase their usage which in turn increases the aggregate traffic reaching the backbone network segment. The model proposed in this thesis uses the traffic burstiness coefficient as a means to preserve the QoS of the network segment under consideration during burst traffic arrival. The result obtained by varying this coefficient is used to show the relationship between power saving and QoS of the network by ensuring that a packet drop in incoming traffic demand will not occur while power is saved during burst traffic increase.

Like the consideration taken for the case of power saving, the traffic burstiness constraint is optimized on both component power consumption profile types, i.e., with proportional power consumption profile and ON/OFF power consumption profile. The power saving obtained and percentage of sleeping links for both profiles using path loss/attenuation metric for the selection of shortest paths is shown in Fig. 5.10 and 5.11. In addition, the optimization is carried out for a modest link utilization threshold of 50% for both cases.

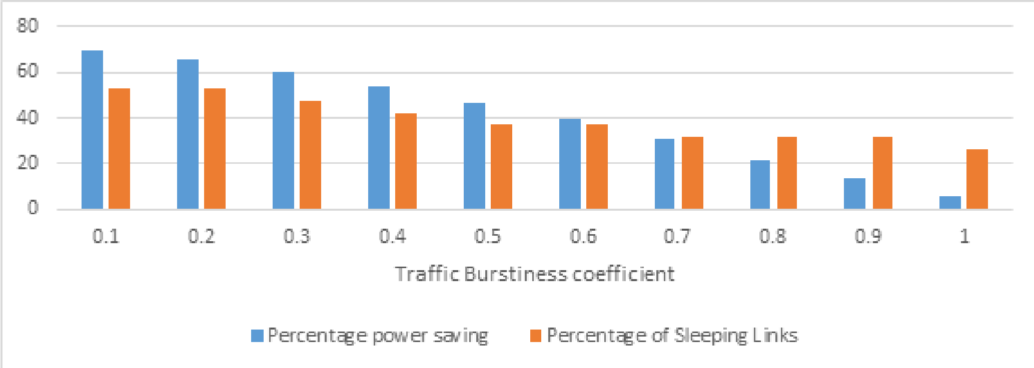

Figure 5.10: Traffic burstiness consideration for AA backbone OTN - proportional power consumption profile

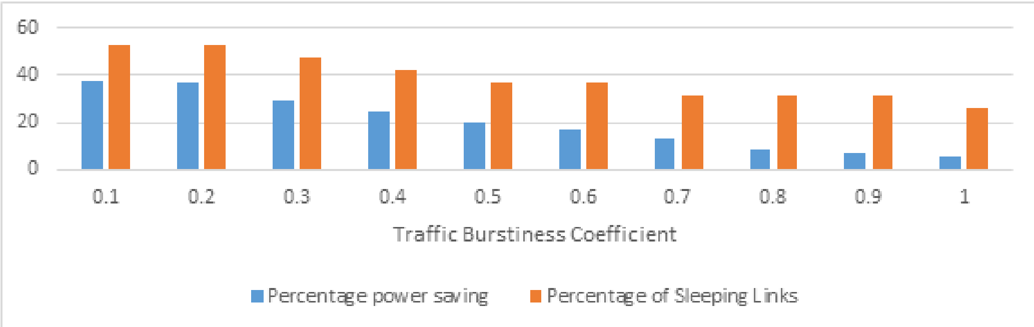

Figure 5.11: Traffic burstiness consideration for AA backbone OTN - ON/OFF power consumption profile

As can be seen from the results, although the exact percentage of power saved varies for the two profiles, for the various levels of burst traffic arriving at the network the model can be efficiently implemented without causing any loss of traffic. In addition, the results of the optimization show that a minimum of about 26% of links can operate in sleep mode in both cases. As stated above these results are obtained for a link utilization threshold of 50% and it can be easily deduced that if higher link utilization thresholds are used better energy savings can be obtained but this will in turn result in link congestion which may lead to traffic drop.

For comparison, the optimization of the model for shortest distance calculation using hop count is also carried out. The results show that the approach of taking power loss as metric to find shortest paths gives a comparable power saving to the former one. Comparison of the two approaches for the proportional power consumption profile is shown in Fig. 5.12. The result for the ON/OFF power consumption profile also follows the same trend.

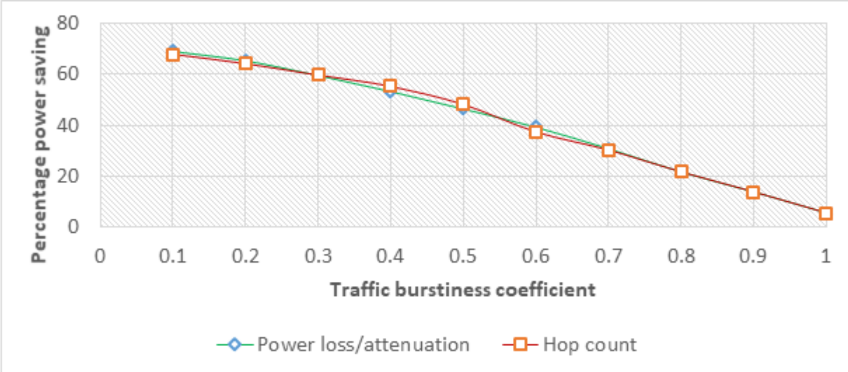

Figure 5.12: Comparison of power loss metric based and hop count based shortest path approaches

5.3 N-E Backbone OTN

5.3.1 Power Saving

The network topology for ET N-E backbone OTN is ring and its features are given in table 5.1. The type of equipments used in this network are the same as those used in AA backbone OTN with the exception of OLAs that are used to amplify the degraded signal due to the power loss that occurs in long distance transmissions. The optimization of this network segment differs from that of AA backbone OTN in two ways.

1. The availability of OLAs allows the usage of another metric in selecting K-shortest paths, link power consumption, which is calculated as the sum of the power consumption of the OLAs available on the link.
2. The number of nodes and the high number of demands and links allows for the evaluation of the model's applicability for wide area backbone networks.

The power saving scenario for N-E backbone OTN is evaluated using the given model by considering three parameters for K-shortest path selection; power loss/ attenuation, link power consumption and hop count. Here to calculate the path power loss an attenuation coefficient α of $0.25dB/KM$ is used. The power saving obtained using power loss/attenuation and link power consumption as a metric to calculate the K-shortest paths and using the proposed proportional power consumption profile is shown in Fig. 5.13 and 5.14 respectively.

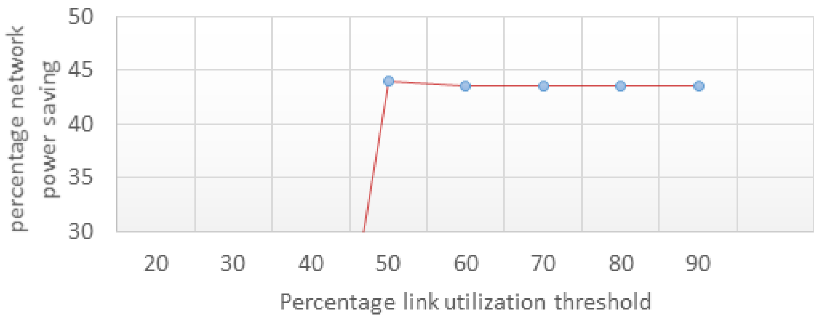

Figure 5.13: N-E backbone OTN power saving using power loss/attenuation for shortest path selection

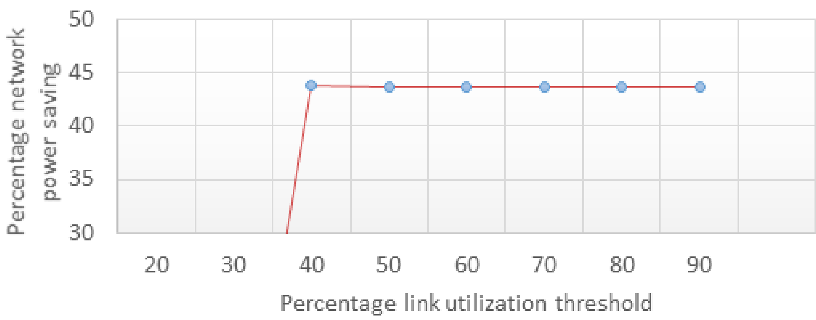

Figure 5.14: N-E backbone OTN power saving using link power consumption for shortest path selection

For these optimization scenarios $K = 3$ is used as number of shortest paths due mainly to the reason that with values of $K > 3$ the execution time of the model increases which also shows a high increase in the amount of memory used for computation.

As the results indicate, the power saving obtained by using the proposed model and metrics is almost similar with both scenarios with an optimal saving of about 44% at 50% link utilization threshold. Although the result indicates a slight increase in power saving as the link utilization threshold increases, for the selected ring topology as most nodes have only two incoming and outgoing links, the 50% utilization helps to have a sufficient amount for protection traffic routing. The result on Fig.5.14 also shows that the model implementation using link power consumption as a metric to choose the shortest paths can save power at lower link utilization levels. Ideally although the placement of line amplifiers in optical backbone networks is recommended to be in a distance of $80KM$, when actual deployments are considered the placement of these amplifiers needs additional preconditions such as availability of power supply and shelters to house the equipment. Thus this leads to less number of amplifiers in some links as compared to the recommended standard which in turn makes the power consumption of the link to be less and the link to be the shortest path although it spans longer distance. Hence the inclusion of these kinds of links in a path leads to a better power saving in using power consumption metric.

In order to compare the results obtained with the above scenarios to the legacy shortest path selection metric, hop count, the model is also optimized using this metric. The comparison of the obtained power saving with the previous scenarios is shown in Fig. 5.15. As shown, the previous scenarios save network power better than the hop count metric usage. This indicates that with the consideration of network performance QoS parameters better power saving can be achieved with the proposed model.

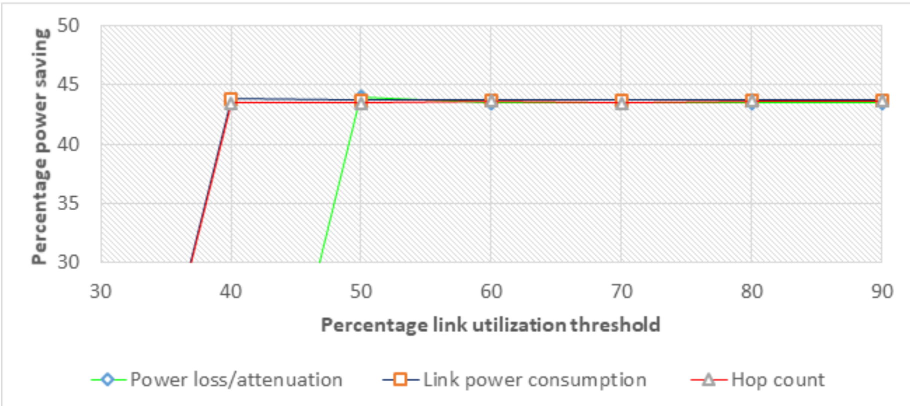

Figure 5.15: Power saving comparison for the three scenarios

5.3.2 Received power

This thesis proposes power loss/attenuation as one metric for the selection of shortest paths in the power consumption minimization model. In addition to the selection of the shortest path, the maximum allowed path power loss is also controlled in the model by using the receiver sensitivity of the line cards. This is done by calculating the received power using the given input power, gain of all amplifiers available on the path and the total path power loss.

$$\text{Received power} = \text{Input power} + \text{total path power gain} - \text{total path power loss} \qquad (5.1)$$

Then the received power is compared to the receiver sensitivity, i.e., the minimum signal power level detected by the receiving line card's receiver module. For the signal to be detected, the received power should be greater than the receiver sensitivity. Fig.5.16 and Fig. 5.17 show the total power loss/attenuation and the received power levels respectively for the scenario of using power loss and hop count metrics in the model.

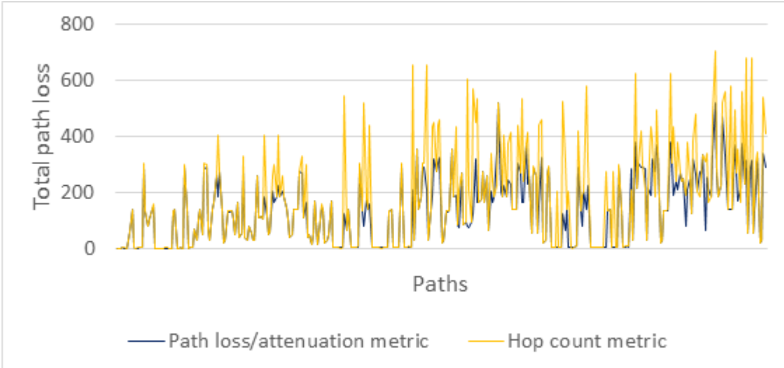

Figure 5.16: Total power loss/attenuation of K shortest paths, power loss/attenuation Vs hop count metrics

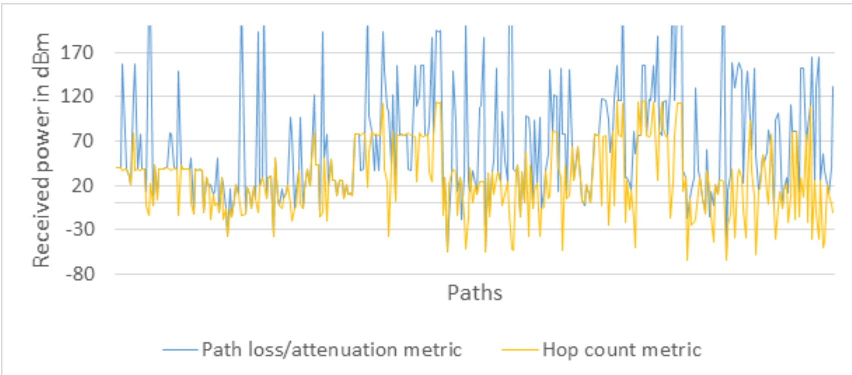

Figure 5.17: Received power comparison for power loss/attenuation and hop count metrics

As seen in Fig.5.16, the total path power loss for the selected shortest paths is greater for the case of hop count metric as it only considers the number of hops and not the power loss/attenuation to select these paths. Fig. 5.17 shows the received power level comparison between the two metrics. In addition to using these metrics to find the shortest path, the model also uses minimum receiver sensitivity constraint on paths selected using power loss metric to further refine and exclude paths with a received power level less than the minimum receiver sensitivity, -28dBm in this case. This leads to an exclusion of 6% of the previously computed shortest paths because their received power is below the stated minimum threshold. This thus avoids packet loss which in turn improves the QoS of the considered network segment.

5.4 Link Utilization

So far the target of power saving by sleep mode operation of links or line cards is shown. This optimization also shows the trade-off between power saving and two network QoS determining factors, power loss/attenuation and traffic burstiness. This section tries to cover another important QoS determining factor, link utilization. To see the impact of the proposed model on link utilization TOTEM toolbox, which is discussed in Section 2.7, is used. As described the TOTEM toolbox is used to simulate network link utilization scenarios using different built in or third party models that can be integrated into the toolbox. For the purpose of this simulation the toolbox is installed on a Linux based Ubuntu operating system on a virtual machine. For the integration of the proposed model into the toolbox the GMPL code is used and the integrated model link utilization is compared with the link utilization of the MCF algorithm distributed with the toolbox. The MCF algorithm is a pure traffic flow algorithm designed to optimize the flow of traffic through available links without considering power saving. The only constraint the MCF algorithm uses is the link utilization constraint.

In order to carry out the simulation the first task is to create the topologies used in this thesis and the traffic matrix in the toolbox to be used as an input for the model. The topologies and traffic matrices are developed using *.xml* formats that are given as an input for the model. The topologies consist of the name, location and type and capacity of links used for each node. The matrix consists of the traffic units, source, destination and the value of the traffic demand. This task is followed by integrating the GMPL code for our model into the toolbox. Then the comparison of link utilization for our model and the MCF algorithm is carried out to see the impact of implementing our power saving algorithm on network performance.

5.4.1 AA backbone OTN

For the AA backbone OTN topology the created topology in TOTEM with the weight of the links being the path loss/attenuation that is used as TE-Metric for shortest path selection is shown in Fig. 5.18. The link capacities are reflected on the topology diagram by the varying line weights of the respective links.

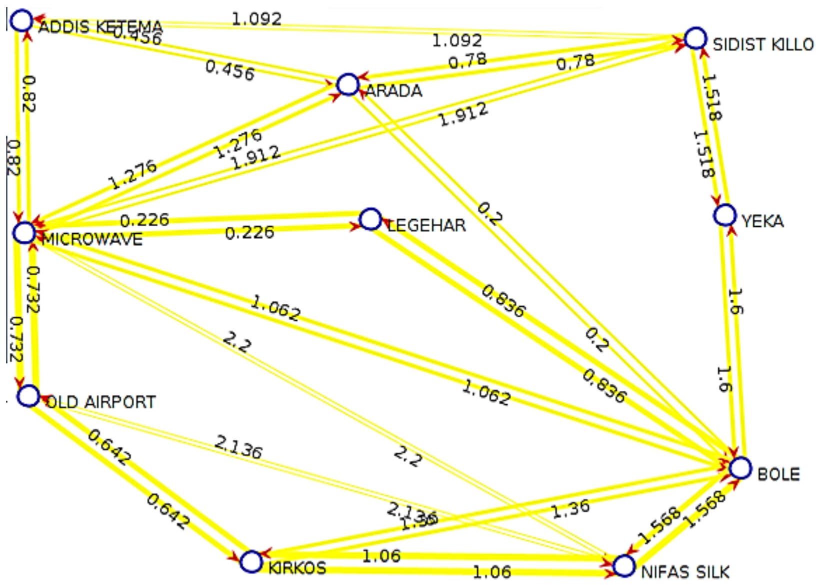

Figure 5.18: AA backbone OTN logical topology

For the topology shown, when only the optimal routing of traffic flow is carried out the scenario can be simulated using the MCF algorithm that uses all the available links and with an objective function of minimizing the link maximum utilization with constraints that enforce the algorithm to use the links for traffic flow to handle the requested demand, have their flows being less than the capacity of the specified link and the link utilization being less than or equal to the maximum utilization. The code snippet on fig. 6.16 shows the constraints section of the GMPL code for MCF algorithm.

```
# ***********************
# CONSTRAINTS
# ***********************

subject to flowC{i in VERTICES, k in COMMODITIES}:
    (sum{l in LINKS} flow[l,k] * OutLinks[i,l]) - (sum{l in LINKS} flow[l,k] * InLinks[i,l]) = ComValue[i,k];

subject to capaC{l in LINKS}:
  sum{k in COMMODITIES} flow [l,k] <= Capa[l];

subject to utilizationC{l in LINKS}:
    utilization[l] = ((sum{k in COMMODITIES} flow[l,k]) / Capa[l]);

subject to maxUtilizationC{l in LINKS}:
    utilization[l] <= maxUtil;
```

Figure 5.19: MCF code snippet

The application of this algorithm gives the traffic flow assignment without considering power saving. This is the optimal traffic flow assignment for the given network topology. The link utilization resulting from the flow assignment is shown in Fig. 5.20. The graph shows that the utilization of the links is in the range of $0-30\%$ which shows that the current demand can be handled with this link utilization values. This is one of the initiatives behind sleep mode operational approach to be used for power consumption saving. Also the result shows that as there are no sleep mode approaches applied, 100% of the deployed links are utilized for flow assignment. This result is expected to show smaller link utilization values as the traffic demand is distributed throughout the available links.

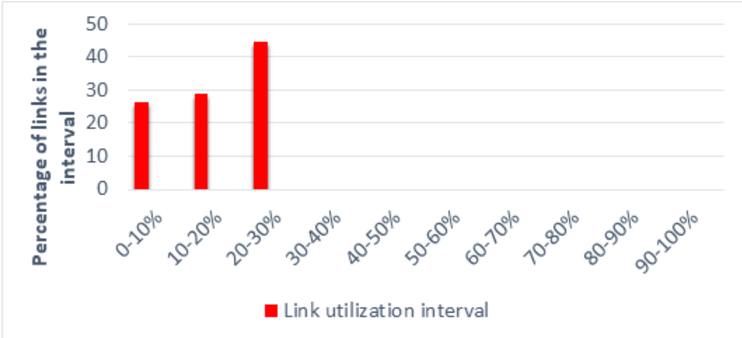

Figure 5.20: Link utilization for AA backbone OTN using MCF

The next step is simulating the proposed model in this thesis to compare its link utilization with that of MCF. As shown in Section 5.2.1, the maximum power saving for AA backbone OTN is obtained for 70% link utilization threshold with 18 links being operating in sleep mode. Thus this scenario is simulated here for the proposed model and MCF algorithm. The scenario is simulated for the model with the "What-If" analysis tool found in TOTEM by sleeping the links that are set to sleep mode in the case of the model's execution. Fig. 5.21 shows the AA backbone OTN topology with the links that are in sleep mode (black color of links indicates a sleeping link).

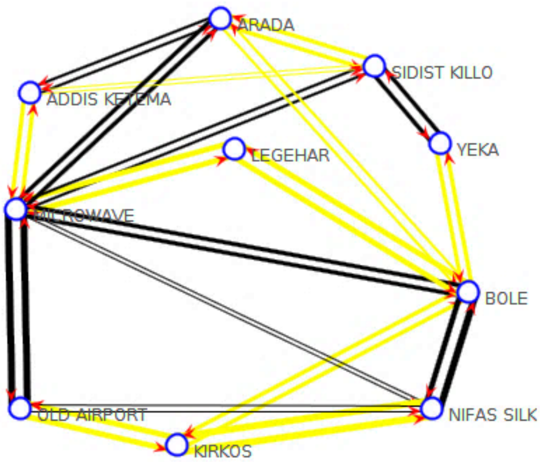

Figure 5.21: Simulation of AA backbone OTN for link sleep

The next task is to run the MCF algorithm on the topology with 18 links are sleeping and find the link utilization for comparison to the proposed model. The comparison of the link utilization for the two algorithms is shown in Fig. 5.22. As seen from the result, the link utilization achieved by using MCF and the proposed model exhibit scenarios that stem from their basic nature. First as the main aim of the MCF algorithm is to distribute traffic flow by minimizing link utilization it tries to distribute the flows evenly throughout the links but our proposed model shows better flow distribution at high link load intervals. In addition, the maximum link utilization achieved by using MCF is 70% which was not bounded by a threshold but the same as that of the model in this thesis which shows that the implementation of the model rather maintains QoS in addition to power saving.

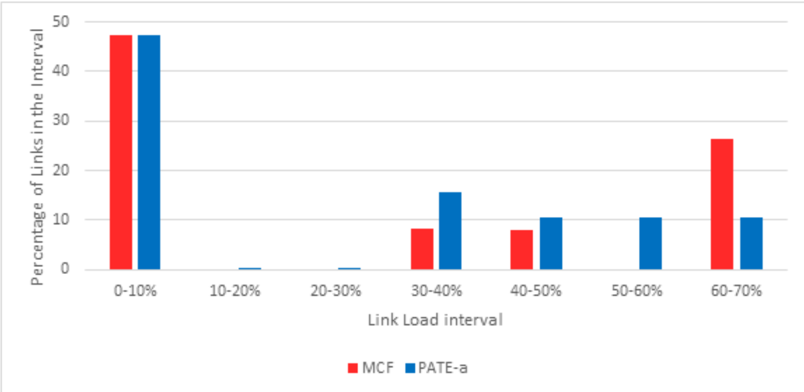

Figure 5.22: Link utilization comparison for AA backbone OTN

5.4.2 N-E Backbone OTN

The same simulation scenario is also carried out for the N-E backbone OTN in order to investigate the impact of the proposed model on link utilization. As seen in Section 5.3.1, maximum power saving is obtained in the given network when the link utilization threshold is 50%. With this threshold set simulation for the proposed model and the MCF algorithm that we have used as a benchmark is carried out. The topology used for the simulation purpose is shown in Fig. 5.23.

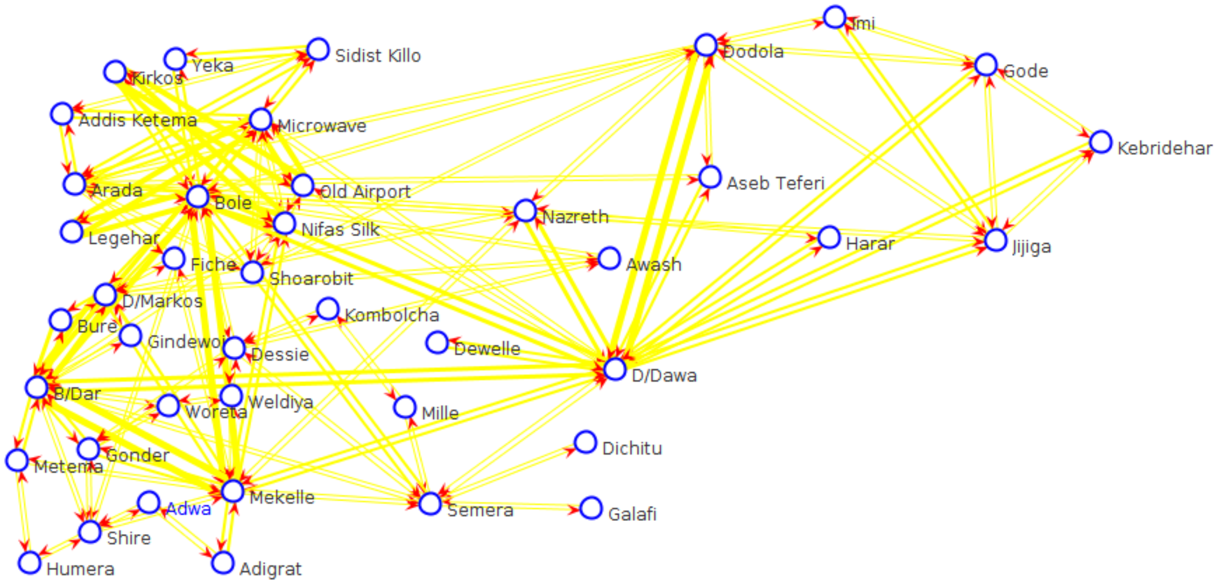

Figure 5.23: N-E backbone OTN topology on TOTEM (Sites are relocated from their original position for better viewing)

The MCF algorithm is used to analyze the link utilization for this network without the consideration of power saving. The result is shown in Fig. 5.24. As shown in the chart, the maximum utilization of links is 50%. This indicates that without considering power saving mechanisms the current traffic demand can be can be handled using these link utilization values.

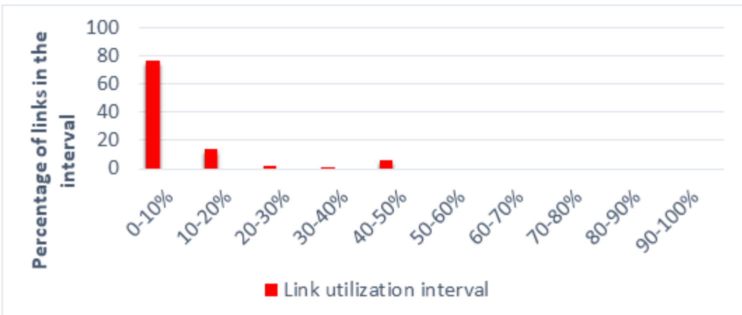

Figure 5.24: N-E backbone OTN link utilization using MCF

The simulation for the PATE-a model using TOTEM gives the link utilization for the available links in the network while executing the model. The comparison between this simulation and MCF algorithm is shown in Fig.5.25. As can be seen from the result, the execution of the PATE-a model gives comparable link utilization as that of the MCF which indicates that the integration of the model into the network will have no effect on the link utilization and does not lead to congestion of links.

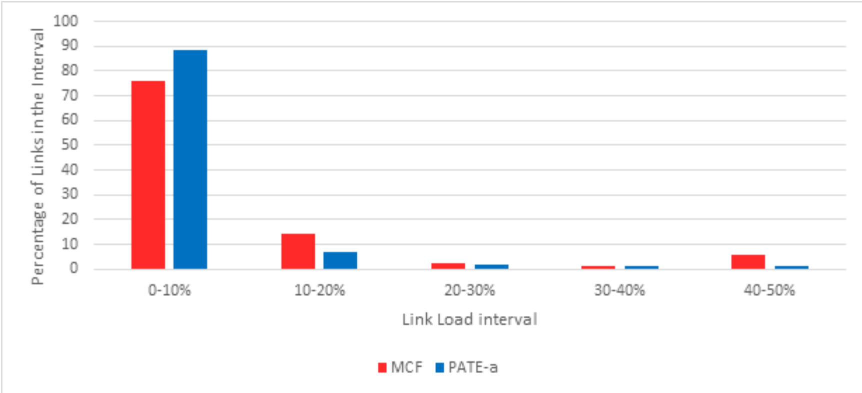

Figure 5.25: Link utilization comparison for N-E backbone OTN

As can be seen from the link utilization results, Fig. 5.22 and Fig. 5.25, the two approaches, MCF and PATE-a, have a somewhat similar trend in link utilization distribution over the available network links. Although PATE-a sets maximum link utilization threshold in order to avoid congestion of links in the network, its load distribution on the available links is better than that of the MCF as it assigns less loads on high percentage of links. For instance, in the case of AA backbone OTN about 47% of the working links are loaded to 10% of their maximum capacity. The same is true for N-E backbone OTN as about 88% of the working links are loaded at a maximum of 10% of their capacity which also shows a significant difference with that of MCF which stands at about 76%.

Another significant result obtained is that in both cases at higher loading of links the proposed approach distributes the load to the available links evenly. This can be shown in the case of AA backbone scenario with link loading greater than 40% are evenly distributed among the available 30% links with each load interval being loaded to 10% of the available links. Whereas the MCF approach loads more than 21% of the available links with 60-70% loading. This scenario is also reflected in N-E backbone case.

Chapter 6

Conclusion and Future Tasks

6.1 Conclusion

The telecommunication sector is growing rapidly with service providers expanding their network both in capacity and type of services provided. In order to accomplish this huge amount of network equipments are being deployed. When the number of these network equipments is growing one of the costs that service providers should cover, the cost of electricity or cost of power consumed by those equipments, is also growing which in turn increases the OPEX of the service providers. In addition to this the increased number of network equipments also increases their contribution for the increase in the global GHG level. This can be due to emissions directly from the equipments themselves or from non renewable energy sources used for the operation of these network equipments.

Stake holders in the sector are striving to find ways to mitigate these problems. These ways can be broadly classified into two categories, usage of renewable energy sources and investigating power consumption minimization approaches. When seen from service provider's network level, the second way can be further categorized into energy aware network design and energy aware network operation approaches. In this thesis one of the approaches in energy aware network operation, sleep mode operation, is covered. This approach can be applied in different segments of a telecommunication network. In this work the application of the sleep mode approach for optical network segment is investigated and a sleep mode operational model using the physical layer constraint, attenuation, and traffic burstiness is proposed. While doing this the QoS constraint is considered from different aspects such as link utilization and received power level. The proposed model is evaluated using two operator networks, AA backbone OTN and N-E backbone OTN from ethio telecom.

The optimization for AA backbone OTN shows a maximum power saving of 51% with a maximum link utilization threshold of 70% using path loss/attenuation as a metric to select shortest paths for rerouting traffic. The result indicates that without congesting the links to an unacceptable levels a considerable power saving can be obtained. The remaining link capacity can be used for protection purpose and handling burst traffic. In addition to this, a traffic burstiness coefficient,$0 < \beta \leq 1$, is used to evaluate the performance of the proposed model in handling burst traffic.

When the N-E backbone OTN is considered, a maximum power saving of up to 44% can be obtained at 50% link utilization threshold. These values indicate that, as is the case for ring type backbone networks, 50% of the remaining links can be used for protection purposes and still a considerable amount of power saving can be obtained. This power saving is also shown to be obtained by sleeping 60% or 116 out of the 194 links available. In addition to the power saving, the received power level is also considered in the proposed model in order to ensure that the received power level of the selected paths for rerouting demands should be greater than the receiver sensitivity, minimum detected power level, by the line card receiver ports. Application of this constraint shows a difference of 6% in the number of paths out of the range set for minimum received power level.

Finally, a comparison of the link utilization in case of the application of the PATE-a model and MCF algorithm which considers only the utilization of links without any power saving/ sleeping criterion is carried out. Results show that the application of the PATE-a model does not result on excessive link utilization which leads to congestion and shows a better performance in distributing load on the available links.

6.2 Future Tasks

This work can be used as a starting point to consider network segments' power consumption minimization incorporating QoS parameters that take into consideration the physical layer impairment, attenuation, and link utilization. As a future task in expanding this work protection paths' power consumption can also be considered using link disjoint or node disjoint algorithms. These protection paths comprise upto about 50% of the total links available when some protection mechanisms, such as 1+1 dedicated path protection are considered. Although these links are idle most of the time unless failure occurs, they consume a considerable amount of power and hence their sleep mode operation can lead to a significant amount of power saving. The model proposed in this thesis can be expanded to handle this scenario.

The inclusion of additional constraints in the model such as delay, blocking probability and others can be taken as a future direction for research in order to further analyze the trade-off between power saving and performance. The introduction of these constraints in the model can be considered from the physical layer level of the network or the upper layers considering routing and wavelength assignment algorithms that are currently in use in the GMPLS control plane.

Although the model in this thesis considers optical networks and properties of optical network components, the model can also be adopted to other network segments considering specific properties of the components available in the considered segment. This can help to increase the power saving of an operator network by considering savings from various segments comprising the network.

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