Heuristic Approaches for Energy-Efficient Shared Restoration in WDM Networks

By

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ABSTRACT

In recent years, there has been ongoing research on the design of energy-efficient Wavelength Division Multiplexing (WDM) networks. The explosive growth of Internet traffic has led to increased power consumption of network components. Network survivability has also been a relevant research topic, as it plays a crucial role in assuring continuity of service with no disruption, regardless of network component failure. Network survivability mechanisms tend to utilize considerable resources such as spare capacity in order to protect and restore information.

This thesis investigates techniques for reducing energy demand and enhancing energy efficiency in the context of network survivability. We propose two novel heuristic energy-efficient shared protection approaches for WDM networks. These approaches intend to save energy by setting on sleep mode devices that are not being used while providing shared backup paths to satisfy network survivability. The first approach exploits properties of a math series in order to assign weight to the network links. It aims at reducing power consumption at the network indirectly by aggregating traffic on a set of nodes and links with high traffic load level. Routing traffic on links and nodes that are already under utilization makes it possible for the links and nodes with no load to be set on sleep mode. The second approach is intended to dynamically route traffic through nodes and links with high traffic load level. Similar to the first approach, this approach computes a pair of paths for every newly arrived demand. It computes these paths for every new demand by comparing the power consumption of nodes and links in the network before the demand arrives with their potential power consumption if they are chosen along the paths of this demand.

Simulations of two different networks were used to compare the total network power consumption obtained using the proposed techniques against a standard shared-path restoration scheme. Shared-path restoration is a network survivability method in which a link-disjoint backup path and wavelength is reserved at the time of call setup for a working path. However, in order to reduce spare capacity consumption, this reserved backup path and wavelength may be shared with other backup paths. Pool Sharing Scheme (PSS) is employed to implement shared-path restoration scheme [1]. In an optical network, the failure of a single link leads to the failure of all the lightpaths that pass through that particular link. PSS ensures that the amount of backup

bandwidth required on a link to restore the failed connections will not be more than the total amount of reserved backup bandwidth on that link.

Simulation results indicate that the proposed approaches lead to up to 35% power savings in WDM networks when traffic load is low. However, power saving decreases to 14% at high traffic load level. Furthermore, in terms of the total capacity consumption for working paths, PSS outperforms the two proposed approaches, as expected. In terms of total capacity consumption all the approaches behave similarly. In general, at low traffic load level, the two proposed approaches behave similar to PSS in terms of average link load, and the ratio of block demands. Nevertheless, at high traffic load, the proposed approaches result in higher ratio of blocked demands than PSS. They also lead to higher average link load than PSS for the equal number of generated demands.

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$G(N,L)$	Network G with N set of nodes and L set of links in the network
R_l	Total number of reserved wavelengths on link l
RW_l	Number of working wavelengths reserved on link l
RB_l	Number of backup wavelengths reserved on link l
S_{ls}	Set of links on sleep mode
S_{ns}	Set of nodes on sleep mode
A_l	Number of wavelengths available on link l
C_l	Maximum number of wavelength supported by each link
L_l	Proportion of working path load on link l to the capacity of link l
NL_n	Node links; Set of active links that ends to or initiates from node n
P_{lk}	Number of wavelengths needed on link l as backup if working link k fails
B_l	Maximum number of backup wavelengths needed on link l if any other links fail
SW_r	Set of links along the working path of demand r
SB_r	Set of links along the backup path of demand r
T_l	The maximum number of backup wavelengths needed on link l if a link in SW_r fails
E_{nt}	Power consumption per wavelength for a transmitter
E_{nr}	Power consumption per wavelength for a receiver
E_{ns}	Power consumption per wavelength for a switching node
F_n	Fixed power consumption at the node n
$\widehat{F_n}$	Fixed power consumption at the node n if the new demand is accepted and routed over the link l

D_l	Distance of link l in kilometer
E_l	Power consumption of an in-line amplifier along link l
$\widehat{E}_l$	Power consumption of an in-line amplifier on the link l if the new demand is accepted and routed over the link l
K_{nt}	Number of wavelengths connections generated by the node n
$\widehat{K_{nt}}$	Number of wavelengths connections generated by the node n if the new demand is accepted and routed over the link l
K_{nr}	Number of wavelengths connections terminated at node n
$\widehat{K_{nr}}$	Number of wavelengths connections terminated at the node n if the new demand is accepted and routed over the link l
K_{ns}	Number of wavelengths connections passes through node n
$\widehat{K_{ns}}$	Number of wavelengths connections passes through the node n if the new demand is accepted and routed over the link l
RW_l	Number of wavelengths connections passes through link l
Y_n	Boolean if node n is on sleep mode or not
X_l	Boolean if link l is on sleep mode or not
W_l	Assigned weight to link l
BSH_l	The computed weight for link l by implementing PSS
BIE_l	The computed weight for link l by implementing math series property
BDE_l	The computed weight for link l by implementing power differential method
$NBSH_l$	Normalized value of BSH_l
$NBIE_l$	Normalized value of BIE_l
$NBDE_l$	Normalized value of BDE_l
b	Number of requested wavelengths
α	The parameter for setting weight in finding backup path

P_n	Total power consumption of node *n*
P_l	Total power consumption of link *l*
P_T	Total power consumption of the network
TRW	Total number of working wavelengths used in the network
TR	Total number of working and backup wavelengths used in the network
TGD	Total number of generated demands
TBD	Total number of blocked demands
RB	The ratio of the total number of blocked demands over the total number of generated demands
PL_l	The "load" on link *l* as the ration of the total reserved working and backup wavelengths of the link *l* and the capacity of the link *l*
$\overline{PL_l}$	The average link load averaged over all links in the network
BR_{il}	The number of backup wavelength required on link *l* if link *i* fails
LP(l)	The power consumed by the link *l* before the new demand arrives
$\widehat{LP}(l)$	The potential power consumption of the link *l* if the new demand is accepted and routed over link *l*
NP(n)	The power consumed by the node *n* before the new demand arrives
$\widehat{NP}(n,l)$	The potential power consumption of the node *n* if the new demand is accepted and routed over link *l*
f_l	The first node of link *l*
s_l	The second node of link *l*
V_i	The population of node *i*
G_i	The total traffic in Gigabits/second generated at node *i*
g_{ij}	The amount of traffic generates at *i* and terminates at *j*
D_{ij}	The number of *OC192* demands between node *i* and *j*, D_{ij} is derived as

LONS	The number of links on sleep mode
NONS	The number of nodes on sleep mode

LIST OF ABBREVIATIONS

ADM	Add/Drop Multiplexer
ASIC	Application-Specific Integrated Circuit
CI	Confidence Interval
CL	Confidence Level
DiffEnS	Differentiated Energy-Saving
DPEA	Direct Power Efficient Approach
DSLAM	Digital Subscriber Line Access Multiplexer
DXC	Digital Cross Connect
E/O	Electrical/Optical
EDFA	Erbium Doped Fiber Amplifier
FDM	Frequency Division Multiplexing
FPGA	Field-Programmable Gate Array
Gbps	Giga bits per second
G-EPON	Gigabit Ethernet Passive Optical Network
HPARND	Heuristic Power Aware Routing and Network Design
ICT	Information and Communication Technologies
ILP	Integer Linear Programing
IPEA	Indirect Power Efficient Approach
ISP	Internet Service Provider
LBPS	Load Balancing Pool Sharing
MC	Minimum installation cost
MINLP	Mixed Integer Non-linear Programming
MP	Minimum power
MP-S	Minimum power with devices in sleep mode

NSF	National Science Foundation
O/E	Optical/Electrical
OEO	Opto-Electro-Optic
OLT	Optical Line Terminal
ONU	Optical Network Unit
OTDM	Optical Time Division Multiplexing
OXC	Optical Cross Connect
PARND	Power Aware Routing and Network Design
PD	Permanent Demand
PON	Passive Optical Network
PoP	Point of Presence
PSS	Pool Sharing Scheme
QoS	Quality-of-Service
RDB	Red-Demand-Based
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RWA	Routing and Wavelength Assignment
SBPSN	Shared Backup Protected Survivable Network
SD	Scheduled Demand
SPR	Shortest Path Routing
Tbps	Tera bits per seconds
TDB	Total-Demand-Based
TDM	Time Division Multiplexing
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WSS-based	Wavelength Selective Switch based

ADM	Add/Drop Multiplexer
ASIC	Application-Specific Integrated Circuit
CI	Confidence Interval

Chapter 1 Introduction

1.1 Energy-Efficiency in Networks

In the past few years, the concept of energy-efficient networking has begun to spread. The increasing number of services that are being provided by Internet Service Providers (ISPs), the continuing increase of customer population, and the rapid spread of broadband access networks have made energy efficiency a high priority for networks and service infrastructures [2]. The operational cost of equipment in all types of networks is increasing dramatically due to the growth of internet traffic. This dramatic increase will lead to more power consumption and, as a result, more heat production. Therefore, two major factors bring about more power consumption: more use of network equipment to fulfil the growing number of customer demands and the utilization of cooling equipment in order to keep network devices within adequate operating temperatures.

R. Bolla *et al.* in [2] argue that ISPs need an increased number of devices in order to support new generation network infrastructure with high capacity demands for a rapidly growing customer population. They state that the devices with sophisticated architectures can perform increasingly complicated operations with more scalability. Hence, their operational capacity is increasing with a factor of 2.5 every 18 months. However, energy efficiency in silicon technologies (e.g. CMOS) is being enhanced at a lower rate than network device capacities and traffic volumes, with a factor of only 1.65 every 18 months [2]. Figure 1.1 provides better insight into the evolution of IP routers, traffic load, and silicon technologies since 1993. According to Figure 1.1, low consumption silicon technologies cannot solely cope with the growing amount of power consumption. Hence there is a need for new protocols and innovative equipment that will lead to a better ratio of performance in energy consumption [2].

Bolla, R. *et al.* in [2] introduce two main motivations for reducing power consumption at the networks. The first motivation is to reduce the environmental impact of consuming energy, which is CO_2 emissions. There are two types of carbon emissions with respect to networking, embodied carbon and carbon footprint from use. Embodied carbon refers to carbon dioxide emitted during the process of manufacturing, transportation, and installation

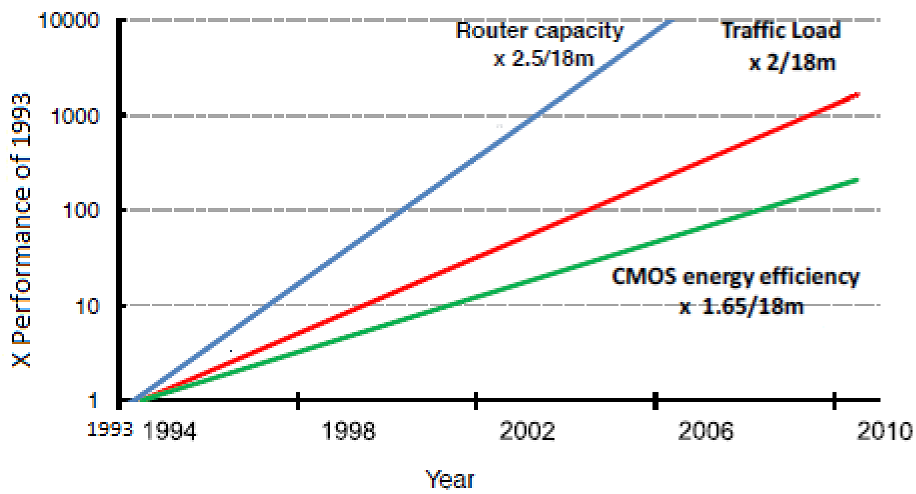

Figure 1.1 Evolution from 1993 to 2010 of high-end IP routers' capacity (per rack) vs. traffic volumes and energy efficiency in silicon technologies [2].

of the network devices. Carbon footprint from use is carbon dioxide emission when the device is under utilization. Figure 1.2 demonstrates estimation of the global carbon footprint of Information and Communication Technologies (ICT). As illustrated in Figure 1.2, CO_2 emissions by ICT is increasing dramatically. Moreover, it is estimated that in the year of 2020, 2.7 percent of the global carbon footprint is caused by ICT. Hence, reducing power consumption of networks leads to reduction in CO_2 emissions. The second motivation is called economical motivation which is the reduction of network equipment under utilization [2].

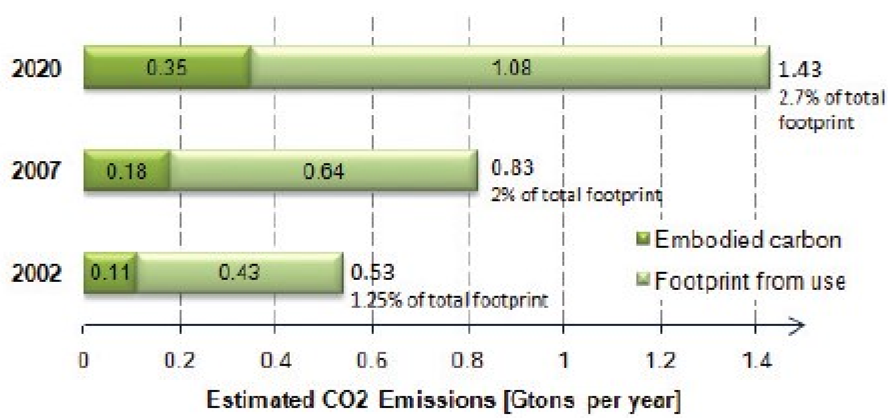

Figure 1.2 Estimate of the global carbon footprint of ICT [2].

M. Gupta *et al.* in [3], categorize motivations for the need of energy efficient networks into three primary categories: current energy inefficiencies, enable greater deployment, and benefits in the event of disaster. They argue that the high energy cost of the Internet is due to the fact that networking devices consume a significant amount of energy, even when idle. This is due to the preference given to maximizing network throughput and minimizing latency in the network design. Moreover, they point out that conserving energy can help in developing the internet in areas of the world with scarce energy resources. Finally, as discussed in [3], designing energy-efficient networks can be useful in the event of a disaster where network equipment in an affected area will rely on their UPS batteries for operation. Indeed, the batteries can last longer with low-power operating networks. Therefore, police departments, hospitals and any other agencies in the disaster area will be able to access data stored in the network devices situated at the affected area for longer time [3].

Numerous methods have been proposed in the literature to implement energy efficiency in different aspects of networking. M. Gupta *et al.* in [3] argue that reduction in energy consumption is feasible by modifying the architecture and protocols deployed in the network. They discuss the possibility of energy saving at the individual network equipment, at the network design, and at the network protocols. At an individual network equipment level such as a switch or a router, this can be done by switching a number of their sub-components to sleep mode. For example, embedded line cards can be put on sleep mode when the traffic load is low and they are idle. At the network design level, energy saving can be done when traffic load level is low by rerouting traffic in order to aggregate traffic along a few routes, which allows devices on the idle routes to be set on sleep mode and, as a result, reduce power consumption. Finally, energy saving is achievable by deploying topologies that are capable of utilizing enough devices as the traffic load demands. More devices will wake up as traffic load increases and more devices can be put on sleep mode as traffic load drops [3]. The concept of sleep mode is described thoroughly in the next section.

1.1.1 Sleep Mode

Sleep mode is proposed as an appropriate approach to minimize energy consumption in a network. In an experiment which exploits sleep mode technique in a network, Muhammad,-

Table 1.1 Power consumption of operational modes [4].

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

-A. *et al.* in [4] propose to put some of redundant resources on sleep mode. Redundant resources, such as protection routers are unused until a failure occurs. Based on the definition of sleep mode in [4], any device in sleep mode is in its lowest-power where it can be woken up immediately by any triggering event.

Three different operational modes for optical devices in WDM networks are defined in [4]. These modes are off, sleep, and active modes. Table 1.1 demonstrates power consumption of each operational mode. Devices on off mode do not consume any power. Devices on sleep mode (inactive) consume a negligible amount of power to ensure that they can be immediately switched to active mode at any time. Finally, devices on active mode consume a fixed (static) amount of power independent of their traffic load (start-up power) and an additional amount of power proportional to their traffic load. Therefore, the total power consumption of an active device is the sum of the fixed power and the proportional power.

Nevertheless, Muhammad, A. *et al.* point out two issues of deploying the sleep mode property in survivable WDM networks. First, it is essential to ensure that there is no working wavelength reserved on devices in sleep mode. Devices that are used exclusively for protection purposes along the backup links or nodes are good examples of devices that can be switched to sleep mode. Examples of these devices are, in-line optical amplifiers, and protection routers. Additionally, it is essential to ensure that the devices on sleep mode can be switched to active mode immediately in case of a network component failure [4].

Furthermore, M. Gupta *et al.* in [3] address challenges to implement sleep mode property in a network. These challenges are: (1) modifying routing protocols in order to allow adaptation of energy consumption to load through aggregation and sleeping; (2) amending the Internet topology in order to provide more choices for routing strategy to allow sleeping and aggregation; (3) redesigning the hardware of networking component in order to allow software-enabled sleep mode; and (4) studying the impact of sleep mode on protocols such as TCP in order to adapt sleep node property.

In conclusion, although there are numerous challenges for the implementation of the sleep mode, its consistent and adequate implementation can lead to positive impact in energy-efficient networks.

1.2 Network Survivability

Survivability of optical networks has been thoroughly investigated because a failure of an optical link or node can cause a significant data loss. Ramamurthy *et al.* in [5] argue that in an optical network topology, the failure of a single link or any other network component leads to the failure of all the lightpaths that pass through that particular link. Such a failure can result in a significant data loss in the network as each lightpath usually operates at a high Gbps rate. Therefore, there is a need for reliable protocols to protect data in times of failure. Each type of network architecture provides its own protection schemes. For instance, an IP network recovers from link failures by rerouting traffic through other links in order to round the failed link. However, IP networks have a long recovery time, which is one of its drawbacks. Having a fast recovery time is one of the goals of any recovery procedure [5].

Two survivability schemes have been widely used in the literature, namely called, protection, and restoration. Protection scheme is a proactive survivability mechanism where backup paths and backup resources are pre-computed and reserved for each demand at the time of setup. Restoration scheme is a reactive survivability mechanism where the backup paths and backup resources are dynamically computed. Figure 1.3 provides better insight into different survivable schemes.

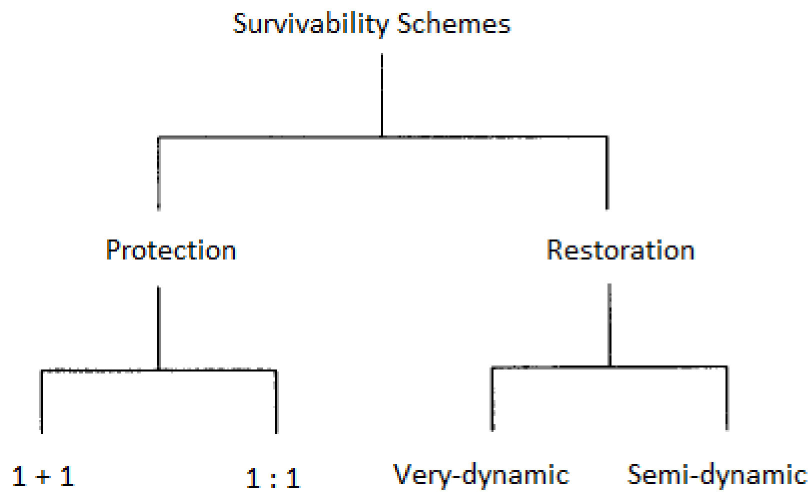

Figure 1.3 Survivability schemes.

Protection scheme includes two protection approaches which are, 1+1, and 1:1. In the 1+1 protection approach, two copies of the traffic, one copy for the working path and one copy for the backup path, are transmitted simultaneously on two separate paths from the source node to the destination node. The destination node can select the data traffic with the better quality between the two copies. In case of failure on one of the two paths, the destinations can still receive the data through the other path (copy). In the 1:1 protection approach, only one copy of data is transmitted along the working path. If failure occurs, the source and destination nodes switch to the backup path which was pre-computed and reserved prior to the occurrence of failure. However, the 1:1 protection approach is not as quick as the 1+1 protection approach in restoring traffic due to additional communication overhead [6].

Restoration scheme encompasses a range of approaches from very-dynamic (fully-reactive) such as IP rerouting, to semi-dynamic (semi-reactive) where backup paths and resources are pre-computed but are allocated after a failure occurs. In the very-dynamic restoration approach, backup paths are computed and backup capacities are allocated after the failure occurs. However, there is no guarantee to find a backup path for the failed demand (there might not be available capacity for the failed demand) when a failure occurs which is one of its drawbacks. In the semi-dynamic restoration approach, backup paths are pre-computed prior to the occurrence of failure, but backup capacities are only allocated after failure occurs.

1.2.1 Dedicated and Shared Backup Path

There are two techniques to allocate backup resources to the backup paths, namely called, dedicated-path protection, and shared-path restoration. In dedicated-path protection technique, a link-disjoint backup path is computed for each working path and dedicated to that working path. The reserved backup capacity for each backup path is exclusively dedicated to that backup path and is not shared with other backup paths. However, this technique leads to considerable capacity consumption at the network [5]. In shared-path restoration technique, a link-disjoint backup path is computed for each working path but the reserved backup resources are not exclusively allocated to that backup path. In this technique, demands can share their reserved capacity along their backup routes. However, sharing is possible when only one failure occurs at one time because only one of these demands at any time can use the resources on any of these shared links. The resources are not available to any other demands while they are in use. Hence, the working paths of the demands that share backup resources have to be mutually disjoint. Consequently, shared-path restoration leads to less capacity consumption compared to dedicated-path protection. In this thesis, shared-path restoration scheme is employed to compute backup paths.

1.3 Wavelength Division Multiplexing Network

Internet traffic has experienced an exponential growth in the past few years, which leads to an explosion in network bandwidth consumption. The emergence of delay-sensitive multimedia applications, such as video-conferencing, Internet telephony, interactive gaming and video on demand also lead to a considerable amount of network bandwidth utilization. All these factors lead to a massive demand for bandwidth capacity on the underlying telecommunications infrastructure [7].

A dramatic change in bandwidth capacity took place in telecommunications networks with the introduction of fiber optics to cope with the exceptional demand for bandwidth capacity. Optical fiber is proven to be an outstanding transmission medium by providing huge bandwidth capacity. In addition to providing the huge bandwidth capacity, optical fibers also possess a number of other significant characteristics, such as low signal attenuation (as low as 0.2 dB/km), low signal distortion, low power requirement, decreased material usage, minimal space requirements and low cost [7].

The multiplexing has great significance due to the fact that it is much more economical to transmit data at higher rates over a single fiber than to transmit it at lower rates over multiple fibers [6]. A single-mode fiber is an optical fiber designed to carry only a single ray of light (mode) which has a potential bandwidth of nearly 50 terabits per seconds (Tbps) [7]. This is nearly four orders of magnitude higher than data rates of a few gigabits per seconds (Gbps) achieved in electronic transmission systems [7]. Exploiting fiber's huge bandwidth in optical communication networks is possible by increasing the data transmission rate on optical fiber [8]. In an optical communication network, there are two fundamental ways to increase the transmission capacity on a fiber. The first way is to increase the bit rate which requires higher-speed circuits in order to perform high-speed switching action of voltage in transistors. Electronic Time Division Multiplexing (TDM) results in increasing the bit rate by multiplexing many lower-speed data streams into a higher-speed stream at the transmission bit rate. For instance, the multiplexer selects one byte of data from the first stream, and the next byte from the second stream, and so on. The highest transmission rate of TDM is less than 100 Gbps [6]. To increase the transmission rate of TDM, there is a method which is aimed at performing multiplexing and demultiplexing functions optically. This method is called Optical Time Division Multiplexing (OTDM). Transmission rates of up to 250 Gbps has been proven for OTDM [6].

Wavelength Division Multiplexing (WDM) is another optical multiplexing method for exploiting the huge capacity of optical fibers. WDM has similar concepts to Frequency Division Multiplexing (FDM) which has been used in radio systems for more than a century. The basic principle is to divide the huge bandwidth of an optical fiber into a number of wavelengths or optical channels and transmit them simultaneously and independently over the single fiber [7]. These wavelengths are kept separated sufficiently in order to avoid interference. Therefore, WDM provides virtual fibers such that it makes a single fiber perform similar to multiple "virtual" fibers in a way that each virtual fiber carries a single data stream [6].

Figure 1.4 illustrates a block diagram of a basic WDM transmission system. The transmitter is composed of a laser and a modulator. The laser (light source) creates an optical carrier signal at either a fixed or a tunable wavelength. The modulator modulates the

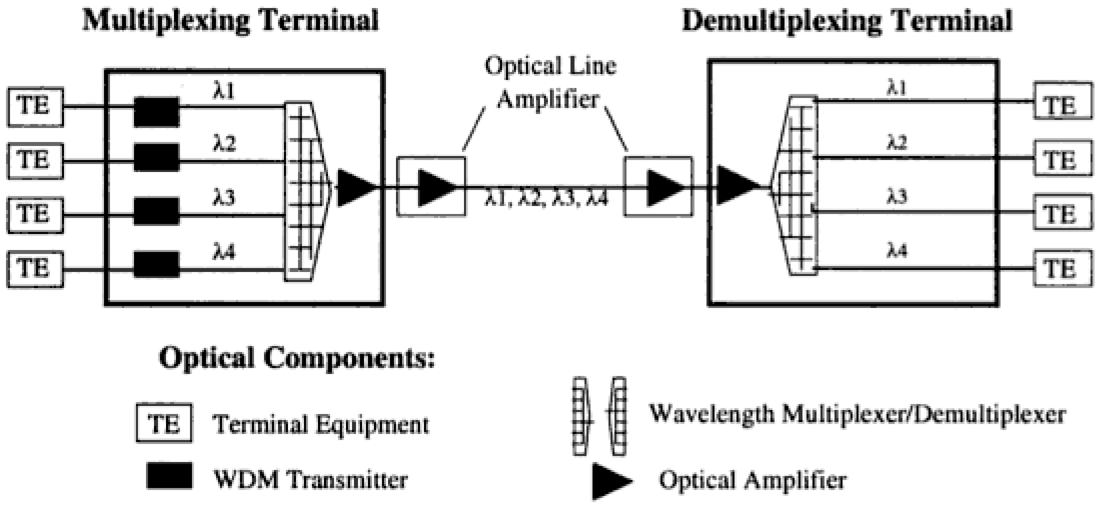

Figure 1.4 WDM transmission system with amplifiers [8].

carrier signal by an electronic signal and then sends the modulated signal to the multiplexer. Multiple optical signals are combined on different wavelengths at the multiplexer input ports into a single optical signal. Then, the single optical signal will be transmitted to a common output port or optical fiber. At the demultiplexer, the optical signal received on the input port is separated into multiple optical signals on different wavelengths by utilizing optical fibers. Separated wavelengths are then sent into the receivers. The receiver is composed of an optical-to-electrical convertor which converts an optical signal to an electronic signal. The optical amplifiers are utilized in order to strengthen the power strength of an optical signal at proper locations in the transmission system [7].

1.4 Thesis Contribution

Current state of the art investigates energy efficiency in every aspects of networking. The researchers in [4], have investigated energy efficiency in the context of survivability with dedicated backup path. Moreover in this context, Cavdar *et al.* in [9] propose an ILP formulation to minimize power consumption of WDM networks with shared backup path.

This thesis proposes two heuristic approaches to reduce power consumption of WDM networks in the context of shared backup path restoration survivability. Although Cavdar *et al.* investigated energy efficiency in WDM networks with shared backup path, they did not take into account the possibility of turning off intermediate nodes in their ILP formulation. In this thesis we investigate reduction in power consumption of WDM networks by setting both links and intermediate nodes on sleep mode. The proposed approaches in [4, 9] will be discussed in details in the section 2.3.8.

1.5 Thesis Organization

The rest of this thesis is organized as follows. In Chapter 2, we explain the basic concepts of how to implement shared backup path restoration survivability. In addition, since part of this thesis deals with computing multi-constraints paths, we also address the methods of finding multi-constraints paths in this section. We also discuss related work in this chapter. In Chapter 3, we discuss power model for nodes and links in WDM networks and propose two heuristic approaches to reduce power consumption in WDM networks. In Chapter 4, we explain details of the simulation and discuss the simulation results. Finally in Chapter 5, we will offer the concluding remarks and possible future works for this thesis.

Chapter 2 Background and Related Work

Network survivability and energy efficiency have been topic of several publications in the recent years. In this thesis, two novel heuristic techniques are proposed to enhance the energy savings in the network while providing uninterrupted service in the network. In this chapter we will discuss previous works related to the techniques proposed in this thesis. Details on the Pool Sharing Scheme (PSS), which is used as benchmark for comparing the performance of the proposed techniques, will also be provided. In section 2.1, we review the implementation of shared-path restoration with PSS. In section 2.2, we review methods of solving multi-constraints routing problems. In section 2.3, we discuss state-of-the-art in energy efficiency in every aspects of networking such as, WDM, optical backbone, survivable networks, routing, grooming, power model, packet processing, Passive Optical Network (PON), etc. Finally, in section 2.4, we will conclude this chapter with a discussion on how previous works and background in energy efficiency are related to our work.

2.1 Pool Sharing Scheme

In this section, we introduce the approach that is used for the purpose of benchmarking. H. Naser and H. Mouftah in [1] discuss PSS, which implements a shared-path restoration scheme. PSS aims at minimizing the reserved capacities required for complete recovery of traffic from any single failure. It ensures that the amount of backup bandwidth required on a link to restore the failed connections will not be more than the total amount of reserved backup bandwidth on that link. PSS maintains records of the backup bandwidth reserved on links in order to use them to compute the minimum cost shared backup path for each working path. Pool Sharing Scheme (PSS) consists of two algorithms with the objective of finding working and backup paths. Both algorithms have to compute the shortest path between the two end-nodes. Shortest path computation is discussed in the following section.

2.1.1 Shortest Path Computation

Shortest path problem is the process of computing a path between two nodes in a graph (network) such that the sum of the weights of the links along the computed path is minimized. There are several methods proposed in the literature to solve the shortest path problem. In this thesis we employ Dijkstra algorithm in order to compute the shortest path between two nodes in the network [10]. The Dijkstra algorithm offers a fast and efficient method to compute the shortest (least-cost) paths from one node to all the other nodes in the network. The network is converted into a graph which consists of the nodes and the links in the network. The algorithm computes the least-cost path to each node until it reaches to the destination node. It is terminated when the least-cost path to the particular destination has been found. Each link has an associated weight (cost) that is used to compute the least-cost path. The cost of the link has to be a nonnegative number and it can be any cost such as the power consumed by the link or the physical length of the link, etc. In the following sections we discuss PSS algorithms for finding working and backup paths which employ the Dijkstra algorithm to compute the least-cost path. The pseudo code of Dijkstra algorithm is presented at the Appendix B.

2.1.2 PSS: Step1 - Working Path Algorithm

The objective of this algorithm is to find the least cost working path. The algorithm assigns weights to the links in the given network topology *G(N,L)*, and then executes the Dijkstra algorithm on the given network topology, and the given links weights. Here *N* is set of nodes and *L* is set of links in the network. Let W_l denote the final assigned weight to link *l*, *b* denote the number of requested wavelengths, and A_l denote the number of wavelengths available on link *l*. By setting W_l to the *infinity*(∞), the algorithm avoids choosing links that do not have adequate capacity to accommodate the newly arrived demand. Otherwise, W_l is set to 1 in order to find the minimum-hop path. The following is the pseudo code for this algorithm:

1. Get the next demand *r* that requests for *b* units of bandwidth between source *s* and destination *d*.
2. Assign weights to the links as follows:

$$W_l = \begin{cases} \infty & \text{if } b \geq A_l \; \forall \; l \in L \\ 1\,, & otherwise \end{cases}$$

3. Execute Dijkstra algorithm to find the least cost path between *s* and *d* using the link weights W_l.
4. If no path has been found then block the demand *else* find backup path

After finding the working path successfully, the backup path has to be computed with a more complex algorithm that it is explained in the next section.

2.1.3 PSS: Step2 - Backup Path Algorithm

The objective of this algorithm is to find a least-cost backup path which must be link-disjoint from the working path computed in the previous step. In order to fulfil this objective it is assumed that only one failure occurs at a time. Therefore, the backup wavelengths reserved on the links of the backup path may be shared with other backup paths. Sharing is possible for the demands that their working paths are link-disjoint. Therefore, failed connections from any single link failure in the network can be fully restored on the backup path. Consequently, using shared backup protection results in reducing capacity consumption.

After finding the working path, weights of links along the working path have to be assigned to infinity (∞) in order to find a link-disjoint backup path. PSS avoids using links along working paths as backup links. Let L denote the total number of links in the network; and let BR_{ij} denote the number of backup wavelengths required on link j if link i fails. In PSS, the maximum number of backup wavelengths needed on link l is defined as B_l which is:

$$B_l = max(BR_{il}) \; \forall \; i \in L \qquad (2.1)$$

Let SW_r denote the set of links along the working path of demand r; and let T_l denote the maximum number of backup wavelengths needed on link l if a link on SW_r fails; and let b denote the number of requested wavelengths for the newly arrived demand. Hence, T_l is formulated as:

$$T_l = b + max(BR_{il}) \; \forall \; i \in SW_r \qquad (2.2)$$

Let W_l denote the final assigned weight to link l, and A_l denote the number of wavelengths available on link l. The weight of link l (W_l) is assigned to infinity (∞) if l is along the working path of demand r. Otherwise, the weight is assigned to a very small number as epsilon (ε) if demand can be restored on link l without reserving any additional backup wavelength on the link. If conditions (a) and (b) are still not met, then the weight of link l is set with the amount of additional backup wavelength required on that link in order to restore demand r, if this additional required bandwidth is available. If the available capacity on link l is not adequate to accommodate this additional wavelength, the weight of link l is assigned to infinity (∞) in (d). The following is the suede code for this algorithm:

1. Get the demand r that requests for b number of wavelengths between the given source s and destination d.
2. Assign weights to the links as follows:

$$W_l = \begin{cases} \infty \; if \; l \in SW_r \\ \varepsilon \; elseif \; T_l \leq B_l \\ T_l - B_l \; elseif \; T_l - B_l \leq A_l \\ \infty \; otherwise \end{cases}$$

3. Execute Dijkstra algorithm for network *G(N,L)* and the given links` weights, s, and d.
4. If no path has been found then block the demand *else* update parameters

After successfully finding the working and backup paths, the related parameters of links and nodes used in PSS have to be updated. Updating parameters is discussed thoroughly in the following section.

2.1.4 Updating Parameters

After computing both working and backup paths, the total reserved working wavelength on links along the working path and the total reserved backup wavelength on links along the backup path have to be updated. In order to update parameters of links along the working path, the number of wavelengths (b) requested by the newly accommodated demand r, is simply added to the total working wavelengths already reserved on these links and is subtracted from the total available wavelengths on those links. Let R_l denote the total number of reserved wavelengths on link l before demand r is accepted. Hence:

$$\forall\, l \in SW_r \qquad R_l = R_l + b$$

In order to update parameters of links along the backup path, the number of requested wavelength b is added to BR_{ij} for every link i along the computed working path and every link j along the backup path. Let SB_r denote to the set of links along the backup path of demand r, hence:

$$\forall\, i \in SW_r \text{ and } l \in SB_r \qquad BR_{il} = BR_{il} + b$$

Finding the backup path algorithm in PSS that is discussed in section 2.1.3 and its method of updating parameters are also employed in this thesis. The proposed approaches in this thesis implement shared-path protection in order to find the least cost shared backup paths. However, the proposed approaches have to take into account both the capacity and the traffic load constraints in the process of finding backup paths. Methods of computing multi-constraints path are discussed in the following section.

2.2 Multi-Constraints Path Computations

Part of this thesis focuses on finding multi-constraint backup paths. One constraint is to compute backup paths such that results in reducing the total power consumption at the network. The second constraint has the objective of finding backup paths in a way that lead to reducing capacity usage at the network. Consequently, a trade-off between the two objectives has to be made in order to fulfill the constraints. In this section, approaches for finding multi-constraint paths and algorithms for solving multi-constraint problems are discussed.

M. Yaghmaei *et al.* in [11] employ fuzzy logic to compute multi-constraint paths. They argue that the fuzzy logic is a particularly useful method to compute multi-constraints path with conflicting objectives. Employing fuzzy logic to describe the state of a link makes it possible to imitate how a person makes a decision but much faster. Mapping values of different criteria into linguistic values becomes possible by employing fuzzy logic method. Fuzzy logic characterizes the level of satisfaction with the numerical value of the constraints. Based on the membership function of each constraint the numerical values are chosen in the interval of (0-1) [11].

Computing multi-constraint paths approaches are not limited to the fuzzy logic methods. One other way to compute a multi-constraint path is to deploy a tunable parameter. The researchers in [12, 13] propose routing algorithms with load balancing by deploying the idea of tunable parameters to compute costs of the links. The proposed algorithm in [13] defines a tunable threshold to avoid using heavily loaded links in both primary and backup paths in order to achieve low connection blocking.

Naser, H. and Ming Gong in [12] propose a two-step Load Balancing Pool Sharing (LBPS) scheme. They show how to minimize the reserved working and backup capacity in the network while balancing the loads on the network links. The LBPS scheme proposes a method to compute link-costs for the working and backup paths computation based on the load balancing technique. They define a measure of load balance on each link with two tunable parameters to find the least cost path by considering two constraints.

The simulation results in [12] show that it is possible to find the least cost path while meeting both constraints criteria by assigning proper values to those parameters. Therefore, in this case the network traffic can evenly (similarly) be distributed among network links at lower computation cost.

2.3 Related Work

2.3.1 Energy efficiency in network equipment

Line cards and chassis of routers consume significantly high amount of power. Therefore, energy-efficient line cards and chassis configuration can lead to reducing the power consumption at the network. The researchers in [14, 15, 16, 17] focus on the energy-aware dynamic traffic grooming problem in optical networks. Hasan, M.M. *et al.* in [15] argue that resources in backbone networks remain under-utilized substantially for most of the time since they are often over-provisioned to handle twice the current peak demand. Hence, these spare under-utilized resources result in huge energy waste and unnecessary operating cost. Hasan *et al.* introduce an approach that significantly reduces the number of active components of a node in its physical architecture during the process of routing the demands when traffic load is low. Hence the proposed approach results in reducing considerable power consumption at the network.

As introduced in [15], WDM node is composed of two main sections: photonic and electronic. Figure 2.1 illustrates physical architecture of a WDM node. Electronic section terminates each incoming wavelength with a transceiver and supports all electronic processing, switching, and routing operations. The electronic section is represented as Add/Drop Multiplexer (ADM). The photonic section consists of optical cross-connects which passes through and switches lightpaths in optical form, as shown in Figure 2.1.

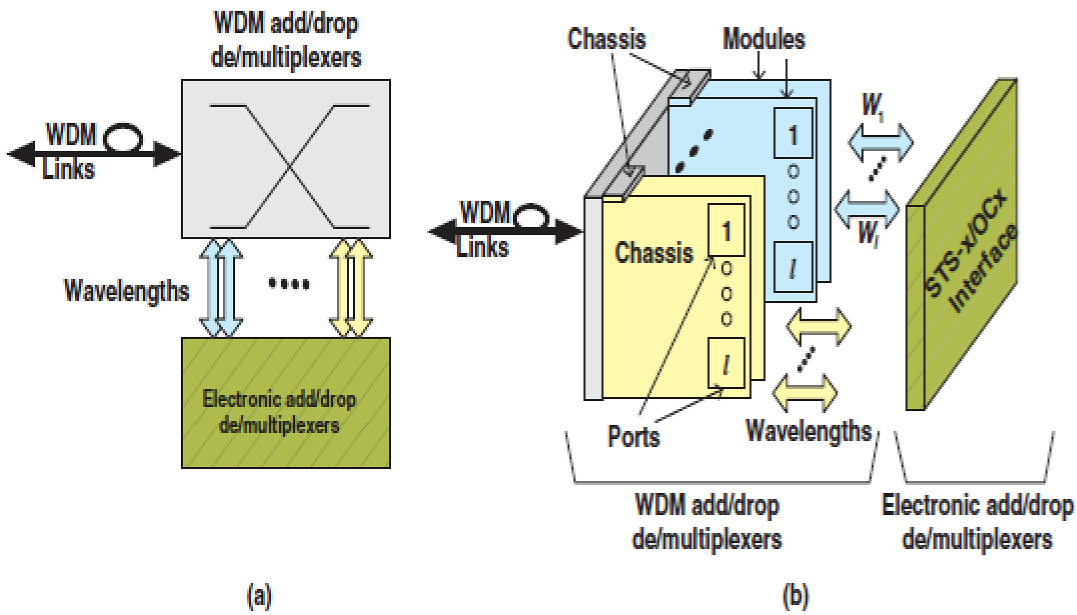

Figure 2.1 An example of modular physical architecture of an optical WDM node [15].

The proposed approach in [15] focuses on utilizing currently active components of a node as much as possible in order to increase the number of components in sleep or idle state and, as a result, reducing fixed power consumption of the node. It is assumed that all line cards in an electronic ADM are always active or powered on. Based on this approach, the modular photonic ADM direct the incoming traffic to already provisioned ports, chassis, and modules in order to power off unused equipment of the node and hence minimizing power consumption at the node. Additional chassis, modules or ports can be utilized if more traffic enters the node. The proposed approach can save as much as 30% power consumption at the network in comparison to approaches that lack energy awareness. This amount of power saving is achievable when the traffic load is low enough that it does not result in blocking any demand.

In another approach, M. Mandviwalla *et al.* in [18] address the issue of the power consumption of line cards that are based on multiprocessor architectures to divide the network traffic load. They propose an approach to reduce power consumption in such kind of line cards. Their proposed approach shows that processors in a line card consume less energy when operating at the same voltage than operating at different voltages for a given task and timing constraint. Furthermore, they propose the optimal configuration for minimizing the power consumption in multiprocessor-based line cards.

M. Youssef *et al.* in [19] argues that in-line optical amplifiers can never be turned off due to their initialization time. Optical amplifiers are used in order to amplify optical signals without converting them into electrical signals. Moreover, they also point out that the network line cards and ADM modules cannot be turned off due to reasons of resilience. Hence, they propose that it is feasible to reduce power consumption at the WDM layer by wisely choosing the number and type of the transceivers that are utilized at each node. Therefore, their operation perfectly coordinates with the exact needs of the network.

Figure 2.2 illustrates two-layer node architecture. As shown in Figure 2.2, WDM layer consists of Wavelength Selective Switch based (WSS-based) Reconfigurable Optical Add/Drop Multiplexer (ROADM) which is capable of dropping any wavelength from any incoming fiber and adding them to any outgoing fiber dynamically and without converting them to electronic signals. Transceivers at the interface between the ROADM and the IP router perform Optical Electrical (OE) and Electrical Optical (EO) conversions. These transceivers consume a considerable amount of power at the WDM layer.

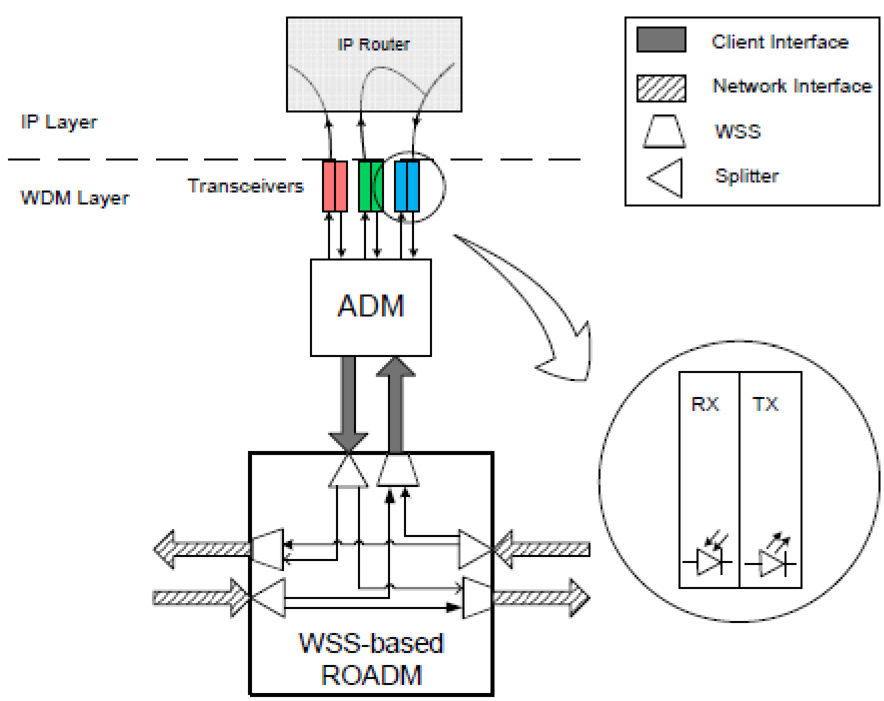

Figure 2.2 Two-layer node architecture [19].

Furthermore, Youssef, M. *et al.* in [19] also propose a method for routing the traffic under Scheduled Demands (SDs). They point out that routing traffic in the context of SDs is difficult since the time-space correlation between traffic demands is exploited in order to re-use network resources. However, routing in the context of Permanent Demands (PDs) only takes into account the number of wavelengths and available transceivers and in the network. In their proposed approach, transceivers are tunable in terms of the number of wavelength channels. However, they have fixed capacity. The numerical results show that deployment of a combination of different types of transceivers with different capacities achieves up to 40 percent energy saving, considering the time granularity of traffic.

Another area of energy-saving in network equipment can be investigated in links. Lin Liu *et al.* in [20] state that the link utilization of the network is pretty low due to the overprovisioned link bandwidth that are designed for peak traffic load. Hence, it results in wasting considerable amount of energy. As addressed in [20] many high-speed fibers are combined together to form bundle links or composite links. Each bundle link consists of a set of links that are referred to as sublinks. Lin Liu argues that, when traffic load is low, selectively turning off sublinks lead to saving a significant amount of energy while keeping the network topology unchanged.

Two types of traffic distribution methods in core networks are introduced in [20]. These methods which apply bundle link technique are load balancing and bin-packing. In load balancing technique, all the traffic is almost evenly distributed over all the sublinks. However, in bin-packing, the traffic is concentrated into the minimum number of sublinks being used. Load balancing leads to almost the same link utilization for the sublinks while in the bin-packing, the utilization of the first several sublinks vary from the utilization of the last sublinks. Lin Liu *et al*. in [20] investigate energy saving under bin-packing traffic method.

The results show that significant energy savings with small risk of data loss is achievable by setting 90% as threshold of traffic load on each link. Based on the experimental results, it is possible to save energy consumed on ports of core routers up to 86% although cost of port operations such as shutting down or bringing up are ignored.

2.3.2 Modeling power in WDM networks

Yetginer, E. *et al.* in [21] model total power consumption of an optical WDM network in terms of the total number of lightpaths in the network. Figure 2.3 illustrates traffic grooming in an optical WDM network. As shown in Figure 2.3, a WDM node consists of Digital Cross Connect (DXC), Optical Cross Connect (OXC), and transceivers. The transceivers connect DXC to OXC and perform Optical/Electrical (O/E) and Electrical/Optical (E/O) conversions. As addressed in [21], O/E and E/O conversions consume significant amounts of power. Moreover, they also argue that DXC input and output ports connected to the transceivers are responsible for the most of power consumption at the network. This is due to high power consuming traffic switching and packet processing which are performed on the line cards and input and output ports of the routers. However, the power consumed in OXC is much less than the power consumed in the DXC and O/E and O/E transceivers.

Figure 2.3 illustrates how a demand (connection) is routed in a WDM network. The connection shown in Figure 2.3 is generated at Node 1 and it is terminated at the Node 4. The connection utilizes two different lightpaths, one lightpath from Node 1 to Node 3 and the second lightpath from Node 3 to Node 4. The traffic which traverses the connection from Node 1 to Node 4 is electronically switched between the two lightpaths at Node 3. As discussed in the previous paragraph, switching traffic electronically results in consuming a

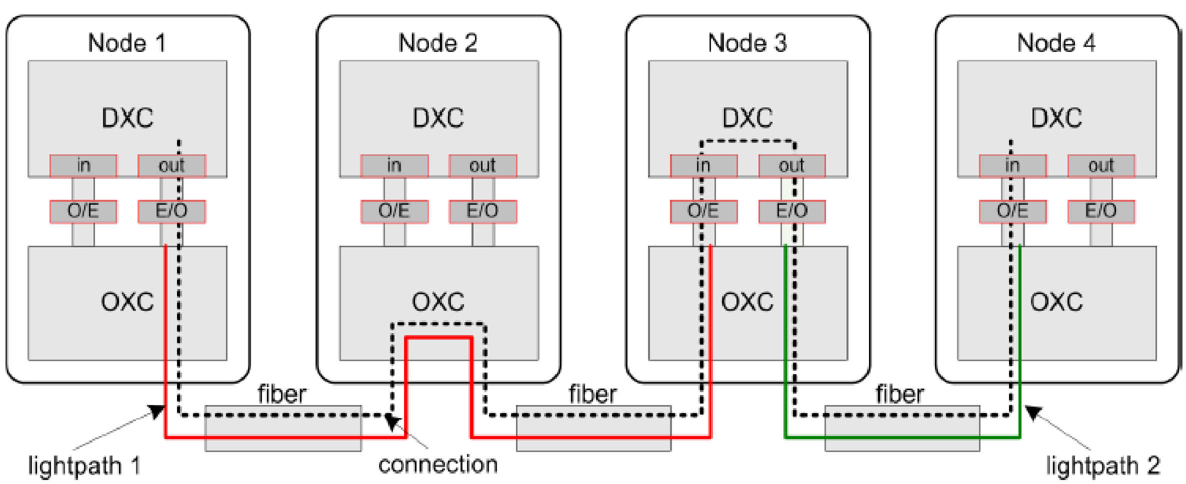

Figure 2.3 Traffic grooming in an optical WDM network [21].

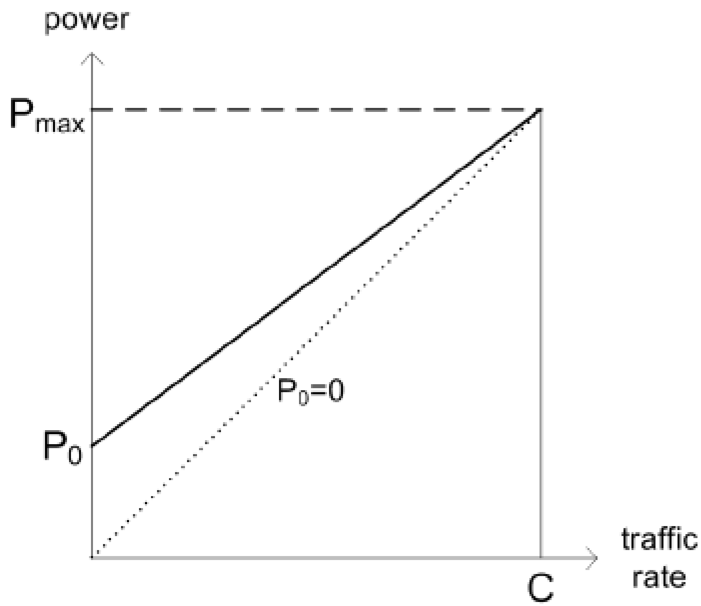

Figure 2.4 Power consumed by a lightpath as a function of carried traffic [21].

considerable amount of power in the E/O and O/E transceivers and in the DXC ports. However, lightpath 1 is optically switched at Node 2 which consumes much less amount of power than switching traffic electronically [21].

Yetginer, E. *et al.* in [21] point out that a generated lightpath consumes an amount of power independent of the traffic it carries and an amount of power dependent on the traffic which traverses the lightpath. Figure 2.4 provides better insight into the power consumed by a lightpath. P_0 in Figure 2.4 corresponds to the traffic independent power consumption of a lightpath. According to the Figure 2.4, the maximum efficiency is achieved when the amount of power independent to the traffic is zero, (P_0=0). The power consumption dependent on the traffic is the power consumed in the DXC ports, the O/E and E/O transceivers and the OXC. Hence, they argue that minimizing the total number of generated lightpaths in the network leads to reducing the total power consumption at the network. Moreover, they also express that it is feasible to reduce the total power consumption at the network by avoid switching traffic electronically as much as possible.

Consequently, they modeled the total power consumption of a WDM network in terms of the total number of generated lightpaths, the power consumed by an individual lightpath independent of the traffic it carries (P_0), and the power consumed by the total amount of electronically routed traffic. They used the power model to formulate an ILP with the objective of minimizing power consumption. Simulation results show that it is feasible to reduce the power consumption at the network up to 25% for low to moderate traffic loads.

2.3.3 Energy efficiency in routing and grooming

The researchers in [22, 23, 24] investigate energy efficiency in the context of Routing and Wavelength Assignment (RWA). Traffic grooming plays a crucial role in the WDM networks. Traffic grooming is the process of combining sub-wavelength traffic onto high-speed optical wavelengths in order to reduce the network cost. It aims at minimizing Opto-Electro-Optic (OEO) process which consumes a considerable amount of power. They propose to reuse the same fiber along the same path as much as possible, in contrast to spreading lightpaths on available fibers and paths. K. Zhu *et al.* in [24] state that the bandwidth request of a demand may be much lower than the capacity of a lightpath in WDM networks. They argue that it is feasible to enhance the network throughput and to reduce the power consumption at the network by efficiently grooming low-speed demands onto high-capacity lightpaths.

A model of optical network node is illustrated in Figure 2.5. The model contains three la-

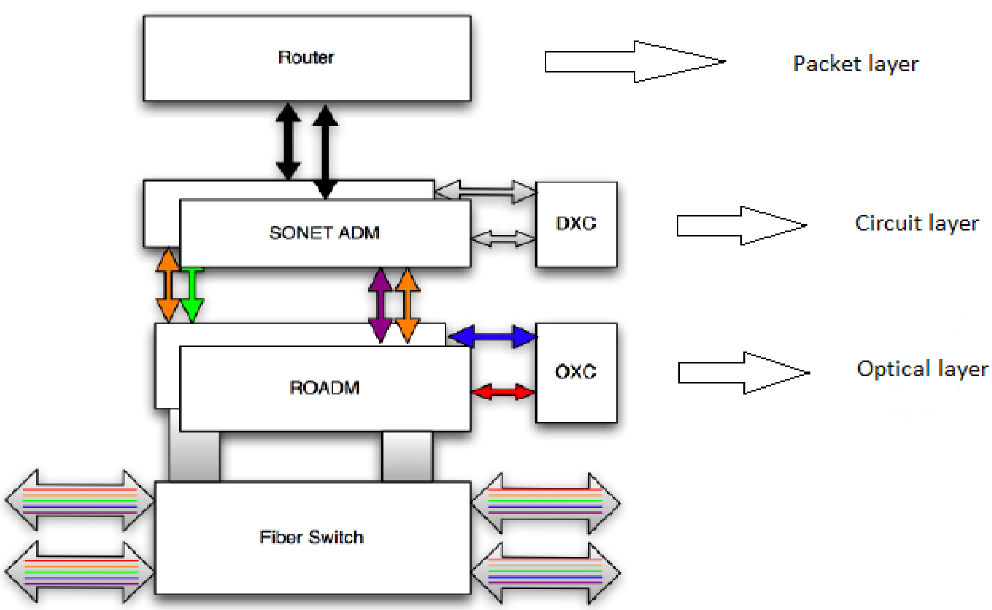

Figure 2.5 Model for an optical network node [23].

-yers: the optical layer, circuit layer and packet layer. Based on this model, there are three ways to process a traffic demand that is not generated or terminated at this node. First, the traffic demand is optically routed by this node which is also called, “bypassing”; second, a switch at the circuit layer process the traffic demand electronically; and third, a router at the packet layer process the traffic demand electronically. Since the regeneration of traffic as OEO processing is responsible for the most of power consumption at the network, the first possibility is the most energy efficient. The third possibility is the least energy efficient due to the high power consuming processes at packet layer such as memory accesses, scheduling, path computation, and table lookups [23].

Shu Huang *et al.* in [23] investigate the grooming problem in an optical node by proposing two different approaches to model the power consumption of the network, namely a flow-based formulation and an interface-based formulation. They point out that the two approaches describe two extreme situations. Hence, the total power consumption at the network always lies in the shaded region shown in Figure 2.6. The flow-based formulation models the total power consumption at the network as a linear function of the traffic load. They modeled the power consumption at the network in precise detail by taking into account all the network equipment at the optical, circuit, and packet layers. This leads -

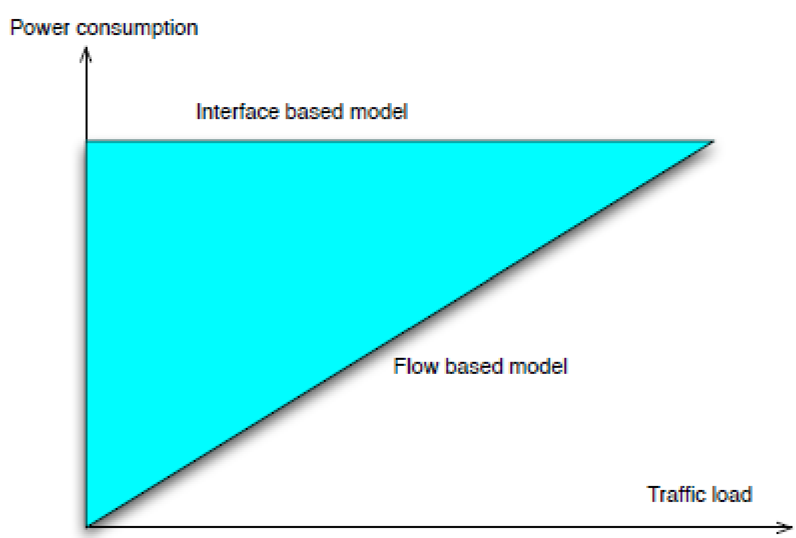

Figure 2.6 Power consumption characteristics of a network [23].

-to the ideal power consumption at the network. However, in interface-based formulation, the impact of traffic load is neglected by only taking into account the fixed (independent of traffic) part of power consumption. They argue that the traffic dependent power consumption at the network equipment such as line cards is negligible compared to the fixed part. Hence, the interface-based formulation represents the maximum possible power consumption at the network.

Each path in a network traverses a set of network interfaces such as routers to reach to the destination. Shu Huang *et al.* propose that power consumption at the network can be significantly reduced by utilizing as less interfaces as possible for each path. The simulation results show that it is possible to turn off network interfaces as much as 12%.

Farahmand, F. *et al.* in [25] introduce Differentiated Energy-Saving (DiffEnS) traffic grooming for optical networks when the traffic is divided into two different classes of services, namely, Green and Red classes. The former is an energy-aware type of services that are provisioned in a way that is aimed at reducing power consumption. However, the latter is a traditional type of services that continue having the same type of service they were receiving before. The two heuristic algorithms for supporting DiffEnS, introduced in [25] investigate the impact of energy-efficient networks on average delay and the energy saving of a gradual shift towards designing such network.

The two heuristic algorithms proposed for routing Red and Green traffic are Red-Demand-Based (RDB) and Total-Demand-Based (TDB). In the RDB algorithm, all the Red demands are sorted in descending order of the amount of traffic and then routed. In the next step, the Green demands are sorted in descending order of the amount of traffic and then routed. Therefore, all the Red traffic demands are routed before the Green demands. In the TDB algorithm, all traffic demands between node pairs are sorted in descending order of the amount of traffic and then routed. However, in such a case that two or more than two traffic demands are equalized by the same amount of traffic, Red demands are routed first and then Green demands are routed. Simulation results show that TDB leads to more energy saving than RDB [25].

They argue that the total power consumption reduces significantly if a larger portion of customers switch to the Green service. Simulation results show that the power saving as much as 30% is achievable at low loads for 14 and 24 nodes networks when almost all the customers switch to the Green service, (e.g. 95% of the traffic is Green). However, DiffEnS becomes less effective at high traffic load (0.7 and above) due to that fact that most network equipment are fully utilized. At high loads, the power saving is possible up to 8% for the 14 nodes network and up to 12% for the 24 nodes network [25].

Nevertheless, they conclude that although the proposed approach leads to reducing power consumption at the network, it may lead to higher average delay, and hence, lower throughput. They also articulate that it may not be a realistic expectation to request all customers to switch to a service with higher average delay in favor of an energy-saving network. Moreover, customers with sensitive tasks will be reluctant to switch to a new type of service.

Garroppo, R.G. *et al.* in [26] propose an approach in order to reduce power consumption of telecommunication networks by designing network power management methods. Power Aware Routing and Network Design (PARND) discussed in [26] aims at minimizing the overall power consumption at the network by taking into account a power-aware routing strategy and by turning off links and nodes in the network.

Nevertheless, the PARND problem results in NP-hard Mixed Integer Non-linear Programming (MINLP). Thus, Garroppo proposes a heuristic approach for finding suboptimal solution of the PARND problem. The Heuristic PARND (HPARND) proposed in [26] articulates that employing the power-aware routing strategy as well as power-efficient design of the network achieves substantial power savings. Moreover, HPARND leads to load-balancing that prevents link congestion even when traffic load increases. Finally, they argue that the most of power saving at the network is obtained by turning off nodes and links in the network as opposed to power-aware routing strategy. However, HPARND leads to reducing power consumption at the network up to 18% compared to Shortest Path Routing (SPR) approach.

2.3.4 Energy efficient network designs and protocols

The researchers in [27, 28] investigate energy efficiency in network designs and protocols. Chabarek, J. *et al.* in [27] argue that variation in traffic flow provides an opportunity to reduce the power consumption at the network by routing traffic efficiently.

In this regard, they propose two directions, power-aware network design and power-aware protocol design, which lead to significant power saving at the network.

Power-aware network design seeks to minimize power consumption at the networks while the robustness and performance constraints are satisfied. Two approaches have been introduced in [27] with respect to power-aware network design. In the first approach, they measured the power consumption of two different types of routers with different configurations of chassis and line cards. They utilized a power measurement device for this purpose. They show that different configurations of line cards and chassis result in different energy consumption. Their approach proves that being aware of power consumption of network component when designing network topologies leads to considerable power savings. The results of this approach indicate that minimizing the number of chassis that are utilized at a given Point of Presence (PoP) as well as maximizing the number of line cards per chassis result in considerable amount of power savings. Second, they also show that in packet processing, packets with larger size consume less power than packets with smaller size. Although they point out that the packet size effects are less significant than configurations of chassis and line cards.

Power-aware protocol is concerned with the design and implementation of network protocols in order to reduce the overall power consumption at the network. It proposes methods for setting network components on sleep mode. Chabarek, J. *et al.* in [27] argue that the development of this protocol makes it possible to set line cards on sleep mode. In addition, it can also results in more efficient traffic profiles. They simulated their proposed approach on different random networks by the employment of two different line cards in order to evaluate the impact of power-awareness on routing protocols. Simulation results prove that power savings up to 11% is achievable.

Yamada *et al.* in [29] propose two approaches, power saving design and power efficient design, to reduce power consumption of network equipment. The former approach aims at reducing power consumption of the network equipment by turning off unused components such as ports and modules. They developed a power control tool which allows turning on and off ports and modules manually. Moreover, they argue that the power consumption of modules is dependent upon the frequency of them. Hence, switching the frequency of the router interfaces to lower frequency leads to reducing the power consumption of them. Results indicate that power savings is achievable up to 20% by deploying the low-frequency mode. In regards to power efficient design, they developed a high-performance router which consumes less amount of power than the conventional routers. In the process of developing the router they first integrated the Application-Specific Integrated Circuit (ASIC), Field-Programmable Gate Array (FPGA) and memories of routers; and then they created a router that adopts a scalable central architecture. Hence, they claimed to successfully developing a router with a throughput over 1 Tbps which decreases the power per throughput (Watt/Gbps) as much as 50%.

2.3.5 Energy efficiency in PON networks

Passive Optical Networks (PONs) were developed in order to deliver broadband services by taking advantage of optical fibers. PON consists of Optical Line Terminal (OLT) where services are generated and Optical Network Unit (ONU) where services are terminated. Terminated data will be further distributed to all the subscribers attached to ONU through other transmission media such as copper [30]. A Gigabit Ethernet PON (G-EPON) consists of one OLT located at a central office and multiple ONUs located at user destinations. Figure 2.7 illustrates downstream buffers and frame flows in a 10G-EPON. Optical fibers and an optical splitter connect the OLT to ONUs [31]. The researchers in [31, 32] investigate energy efficiency in PON networks.

Uzawa, H. *et al.* in [31] propose an approach in order to reduce the power consumption of Optical Network Units (ONUs). They argue that the large-capacity buffer in the convention-

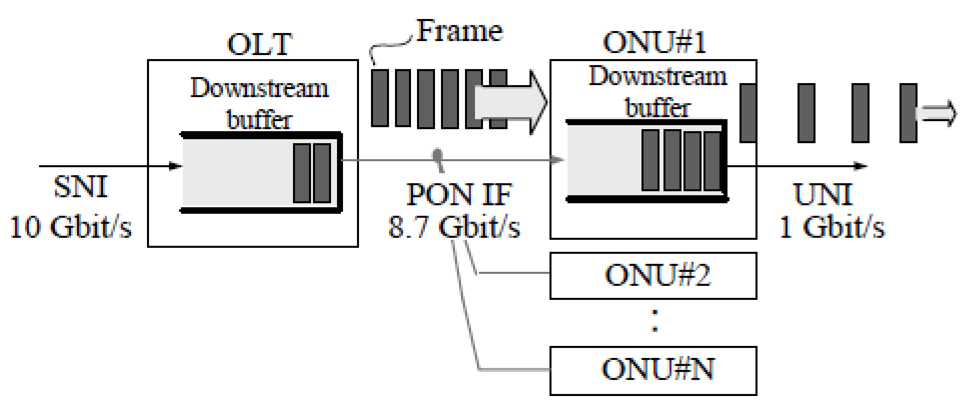

Figure 2.7 Downstream buffers and frame flows in 10G-EPON [31].

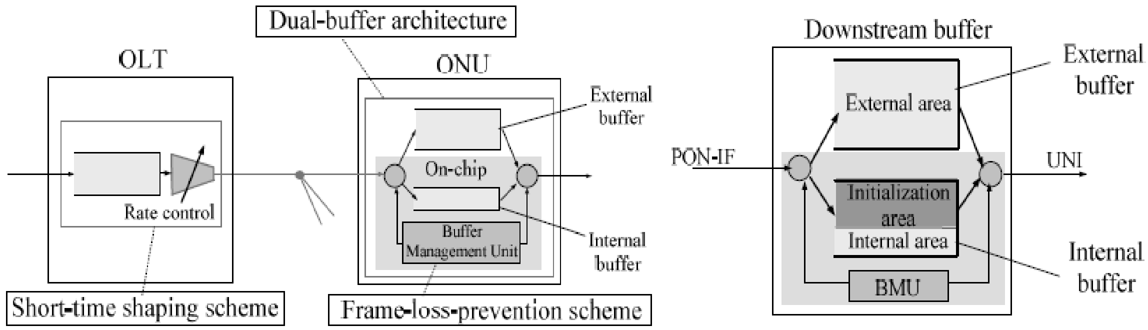

Figure 2.8 Proposed dual-buffer architecture and control scheme [31].

-al architecture of ONUs is always active even when there is not even one frame stored on them. This results in inefficient power consumption in ONUs. Each ONU is composed of an internal buffer with small on-chip memory and an external buffer with large off-chip memory forming dual-buffer architecture.

Nonetheless, they point out the issues regarding implementation of dual-buffer architecture that how to prevent frame loss and how to minimize the internal buffer in order to avoid increasing in cost. Three approaches are proposed by Uzawa, H. *et al.* in order to tackle these problems. First, they propose an internal buffer with a frame storage area which is utilized only when the external buffer is initializing. Second, in order to minimize the internal buffer they propose a short-time shaping scheme which operates cooperatively with OLT. This scheme aims at controlling the downstream data rate transmitted to the ONU. Third, they propose an approach in order to prevent frame-loss. Figure 2.8 provides better insight into proposed approaches. Frames are only stored in the internal buffer when the data rate is low. Hence, the external buffer is turned off. By increasing data rate, initialization occurs, which is the process of activating the external buffer. The external buffer begins to store frames after the initialization process is completed [31]. It is concluded in [31] that considerable energy saving in the ONU's downstream buffer can be achieved by the proposed approach at different traffic load levels.

2.3.6 Energy efficiency in optical backbone networks

In [33, 34] Chiaraviglio, L. *et al.* investigate energy efficiency in backbone networks. In [33] Chiaraviglio *et al.* state that in large networks, such as backbones, network resources a-

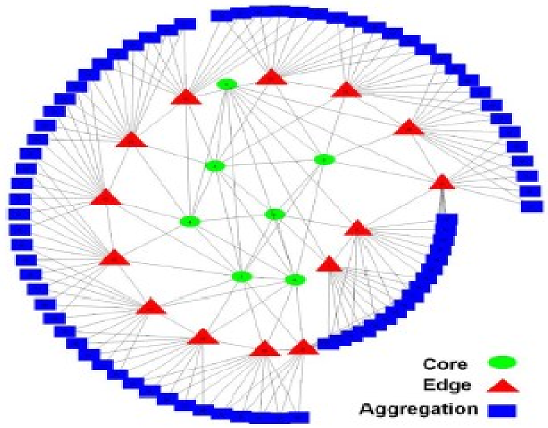

Figure 2.9 An example of random backbone topology [33].

-re overprovisioned in order to support the dynamic traffic flow and to provide protections at the network for any failure. They propose to reduce the power consumption in a wide-area network scenario by turning off nodes and links at the network while guaranteeing connectivity and QoS.

A hierarchical topology, which is typical of Wide Area Networks (WAN), is chosen in [33] for the heuristic algorithm. This topology consists of core, edge and aggregation nodes. In their proposed topology, one or more edge nodes exist in cities which collect traffic from aggregation nodes that are spread throughout the city boundaries. End-users are connected to the aggregation nodes such as a Digital Subscriber Line Access Multiplexer (DSLAM) or an OLT. Each node is dual-homed to guarantee alternate paths in case of failure. Figure 2.9 provides better insight into the random backbone hierarchical topology.

Chiaraviglio *et al.* argue that it is feasible to reroute the traffic on a set of network resources and hence turn off a noticeable number of nodes and links when traffic load is low. For instance, they point out that it is feasible to turn off one out of two links between the aggregation and edge nodes. These links do not carry traffic in normal conditions since they are only utilized for protection purposes. Consequently, results indicate that reducing powered-on nodes and links up to 30% and 50% respectively is achievable while maintaining the resource utilization below a given threshold [33].

In a related research, Chiaraviglio, L. *et al.* in [34] exploit their proposed approach in [33] to turn off network resources and therefore reducing power consumption at the network. In

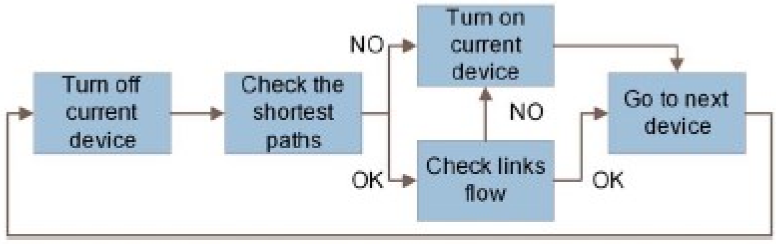

Figure 2.10 Turning off technique [34].

their study, they investigate the power savings in an actual ISP network topology by modeling the power consumption of nodes and links in the network.

They used a hierarchical topology in [34] in which four types (levels) of nodes are utilized: core, backbone, metro, and feeder nodes. In their proposed approach the devices in the network are sorted based on the amount of energy they consume. Then, the approach attempts to power off first nodes that consume more energy. In the next step, it attempts to power off the remaining links of the turned off nodes. Figure 2.10 provides better insight into the turning off approach. According to the Figure 2.10, the algorithm first turns off a node and all the links originating and terminating at that node. Then it attempts to compute the shortest path by the remaining active resources. If no path is found, it will turn on the node and implement the same procedure for the next node. If a path is found, the algorithm checks links flow to determine if it is possible to turn off links as well or not. If links are under utilization, it will turn on the node and implement the same procedure for the next node. If the links have no load, then the algorithm successfully turns off the node and its corresponding links. The same process applies for all the remaining nodes.

Chiaraviglio concludes that the energy efficiency up to 34% is achievable due to the variation in traffic flow over time when traffic load is low, although the most of network resources have to be fully available at high traffic load levels. The results also indicate that energy saving up to 23% of total energy consumption per year is achievable [34].

In another related context, the researchers in [35, 36] compare the performance of optical bypass and traffic grooming in terms of power consumption. Optical bypass refers to the process of switching the path of an optical lightpath in the OXC. M. Xia *et al.* in [37] argue that although the traffic grooming reduces traffic-independent power consumption at the network, it leads to high power consuming electrical to optical (E/O) and optical to electrical (O/E) conversions. Hence, they point out that optical bypassing consumes less power than traffic grooming. In this regard, they propose a power-aware approach which results in reducing the power consumption in backbone networks by searching for an optimal route. Results indicate that the proposed power-aware traffic grooming results in considerable amount of power saving compared to the traditional traffic grooming scheme.

2.3.7 Energy efficiency in IP layer

Energy efficiency is also investigated in IP over WDM network. IP over WDM network is developed in order to benefit from both the high capacity of WDM network and the global connectivity of IP [38]. Gangxiang Shen *et al.* in [39] express that power consumption of backbone networks significantly increases with the user applications such as high-definition IPTV which require high bandwidth capacity. Furthermore, they argue that in backbone networks, energy consumption is often limited into a few buildings. Gangxiang Shen *et al.* address the importance of energy reduction in the IP over WDM backbone networks due to above reasons.

Figure 2.11 illustrates the architecture of IP over WDM optical network. The architecture includes two layers including IP layer, and optical layer. In the IP layer, a core IP router collects data traffic from low-end access routers. It is also connected to an optical switch node through network interfaces. In the optical layer, optical nodes are interconnected with physical fiber links. The physical fiber links provide high-bandwidth capacity for the communications between IP routers. Each link may consist of multiple fibers. A pair of wavelength multiplexers/demultiplexers is utilized for each fiber. For each wavelength, a pair of transponders is connected in order to transmit data traffic. Finally, Erbium Doped Fiber Amplifier (EDFA) amplifiers are utilized on fiber links in order to make optical signals stronger so that they can travel longer distance [39].

Gangxiang Shen *et al.* in [39] propose a MILP formulation model and two efficient heuristics in order to minimize energy consumption. They exploited the lightpath bypass concepts to reduce the number of required IP router ports. They addressed two possible methods to implement IP over WDM networks which are: lightpath non-bypass and lightpath bypass. In the lightpath non-bypass approach, all the lightpaths passing through a specific node must be terminated and the traffic that traverses the lightpaths has to be first -

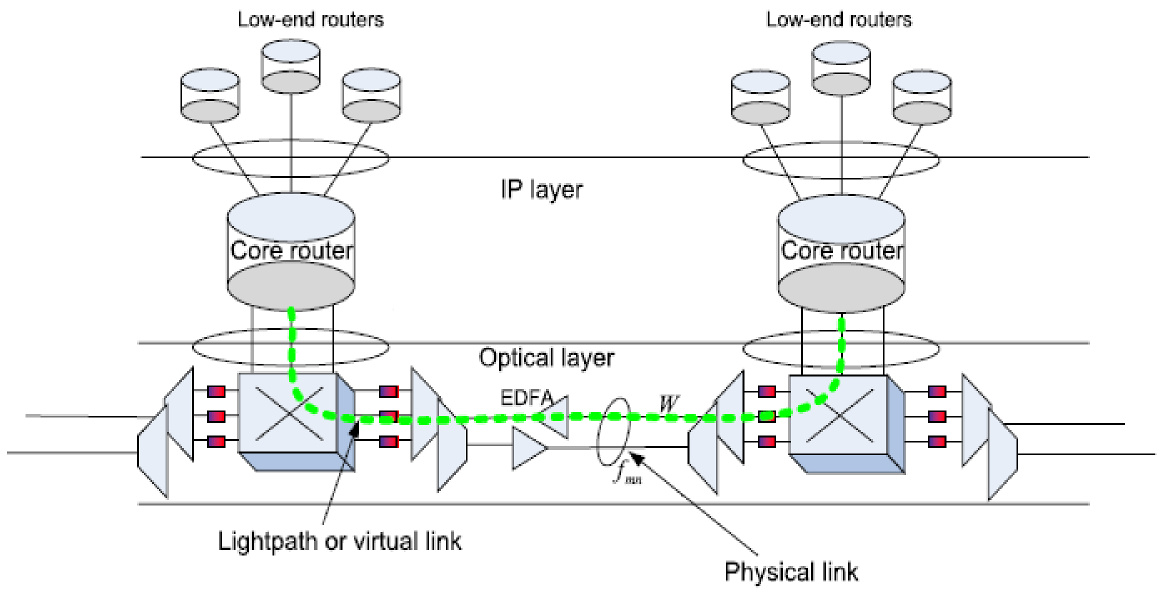

Figure 2.11 Architecture of an IP over WDM optical network [39].

-processed and then routed again by IP routers. However, in the lightpath bypass approach, IP traffic whose destination is not the intermediate node is optically routed (bypassed) without being processed.

The simulation results in [39] indicate that the lightpath bypassing approach leads to considerable power saving ranging from 25% to 45% over the lightpath non-bypassing approach. Gangxiang Shen *et al.* also conclude that since the IP routers consume over 90% of the total power consumption at the network, they are a major power consumer over WDM networks. Moreover, they point out that the lightpath bypass approach also results in equalizing the geographic distribution of power consumption. Finally, they articulate that due to the crucial role of IP routers in power consumption, energy-efficient design of the network can also be cost-efficient.

2.3.8 Energy efficiency and survivability in WDM networks

In [40] Wosinska, L. *et al.* address the importance of investigating technologies, methodologies and approaches that can result in minimizing power consumption. They discuss that the spare backup resources in a WDM network consume considerable amount of power. The reason for this is that backup resources in WDM networks are always active despite the fact that they will be used only when a failure occurs. Furthermore, backup paths are typically longer than their corresponding working paths which demand more power consumption.

Wosinska, L. *et al.* propose an approach to reduce power consumption in WDM networks. Their proposed approach aims at efficiently utilizing protection resources in order to exploit a trade-off between recovery time and energy consumption. Simulation results indicate that it is feasible to reduce power consumption by 30% with respect to the Pan-American (NSFNet) network and 40% with respect to the Pan-European (Cost 239) network. They also show that employing the energy-aware routing approach achieves an additional 20% energy saving.

Muhammad, A. *et al.* in [4] propose three ILP formulations based on the power consumption of the different operational modes of network devices. These operational modes are off, sleep, and active modes. As discussed in section 1.1.1 of this thesis, devices on off mode do not consume any power. Devices on sleep mode consume a minimal amount of power only to assure that they can be switched to active mode promptly. Finally, devices on active mode consume a fixed amount of power independent of their traffic and an additional amount of power proportional to their traffic load. Their objective is to reduce overall power consumption of a network while providing dedicated backup path protection.

They propose three algorithms: minimum power which supports sleep mode (MP-S), minimum power without supporting sleep mode (MP), and minimum installation cost (MC). MP-S aims at optimally computing working and backup paths for all the demands in order to minimize the overall power consumption at the network. In MP-S, the power consumption of devices in active mode is only taken into account. MP aims at minimizing the overall power consumption at the network by routing the demands optimally, however, sleep mode is not supported. The objective of MC approach is to minimize the installation cost for working and backup resources at the network [4].

The ILP results in [4] demonstrate that considerable power saving up to 25% is achievable by taking into account sleep mode and efficiently routing the demands. MP approach results in 10% more power saving compared to MC approach. MP-S approach which exploits sleep mode leads to up to 15% more power saving at low loads and 10% more power saving at high loads compared to MP approach.

Cavdar, C. *et al.* in [9] investigate energy efficiency in survivable network with shared backup protection. However, they argue that there has to be a trade-off between energy-efficiency and survivability. They point out that the energy efficient network methods aim at increasing the traffic load on a set of links in order to concentrate the traffic on them and hence, set on sleep mode network resources as much as possible. In contrast, network survivability methods result in lightly loaded links in order to maximize the amount of shared capacity in backup resources and to minimize the amount of data that would be lost in case of failure.

Cavdar, C. *et al.* propose an ILP formulation which aims at reducing the total power consumption at the shared backup protected survivable networks by exploiting sleep mode. It is assumed in their approach that links with only reserved backup capacity can be set to sleep mode with negligible idle power consumption. However, in their study, the sleep mode feature was not exploited for nodes since all the nodes were aggregate nodes.

The results indicate that it is possible to reduce both capacity and power consumption at networks simultaneously despite the trade-off between energy-efficiency and survivability. They show that power saving up to 40% is achievable with only a small increase in the capacity consumption when traffic load is low.

2.4 Summary

In this chapter, we presented a background in computing shared backup paths and discussed related work. We explained the details of pool sharing scheme. Pool sharing scheme first computes minimum-hop working path and then it finds the proper backup path for the corresponding working path. However, energy efficiency is not taken into account in pool sharing scheme. The working and backup paths are computed regardless of considering power consumption of network equipment, i.e., nodes and links. We also discussed the importance of multi-constraints routing algorithms in this thesis. In this regard, different methods of computing a multi-constraint path were pointed out.

In related works section we presented state-of-the-art methods of reducing power consumption at the network components and, in general, at the different areas of networking. It has been shown in this chapter that the power saving is possible by putting sub-components (i.e. line cards) of network equipment such as routers on sleep mode when traffic load is low. In addition, power saving has also been investigated at routing and grooming. It has been shown that, when traffic load is low, rerouting traffic along a few routes in order to aggregate traffic on them allows devices on idle routes that have no traffic load to be set on sleep mode and, as a result, reduce power consumption. Finally, some researchers demonstrated that power saving can also be obtained by utilizing sufficient and proper devices as the traffic load demands. More devices can be utilized as traffic load increases.

We also presented the state-of-the-art methods of modeling and calculating the power consumption of network equipment such as nodes. It has been shown that power consumption of a WDM node is modeled as sum of a fixed amount of power independent of their traffic and an additional amount of power proportional to their traffic load. We use this idea in this thesis in order to formulate the power consumption of a WDM node in our network topology.

In this thesis, we use the concept of sleep mode proposed in the literature in order to put network equipment such as links and nodes on sleep mode. We also use the rerouting traffic idea in order to propose two novel approaches with the objective of aggregating traffic along a few nodes and links. This allows devices with no traffic load to be set on sleep mode and hence reducing the total power consumption at the network. In the next chapter, we present the two approaches that compute working and backup paths by taking into account power consumption of network nodes and links.

Chapter 3 Power Model, and Energy Efficient Approaches

Our goal in this thesis is to find working and backup paths in a way that results in reducing overall power consumption in the network. In this chapter, the concept of power consumption of nodes and links presented in [9] are used in order to introduce a power model which will be employed to calculate power consumption at nodes and links in a network. Moreover, we propose approaches that are aimed at finding working and backup paths for each demand. Paths are computed in the context of shared-restoration survivability with an eye to keep the total power consumption low. The basic idea behind reducing the total power consumption of the network is to compute working paths in a way that results in having more number of nodes and links with no working wavelength reserved on them.

The rest of this chapter is organized as follows. In section 3.1, we present the motivation behind this work. In section 3.2, we introduce the network model used in this thesis. Furthermore, we also discuss the power model for nodes and links in this section. In sections 3.3 and 3.4, we present the approaches for finding working and backup paths. Eventually, section 3.5 summaries this chapter.

3.1 Motivation

The goal in the design of Shared Backup Protected Survivable Network (SBPSN) is to consume as lowest capacity as possible for the purpose of finding backup paths. In such a network, the traffic needs to be distributed evenly among network links in order to maximize the amount of shared backup capacity along the backup paths. Therefore, SBPSN results in lightly-loaded links and nodes [12]. However, in optical WDM networks, links and nodes consume a certain amount of power regardless of the load. Hence, SBPSN results in inefficient use of network equipment and consequently more power consumption.

The way to reduce the power consumption of networks is by switching lightly-loaded links and nodes into sleep mode. This is possible by rerouting the traffic through other links and nodes.

3.2 Network Model

In this section we introduce the network model which will be used in this thesis to simulate the proposed approaches. The network consists of a grid of WDM nodes interconnected using fiber links. Two types of nodes are used in this model: nodes that generate traffic and nodes that only route traffic. The first type of node called aggregate nodes which generates and terminates traffic in terms of the number of wavelengths. The second type of node called intermediate node is only utilized for the purpose of protection, hence they only reroute traffic towards other nodes.

Each node is modelled as being integrated by two main parts. The first, consumes energy regardless of the traffic going through it. This static power component accounts for the basic operational capabilities of the node. The second is a dynamic part which consumes variable power depending on the traffic being generated, routed or received by the device.

Links are modelled as physical optical connections with a set of amplifiers along the link. The amount of power consumed by a link depends on the number of amplifiers in it. A fixed amount of available wavelength is defined for each link. A link consumes power if at least one working wavelength has been reserved for it. This consumption is constant regardless of the number of wavelengths in use. In this model all links are bidirectional.

3.2.1 Power Model

In this section we discuss the power model for links and nodes in a WDM network. The power model for nodes consists of a fixed (static) part and a dynamic part. The static part is independent of the traffic load, whereas the dynamic part is proportional to the traffic load at the node. The proportional power is dependent on the number of working wavelengths passing through the nodes. Therefore, the total power consumption of a WDM node is the sum of the fixed power and the dynamic (proportional) power.

Total power consumption of a node (P_n) is simply modeled as the sum of the fixed power and the proportional power components. The proportional part is dependent on the number of working wavelengths generated by, terminated to, or passing through a node. P_n is formulated as the following:

$$P_n = F_n + (K_{nt} \times E_{nt}) + (K_{nr} \times E_{nr}) + (K_{ns} \times E_{ns}) \qquad 3.1$$

where F_n is the fixed power consumption at the node which is assigned to zero when the node is inactive (i.e. does not carry traffic or when K_{nt} , K_{nr} , and K_{ns} are all zero). E_{nt} is the power consumption per wavelength for a transmitter node, E_{nr} is the power consumption per wavelength for a receiver node, and E_{ns} is the power consumption per wavelength for a switching node. K_{nt} is the number of working wavelengths generated by node n, K_{nr} is the number of working wavelengths terminated at node n, and K_{ns} is the number of working wavelengths passing through node n. In this thesis, F_n ,E_{nt} , E_{nr} , and E_{ns} are set to 150 Watt(W) 2.45W, 1.757W, 2.45W. These values have been widely used in the literature [9, 4]. They are originally proposed by S. Aleksic in [41]. S. Aleksic in [41] analyzes different types of WDM node and estimates the power consumption of the nodes.

Power consumption at a link (P_l) is simply modeled as the number of in-line amplifiers multiplied by power consumption of each of them. P_l is formulated as the following:

$$P_l = E_l \times ((\frac{D_l}{80}) + 2) \qquad 3.2$$

where E_l is the power consumption for each in-line amplifiers on like l, and D_l is the distance of link l in kilometers. The number 80 in the equation 3.2 means that every 80 kilometers one in-line amplifier exists on the link. Hence, diving D_l by 80 yields the total number of in-line amplifiers on the link. Moreover, the number 2 in the equation 3.2 represents two in-line amplifiers at the two end points of the link. Similar to the nodes, S. Aleksic in [41] estimates the power consumption of an optical amplifier. Aleksic argues that the power consumption of an optical amplifier ranges from 3W to 12W. In this thesis, E_l is set to 9W according to [9].

Hence, the total power consumption at the network (P_T) is simply the sum of power consumption of all nodes, plus the sum of power consumption of all links. P_T is formulated as follows:

$$P_T = \sum_1^N P_n + \sum_1^L P_l \qquad 3.3$$

where N is the total number of nodes in the network and L is the total number of links in the network.

3.3 Indirect Power Efficient Approach

In this section, we propose an approach that aims at routing traffic through the network with the goal to reduce the number of utilized (active) links and nodes and hence reduce the total power consumption at the network. Routing traffic on a set of links and nodes that are already active makes it possible for the links and nodes with no load to be switched off. Indirect Power Efficient Approach (IPEA) implements this idea by giving preference to those links with higher working load on them. IPEA takes advantage of a math series to prioritize links. In the following section properties of this math series are described.

3.3.1 Math Series Properties

IPEA uses the following math series to assign weights to the links such that the links with higher load are assigned a lower weight and the links with lower load are assigned a higher weight. Therefore, during the process of path computation the Dijkstra's path computation algorithm prefers the links with lower weights over those links with higher weights. The math series is as follows:

$$\sum_{C=0}^{L} (1/2)^{c} < 2$$

Or,

$$1/2^0 + 1/2^1 + 1/2^2 + 1/2^3 + \ldots + 1/2^L < 2$$

One major property of this series is that each element ($1/2^n$) on the left side of the inequality is bigger than the sum of all elements on its right side (i.e. $1/2^n > 1/2^{n+1} + 1/2^{n+2} + \ldots + 1/2^L$ where $n < L$), (see Appendix A for the proof). For instance, $1/2^0$ is greater than $1/2^1 + 1/2^2 + 1/2^3 + \ldots 1/2^L$; $1/2^1$ is greater than $1/2^2 + 1/2^3 + \ldots 1/2^L$. By using this property of the series in our approach, we can assure that each link with a high load is given preference over all other links with lower load levels. This series is used in the next two algorithms to find working and backup paths for a demand.

3.3.2 IPEA: Step 1 – Finding Working Path

The objective of this algorithm is to find the least-cost working path for every demand by giving preference to links with higher working load. Giving preference to the links with high loads leads to concentrating the traffic on a set of links and nodes in the network. Hence, it provides opportunity to put the nodes and links with no load on sleep mode.

At first, IPEA eliminates those links with not enough available capacity. Let W_l denote the final assigned weight to link *l*, *b* denote the number of requested wavelengths, and A_l denote the number of wavelengths available on link *l.* Therefore, if the number of requested wavelengths (*b*) of demand *r* is more than the available wavelengths A_l of link *l*, IPEA assigns *infinity* (∞) to weight of the link (W_l). Let RW_l denote the number of reserved working wavelengths on link *l.* In the next step, IPEA sorts all the remaining links based on their working load (RW_l) in ascending order of load. It assigns the first rank (i.e., rank 0), to the link with the lowest load and the next rank (i.e., rank 1), to the link with the second lowest load and so forth. Therefore, it assigns the last rank to the link with the highest load. Links with equal reserved working wavelengths would receive equal rank.

After ranking all the links, IPEA assigns the weight $½^k$ to the links with rank *k*. Once the weights are assigned, the Dijsktra algorithm is executed for the given network *G(N,L)* to find the least cost working path, where *N* is the set of nodes and *L* is the set of links in the network. The following is the pseudo code for this algorithm:

1. Get the next demand *r* that requests *b* units of bandwidth between source *s* and destination *d*.
2. Assign weights to the links as follows:
    a) $W_l = \infty$, if $b \geq A_l$ for all *l*
    b) Sort all the remaining links with available capacity for demand *r* based on their number of working wavelengths reserved RW_l in ascending order of RW_l.
    c) Rank all sorted links, the first link with the lowest RW_l receives rank 0 and so on.
    d) After ranking all the links, assign weight to each link *l* as follows:

- $W_l = \frac{1}{2^k}$ where *k* is the rank of link *l* in the ranking table

3. Execute Dijkstra algorithm for the given network *G(N,L)* and the assigned weights.
4. If no path has been found then block the demand, *else* find the backup path as described in the next section.

After finding the working path successfully, the backup path has to be computed with the proper algorithm that is explained in the next section.

3.3.3 IPEA: Step 2 – Finding Backup Path

The objective of this algorithm is to find the least-cost shared backup path while maintaining a trade-off between link-load and link capacity constraints. Shared backup protected survivable networks tend to distribute traffic evenly among the links in order to minimize data loss in case of failure. Moreover, such a network also aims at increasing shared backup resources in order to reduce the total capacity consumption at the network. However, energy-efficient networks tend to concentrate traffic on a set of nodes and links in order to make it possible to put network resources on sleep mode as much as possible and hence reducing the total power consumption at the network. Consequently, there has to be a trade-off between the two approaches in order to fulfill the constraints.

In this algorithm, one constraint is to choose those links that demand less capacity for the backup path which will lead to reduced capacity usage. The PSS introduced in section 2.1 is used as the base for this algorithm in order to increase backup capacity sharing and hence reduce capacity usage. The second constraint is to give preference to those links with higher working load in order to avoid routing traffic through the links with lower load. Therefore, it provides opportunity to put links and intermediate nodes with no load on sleep mode.

The first step in this algorithm is to compute weights of links for the first constraint with the second step (algorithm) of PSS. Let BSH_l denote the computed weight for link *l* by implementing PSS. Therefore, BSH_l holds computed weights for the first constraint. Implementation of PSS that is used for the first constraint is thoroughly explained in the section 2.1.3. As discussed in the section 2.1.3, the calculated weight of link *l* based on the first constraint (BSH_l) is assigned to infinity (∞) if *l* is along the working path of demand *r*. Otherwise, the weight is assigned to a very small number such as epsilon (ε) if demand can be restored on link l without reserving any additional backup wavelength on the link. If neither of above conditions is still not met, then the weight of link l is set with the amount of additional backup wavelength required on that link in order to restore demand r, if this additional required bandwidth is available. If the available capacity on link l is not adequate to accommodate this additional wavelength, the weight of link l is assigned to infinity (∞).

The next step is to assign weight to the links for the second constraint. Let BIE_l denote the computed weight for link l by implementing the math series property. Thus, BIE_l holds computed weights for the second constraint. Implementation of the second constraint is also explained in details in section 3.3.2.

After computing values of BSH_l and BIE_l, they have to be normalized in order to meet the trade-off between both constraints. Therefore, the first step is to find their maximum finite number for the purpose of normalizing. Since in normalizing the maximum number has to be finite and BSH_l and BIE_l may hold *infinity* value, the method used for finding maximum number has to seek the number among the finite values. In order to find the maximum finite number among BSH_l values a method which is named *max* is used to find it by comparing all the values with each other. Then, the algorithm normalizes the BSH_l values by dividing them by their maximum finite number and then stores the new values in $NBSH_l$. In the next step, the algorithm performs the same procedure for BIE_l values. At first, it uses the same method (*max*) to find the maximum finite number among BIE_l values by comparing the values with each other. Then, it normalizes the BIE_l values by dividing them by their maximum finite number and then stores the new values in $NBIE_l$. At the end, the normalized values are used to calculate the final weight of each link.

In order to achieve our goal, which is a trade-off between both constraints, we define a measure of weight for link l as shown in the equation 3.4. Let W_l denote the final assigned weight to link l, hence:

$$W_l = \alpha \times NBSH_l + (1 - \alpha) \times NBIE_l \qquad 3.4$$

In order to satisfy the trade-off between constraints α is set to (0.5) to take into account both the normalized value equally.

Finally, the Dijkstra algorithm is executed for the given network *G(N,L)* and the given link costs W_l. The path found by the Dijkstra algorithm is the least cost shared backup path. If no path was found, the algorithm will block the demand. At the end the algorithm updates the values of all system parameters for all nodes and links along with backup path. Updating parameters is thoroughly explained in section 2.1.4.

Let SW_r denote the set of links along the working path of demand *r;* T_l denote the maximum number of backup wavelengths needed on link *l* if a link on SW_r fails; B_l denote the maximum number of backup wavelengths needed on link *l*; *b* denote the number of requested wavelengths; and A_l denote the number of wavelengths available on link *l.* The following is the pseudo code for this algorithm:

1. Get the next demand *r* that requests *b* units of bandwidth between source *s* and destination *d*.
2. Compute BSH_l for every link *l* by the following rules

$$BSH_l = \begin{cases} \infty \ if\ l \in SW_r \\ \varepsilon\ elseif\ T_l \le B_l \\ T_l - B_l\ elseif\ T_l - B_l \le A_l \\ \infty\ otherwise \end{cases}$$

3. Compute BIE_l for every link *l* as follows:
   a) $BIE_l = \infty$, *if* $b \ge A_l$ for all *l*
   b) $BIE_l = \infty$ *if* $l \in SW_r$
   c) Sort all the remaining links that do not satisfy steps 3.a and 3.b based on their reserved working wavelengths RW_l in ascending order of RW_l.
   d) Rank all sorted links: the first link with the lowest RW_l receives rank 0 and so on.
   e) After ranking all the remaining links assign weight to each link *l* as follows:
      - $BIE_l = 1/2^k$ where *k* is the rank of link *l* in ranking table
4. Normalize BSH_l values for every link *l* by the following rule:
   - $NBSH_l = \frac{BSH_l}{\max(BSH_j)}\ \forall j \in L$
5. Normalize BIE_l values for every link *l* by the following rule:
   - $NBIE_l = \frac{BIE_l}{\max(BIE_j)}\ \forall j \in L$

6. Compute W_l for every link l by the following rules
    - $W_l = \infty$ *if* $NBSH_l = \infty$ or if $NBIE_l = \infty$
    - $W_l = \alpha \times NBSH_l + (1- \alpha) \times NBIE_l$ for all remaining l
8. Execute Dijsktra algorithm for network $G(N,L)$ and the given weights W_l
9. If no path has been found then block the demand, *else* update parameters

3.4 Direct Power Efficient Approach

In this section, we propose another approach, called Direct Power Efficient Approach (DPEA), which aims at dynamically routing traffic through nodes and links with high load levels. Routing traffic on nodes and links with high load levels leads to avoiding links and nodes that currently experiencing low load or no load at all. Hence, the total power consumption of the network can be reduced by putting links and nodes with no traffic on sleep mode. Similar to the IPEA, the DPEA algorithm computes a pair of paths for every new demand upon the arrival of that demand. The DPEA algorithm computes these paths for every new demand by comparing the power consumption of nodes and links in the network before the demand arrives with their potential power consumption if they are chosen along the paths of this demand.

Let $LP(l)$ denote the power consumed at the link l before the new demand arrives; and $NP(n)$ denote the power consumed at the node n before the new demand arrives. Let $\widehat{LP}(l)$ denote the potential power consumption at the link l if the new demand is accepted and routed over the link l; and $\widehat{NP}(n, l)$ denote the potential power consumption at the node n if the new demand is accepted and routed over the link l. The final weight of a link is obtained by subtracting the power consumption of the link and its nodes prior to the arrival of the new demand from the potential power consumption of the link and its nodes if the new demand is accepted and routed over the link. Let f_l denote the first node of link l and s_l denote the second node of link l. Hence the final weight of link l is:

$$W_l = (\widehat{LP}(l) - LP(l)) + (\widehat{NP}(f_l) - NP(f_l)) + (\widehat{NP}(s_l) - NP(s_l)) \qquad 3.5$$

Equation (3.1) is used to calculate the power consumption at nodes, and Equation (3.2) is used to calculate the power consumption at links. Hence $LP(l)$ and $NP(n)$ is formulated as the following:

$$LP(l) = E_l \times ((\frac{D_l}{80}) + 2) \qquad 3.6$$

$$NP(n) = F_n + (K_{nt} \times E_{nt}) + (K_{nr} \times E_{nr}) + (K_{ns} \times E_{ns}) \qquad 3.7$$

where E_l is set to zero if number of reserved working wavelengths (RW_l) is zero; and F_n is assigned to zero when the node is inactive (i.e. does not carry traffic or when K_{nt}, K_{nr}, and K_{ns} are all zero).

The values of E_l , F_n , K_{nt} , K_{nr} , and K_{ns} will change upon the condition that the new demand is accepted and routed over the link *l*. Hence, if $\widehat{E_l}$, $\widehat{F_n}$, $\widehat{K_{nt}}$, $\widehat{K_{nr}}$, and $\widehat{K_{ns}}$ holds the new values based on the condition, $\widehat{LP}(l)$, and $\widehat{NP}(n, l)$ are calculated by the following formulation:

$$\widehat{LP}(l) = \widehat{E_l} \times ((\frac{D_l}{80}) + 2) \qquad 3.8$$

$$\widehat{NP}(n, l) = \widehat{F_n} + (\widehat{K_{nt}} \times E_{nt}) + (\widehat{K_{nr}} \times E_{nr}) + (\widehat{K_{ns}} \times E_{ns}) \qquad 3.9$$

However, the value of $\widehat{E_l}$, and $\widehat{F_n}$ will never be zero due to the assumption that the link or the node will be along the computed path of the new demand. Hence, the calculated weight of the link (W_l) will be a large number if the link or any of its nodes were inactive prior to the arrival of the new demand. Consequently, since in the execution of the Dijkstra algorithm the preference is given to the links with low weights, it will be fairly unlikely that inactive links and nodes are chosen along the computed path.

The DPEA has two steps: in step 1, a working path is found, and then in step 2 a backup path is found.

3.4.1 DPEA: Step 1 - Finding Working Path

The objective of this algorithm is to find the least cost working paths. This algorithm dynamically compares the power consumed by the nodes and links prior to the arrival of the new demand with their potential power consumption if they are chosen along the working path of this demand. The difference in power consumed by the nodes and links between the two situations is used as the weight of the link.

Let W_l denote the final weight of a link. At first, DPEA eliminates those links with not enough available capacity. Therefore, if the number of requested wavelengths (b) of demand r is more than the available wavelengths A_l at link l, DPEA assigns *infinity* (∞) to weight of the link (W_l). Otherwise, the final weight of link l is calculated by the Equation (3.5) which was described in the previous section. Finally, the Dijkstra algorithm is executed with the given network *G(N,L)*, and the link weights W_l. Let f_l denote the first node of link l and s_l denote the second node of link l. The following is the pseudo code for this algorithm:

1. Get the next demand r that requests b units of bandwidth between source s and destination d.
2. Assign weights to the links as follows:

$$W_l = \begin{cases} \infty \; if \; b \geq A_l \quad \forall \, l \in L \\ (\widehat{LP}(l) - LP(l)) + (\widehat{NP}(f_l) - NP(f_l)) + (\widehat{NP}(s_l) - NP(s_l)) \;\; otherwise \end{cases}$$

3. Execute Dijkstra algorithm for network *G(N,L)* and the given links weights.
4. If no path has been found then block the demand *else* find the backup path as described next

After finding working path successfully, the backup path has to be computed with the proper algorithm that it is explained in the next section.

3.4.2 DPEA: Step 2 - Finding Backup Path

The objective of this algorithm is to find the least-cost shared backup paths while maintaining a trade-off between two constraints. One constraint is to choose backup links that require less (or no) new backup capacity for the backup path which will lead to capacity usage reduction. The PSS method described in section 2.1.3 is used in this algorithm in order to implement the first constraint. The second constraint is to give preference to high load links and nodes in order to increase the number of inactive nodes and links and hence reducing the total power consumption at the network. The method of computing the weight of links for the second constraint was thoroughly described in section 3.4.

Similar to section 3.3.3, the first step in this algorithm is to compute weight of the links with respect to reducing capacity usage of the network. Let BSH_l denote the computed weight of link l by the goal of reducing shared backup capacity. The next step is to assign weight to the links for the second constraint. Let BDE_l denote the computed weight for link l by the power differential method described in section 3.4.

After computing values of BSH_l and BDE_l, they have to be normalized in order to meet the trade-off between both constraints. The method of normalizing the values is also described in section 3.3.3. Let $NBSH_l$ denote the normalized value of BSH_l ; and $NBDE_l$ denote the normalized value of BDE_l. The normalized values are used to calculate the final weight of each link.

In order to maintain a trade-off between both constraints, we define a measure of weight for link l as shown in the Equation 3.10. In this Equation α is set to (0.5) in order to satisfy the trade-off between the constraints equally. Let W_l denote the final assigned weight to link l, hence:

$$W_l = \alpha \times NBSH_l + (1 - \alpha) \times NBDE_l \qquad 3.10$$

Finally, the Dijkstra algorithm is executed for the given network $G(N,L)$ and the given link weights W_l. If the Dijkstra algorithm is unable to find a backup path, the algorithm will block the demand. At the end, the algorithm updates the values of all system parameters for all nodes and links along with backup path including the power consumption at the nodes and links after successfully accepting the new demand.

Let SW_r denote the set of links along the working path of demand r; T_l denote the maximum number of backup wavelengths needed on link l if a link on SW_r fails; B_l denote the maximum number of backup wavelengths needed on link l; b denote the number of requested wavelengths; and A_l denote the number of wavelengths available on link l. Let f_l denote the first node of link l and s_l denote the second node of link l. The following is the pseudo code for this algorithm:

1. Get the next demand r that requests for b units of bandwidth between source s and destination d.
2. Compute BSH_l for every link l by the following rules

$$BSH_l = \begin{cases} \infty \ if \ l \in SW_r \\ \varepsilon \ elseif \ T_l \le B_l \\ T_l - B_l \ elseif \ T_l - B_l \le A_l \\ \infty \ otherwise \end{cases}$$

3. Compute BDE_l for every link l by the following rules:

$$BDE_l = \begin{cases} \infty \ if \ b \geq A_l \quad \forall \ l \in L \\ (\widehat{LP}(l) - LP(l)) + (\widehat{NP}(f_l) - NP(f_l)) + (\widehat{NP}(s_l) - NP(s_l)) \ \ otherwise \end{cases}$$

4. Normalize BSH_l values for every link l by the following rules
   - $NBSH_l = \frac{BSH_l}{\max(BSH_j)} \ \forall \ j \in L$
7. Normalize BDE_l values for every link l by the following rules
   - $NBDE_l = \frac{BDE_l}{\max(BDE_j)} \ \forall \ j \in L$
5. Compute W_l for every link l by the following rules
   a) $W_l = \infty$ *if* $NBSH_l = \infty$ or $NBDE_l = \infty$
   b) $W_l = \alpha \times NBSH_l + (1 - \alpha) \times NBDE_l$ for all remaining l
6. Execute Dijkstra algorithm for network *G(N,L)* and the given weights W_l
7. If no path has been found then block the demand *else* update parameters

3.5 Summary

In this chapter, we first presented the network model which consists of a set of WDM nodes and fiber links with amplifiers. Then, we discussed the power model for nodes and links in the WDM network. The total power consumption of a WDM node is the sum of a fixed power and a proportional power. The proportional power is dependent on the traffic load. The power consumption of a link is modeled as the power consumed by the total number of amplifiers along the link. The power model is used to calculate the total power consumption of the WDM network.

Moreover, two approaches were proposed that aim at reducing power consumption of a network. The first approach is called, Indirect Power Efficient Approach (IPEA), which routes the traffic through the network in order to decrease the number of lightly-loaded links and nodes and hence reduce the total power consumption at the network. Routing traffic on links and nodes with high load levels makes it possible for the links and nodes with no load to be switched off. IPEA deploys the property of a math series in order to concentrate traffic on the nodes and links with high load levels. Direct Power Efficient Approach (DPEA) is the second proposed approach. DPEA attempts to route the traffic through nodes and links with high load levels dynamically. Therefore, this will lead to a set of nodes and links with no load and hence reducing the power consumption at the network. For every newly arrived demand, DPEA computes a pair of working and backup paths similar to IPEA. However, the DPEA algorithm compares the power consumption of nodes and links in the network before the demand arrives with their potential power consumption if they are chosen along the paths of this demand.

Chapter 4 Simulation Setup and Analysis

In this chapter we simulate the approaches proposed in the previous chapter as well as the benchmark approach in order to evaluate and compare their performance. We use two different networks in order to evaluate the performance of all the approaches. The rest of this chapter is organized as follows. In section 4.1, we will explain the simulation development used in this thesis. In section 4.2, the structure of networks used for simulation and details of metrics for analysis will be discussed. Section 4.3 presents confidence interval and how to calculate sample size for a particular population. The proposed approaches along with the benchmark approach are compared in section 4.4 and their performances are evaluated. Eventually, section 4.5 summaries this chapter.

4.1 Simulation Setup

The simulation program has been developed in Java 6 with the following structures. It contains seven classes, including the classes: `Network`, `DemandGenerator`, `Demand`, `Link`, `Node`, `Path`, and `Dijkstra`. Each class is described separately in the following paragraphs.

Network class is the main class in our program. The network contains a set of data structures to hold nodes and links. It also incorporates functions used to find the working and backup paths for each demand. During the initialization stage of the `Network` object, information about nodes and links is imported into the program from an excel file. This information includes nodes' names and their population sizes as well as link capacities and their lengths. Each link is defined by two nodes and is bidirectional.

After importing nodes and links into the program, the populations of nodes are used to calculate traffic demands for each node. H. Naser *et al.* in [42] propose an approach to simulate the traffic in the network. The proposed approach generates traffic for each node according to their populations. Let V_i denote the population of node i, and G_i denote the total traffic in Gigabits/second generated at this node, and x be a positive integer. The following relation is assumed between V_i, G_i and x:

$$\forall\ i : G_i = \frac{x * Vi}{10^6} \qquad 4.1$$

This formula generates x Gbps for every one million people. Hence, increasing the parameter x intensifies the generated amount of traffic for the node i in terms of Gbps. The portion of G_i being destined to an arbitrary node j is then obtained based on the population of node j and the overall population of all nodes in the network. If we denote g_{ij} the amount of traffic generated at i and terminated at j, g_{ij} is obtained as:

$$\forall j \neq i : g_{ij} = G_i \frac{Vj}{\sum_n Vn} \qquad 4.2$$

From these two formulas it is proven that the traffic generated between any nodes i and j is symmetric $g_{ij} = g_{ji}$. In the analysis and simulation presented in this thesis, we normalized each element g_{ij} to the bandwidth required by and *OC192* channel (i.e. 10 Gbps). If we denote D_{ij} the number of *OC192* demands between nodes i and j, D_{ij} is derived as:

$$\forall i,j,(j \neq i): D_{ij} = \left\lceil \frac{gij}{10} \right\rceil \qquad 4.3$$

D_{ij} is used to generate the total demand matrix which includes all the possible demands between all nodes. Some nodes in the network are used only for the purpose of switching traffic. Hence, their population is counted as zero and as a result their generated traffic is zero. After calculating demand matrix, `DemandGenerator` class is called to find the working and backup paths for each of the demands on the demand matrix. All the demands in demand matrix are processed one after the other. Therefore, in our simulation it is assumed that if a link or a node has no working load reserved on them at the end of simulation, they can be put on sleep mode. Hence, in this thesis network devices do not switched to active mode.

The last part of the `Network` class is to calculate power consumption of the network after simulation is complete and all demands have been processed. Equations (3.1), (3.2), and (3.3) are used to calculate total power consumption of the network.

Class `Demand` is used to create a *demand* object. Each *demand* object includes a *source* node and a *destination* node which are both of the type `Node` objects, *demandSize* which is set to 1 wavelength (equal to 10 Gigabit/sec); and *workingPath*, and *backupPath* structures which are both of the type `Path` object.

Class `Path` is used to create a *path* object. Each *path* object has a node as the source, a node as the destination and a set of nodes as intermediate nodes. It also stores the value of calculated distance.

Class `Node` is used to create a *node* object. Each *node* object has the following characteristics: total traffic generated in Gbps and in the number of wavelengths, population, number of generated wavelengths, number of terminated wavelengths, number of passing wavelengths, number of links terminated at the node, and a list of existing demands between that node and the other nodes. Another characteristic of the node is to define whether it is an intermediate node or not.

Class `Link` is used to create a *link* object. Each *link* object has two terminating end nodes. Each link has the following characteristics: length of the link in kilometers, capacity of the link, number of reserved working wavelengths, total number of reserved working and backup wavelengths, and available capacity on that link.

Class `Dijkstra` is used to find the shortest distance between any source and destination with the given links' weights. The links' weights are calculated in `DemandGenerator` class where actually Dijsktra is called to find the shortest path.

The last class is the `DemandGenerator` class. The proposed algorithms for finding working and backup paths are implemented in this class. In each iteration, first a source node is chosen randomly. After choosing the source, a destination node is chosen. By having the source and destination nodes and a demand size of 1 wavelength, a demand is generated. At this point, one of the proposed methods is called to find the working path for the given demand. If a working path is not found, the demand will be blocked; otherwise the method for finding backup path is called. If a backup path is not found, the demand will be blocked, as well.

After computing working and backup paths for the demand, the parameters of the nodes and links are updated as follows: for each node along the computed path, the demand size is added to the node's current number of passing through wavelengths attribute. For the source node, the demand size is added to its number of generated demand wavelengths attribute. For the destination node, the demand size is added to its number of terminated demand wavelengths attribute. After updating the node's parameters, the link's parameters are updated. For each link along the working path, the demand size is added to its current number of working reserved wavelengths as well as the number of total working and backup reserved capacity, and it is deducted from the available reserved capacity on the link. Finally, the parameters in regard of the computed backup path are updated according to the weight of each link previously assigned by the Pool Sharing Scheme. If the link can accommodate the new demand without reserving any capacity, the number of total reserved working and backup capacity attribute of the link remains unchanged. Otherwise, the demand size will be added to the number of working and backup capacity attribute since the demand size is always one in this thesis. Again, in the next iteration all the above steps are executed for the next demand. This continues until no more demands in the demand matrix are left.

4.2 Simulated Networks and Analysis

Two different networks are used in this thesis in order to simulate the proposed approaches. National Science Foundation (NSF) is one of the networks with 16 nodes and 25 links [42]. The other network is the Northern American BT-Global with 35 nodes and 74 links [43]. Table 4.1 shows the detail characteristics of both networks. All the experiments have been run on both networks. These networks have been chosen for the purpose of testing the approaches on a relatively moderate size network such as NSF and a large size network such as BT-Global. Figure 4.1 and Figure 4.2 illustrate NSF network and BT-Global network topologies, respectively.

We have simulated IPEA and DPEA, which aim at reducing power consumption of the whole network while providing shared backup path for each demand. Shared backup protec-

Table 4.1 Network Characteristics

Name of the Network	**Nodes**	**Links**	**Nodal degree**	**Links Distance Range**	**Links Capacity Range**
NSF	16	25	1.56	372km – 1860 km	32 λ – 128 λ
BT-Global	35	74	2.11	18km – 4524km	32 λ – 256 λ

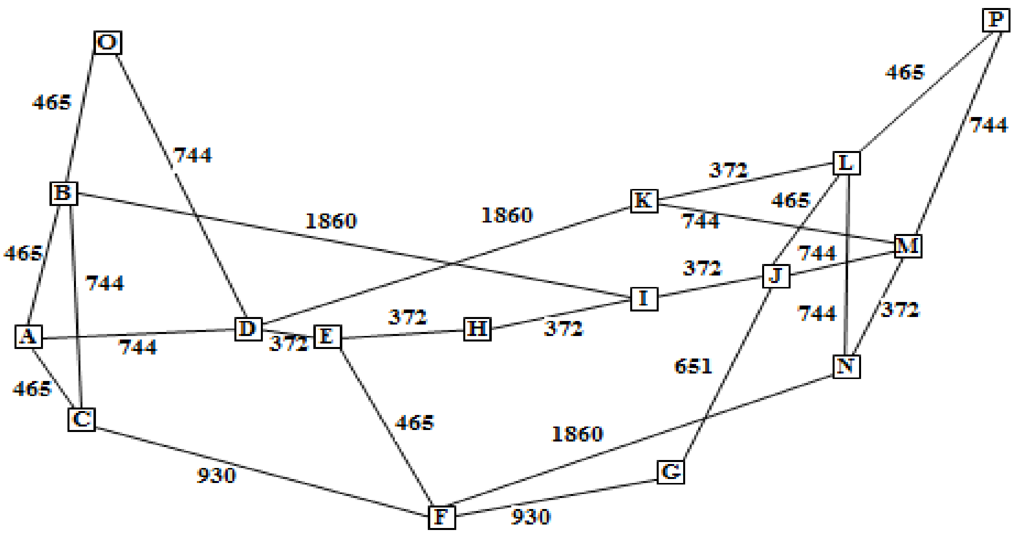

Figure 4.1 NSF network topology with link distance in kilometer.

-tion leads to reducing capacity consumption of the whole network. For the purpose of benchmarking, we have also simulated PSS which finds working and backup paths without taking into account power consumption of the network equipment.

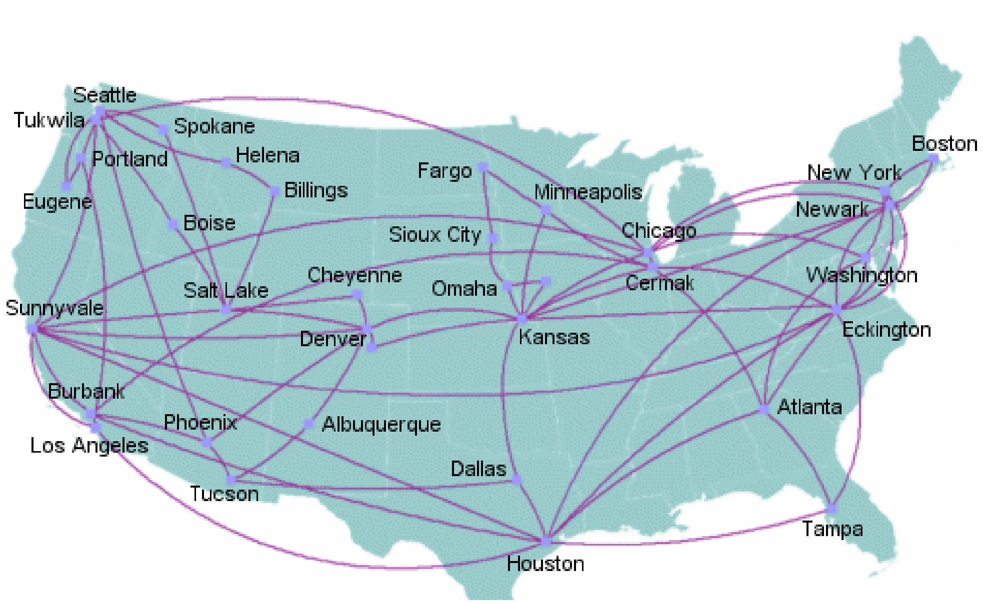

Figure 4.2 BT-Global network topology.

We had run each simulation 400 times in order to achieve a reasonable confidence interval in the results. As nodes are chosen randomly, the results of each simulation experiment may vary from other experiments slightly. In each experiment the seed for the random number generator is changed in order to ensure different results. Hence, for 400 different runs, 400 different seeds are used and as a result 400 different set of results are generated. This was done when all the three algorithms (PSS, IPEA, DPEA) were executed.

In our simulations, we designed and measured the following metrics to evaluate the performance of the above three algorithms. Let *TRW* denote to the total number of working wavelengths used in the network, hence:

$$TRW = \sum_{1}^{L} RW_l \qquad 4.4$$

Let R_l denote the total number of reserved wavelength on link l, and *TR* denote to the total number of working and backup wavelengths used in the network, hence:

$$TR = \sum_{1}^{L} R_l \qquad 4.5$$

Let PL_l be the "load" on link *l*, which is defined as the ratio of the total reserved working and backup wavelengths of the link *l* (R_l) and the capacity of the link (C_l), hence:

$$PL_l = \frac{R_l}{C_l} \qquad 4.6$$

Let $\overline{PL_l}$ be the average link load averaged over all links in the network, that is:

$$\overline{PL_l} = \frac{\sum_{1}^{L} PL_l}{L} \qquad 4.7$$

Let *TGD* denote the total number of generated demands and *TBD* denote the total number of blocked demands. Let *RB* denote the ratio of the total number of blocked demands over the total number of generated demands, hence:

$$RB = \frac{TBD}{TGD} \qquad 4.8$$

Let *LONS* denote the number of links on sleep mode and *NONS* denote the number of nodes on sleep mode. All the above metrics from (4.4) to (4.8), together with the total power consumption at the network (equation 3.3), *TGD*, and *TBD* are used for comparing the proposed algorithms IPEA, and DPEA with the benchmark algorithm PSS.

4.3 Confidence Level and Confidence Interval

In research, it is frequent to find situations where samples of the phenomenon under study must be collected in order to understand its properties. The amount of samples depends on the size of the population and the level of reliability the researcher wants to attain with the study. A population for statistical purposes is the total available entities which represent a phenomenon or contain a property under study. By selecting the appropriate amount of samples, the researcher ensures that enough information is collected from the population to incorporate most of the variables of the property under study. When this statistical process is performed, a Confidence Interval (CI) is set, which is a range of values for the property under study, among which the real value of the property for the whole population is estimated to be found. To indicate the probability that the true value of the property under study is within the confidence interval, a Confidence Level (CL) is defined. The CL is set by the researcher; typical values for it are 90%, 95% and 99%. Based on the CL, the desired size of the CI and the size of the population, the required amount of samples is calculated. The values of the confidence interval are a result of the sampling process.

In this thesis the confidence level is set to 95% and confidence interval is set to 10%. The population parameter in this thesis is dependent on the number of nodes and the total number of generated demands. In the worst-case scenario, for any incoming demand, there are N possible source nodes and (N-1) possible destination nodes, where N is the number of nodes in the network. Let TGD denote the total generated demand in the network. Hence, in the worst case scenario, the total population will be much greater than a hundred thousand (>>100000), which is:

$$(N \times (N-1))^{TGD}$$

Now that we have calculated the total population, we can estimate the sample size for the experiments. L. M. Rea *et al.* in [44] discuss how to calculate sample size for the particular population. A sample size table based on confidence level, confidence interval, and population size is introduced by IEEE in [45] . Since the population calculated in this thesis is greater than 100000 the proper sample size is 400 based on the table in [45].

4.4 Performance Evaluations

In this section, we evaluate the performance of the two algorithms proposed in this thesis and compare them with the PSS algorithm. As described in section 4.2, our performance metrics are: the total power consumption at the network, the ratio of blocked demands, the total number of working wavelengths, the total number of working and backup wavelengths, average link load, number of links and nodes on sleep mode. As discussed in section 4.3, we ran each simulation scenario 400 times, and then computed the average values of the above metrics over all simulation runs.

4.4.1 Power Consumption

Figure 4.3 presents the power consumption at the NSF network for different numbers of generated demands. The horizontal axis represents the total number of generated demands and the vertical axis represents the total power consumption of NSF network. As indicated in Figure 4.3, the total power consumption as a function of generated demands (*TGD)*. Figure 4.3 also shows that DPEA outperforms IPEA marginally in terms of power consumption. Moreover, both DPEA and IPEA outperform PSS significantly. Dividing the power consumption of the DPEA algorithm over the power consumption of the PSS algorithm and subtracting it from 1 yields the fraction of power saving. Hence, in the NSF network power savings can reach up to 24% in the overall power consumption.

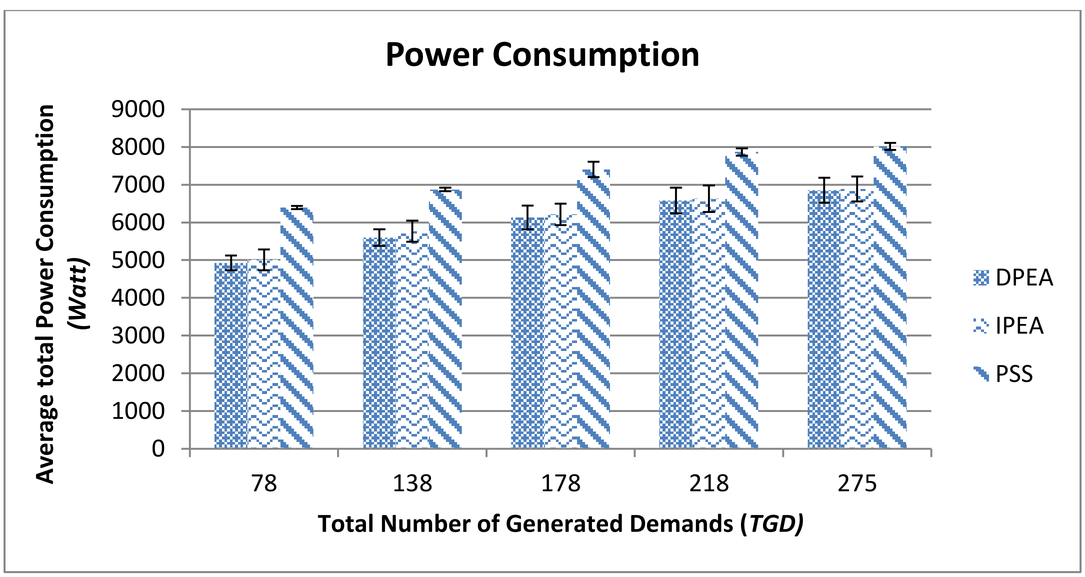

Figure 4.3 Total power consumption of NSF network.

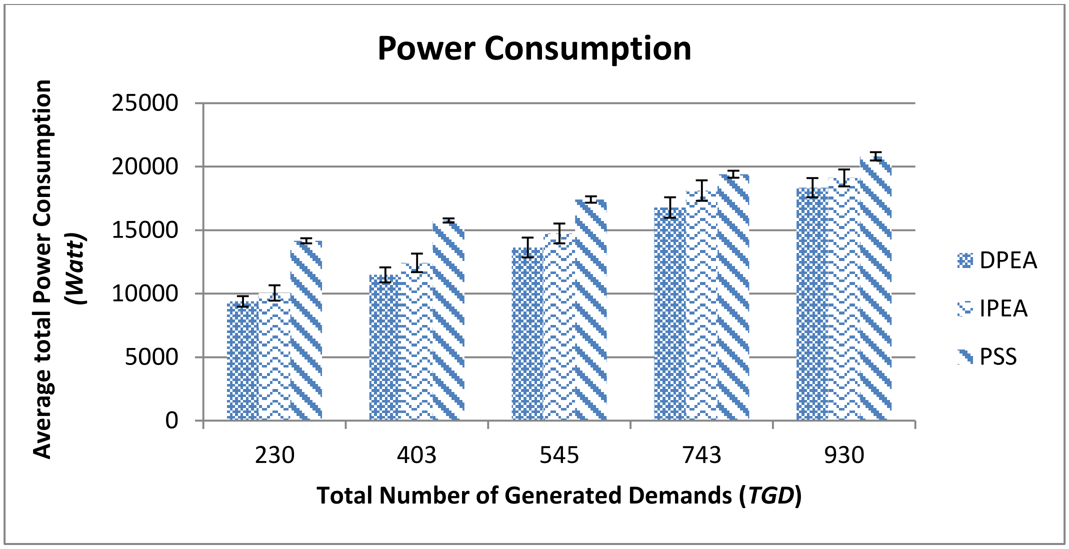

Figure 4.4 Total power consumption of the BT-Global network.

Figure 4.4 illustrates the power consumption at the BT-Global network for as the function of the number of generated demands. BT-Global is a relatively larger network than NSF; hence, it can accommodate more demands than the NSF network. Similar trends can be observed for the total power consumption in the BT-Global network as those observed in the NSF network. DPEA outperforms IPEA marginally and both DPEA and IPEA outperform PSS significantly. The power savings in the BT-Global network can reach up to 35% in the overall power consumption which is the smaller fraction of the power consumption of DPEA algorithm over the PSS algorithm for low load level, *(TGD = 230)*. However, this value is 24% in the NSF network. The reason is because the link-to-node ratio of BT-Global network is 2.11 while this is 1.56 for the NSF network. Therefore, there is an increased number of links for each node in the BT-Global compared to the NSF network. This provides more opportunity to switch off nodes and links, consequently reducing the total power consumption.

Furthermore, it is shown in both Figure 4.3 and Figure 4.4 that power-saving with respect to the PSS algorithm is decreasing considerably by increasing the number of demands in a network. Increasing the number of demands (or network load) in the network leads to more utilization of nodes and links. Hence, there will be less opportunity to switch off nodes and links, consequently reducing the total power consumption.

4.4.2 Blocked Demands

The next factor that has to be considered is the fraction of demands blocked. A demand is blocked when the path computation algorithm fails to find a working or backup path for the demand. Figure 4.5 illustrates the fraction of demands blocked as a function of the total generated demands in the NSF network. As can be seen, the ratio of blocked demands increases as a function of generated demands. At lower load levels (*TGD*=78) and (*TGD*=138), IPEA and PSS behave similarly with approximately zero blocked demands. However, DPEA results in slightly more blocked demands than PSS and IPEA.

Figure 4.6 demonstrates the fraction of demands blocked as a function of the total number of generated demands in the BT-Global network. For all the algorithms as the total number of generated demands is increasing the ration of blocked demands also increases. The behaviour of all the algorithms on BT-Global network is similar to NSF. At lower load levels (*TGD*=230), (*TGD*=403), and (*TGD*=545), IPEA and PSS behave similarly with approximately zero blocked demands. However, DPEA results in slightly more blocked demands than PSS and IPEA.

At higher loads, as expected, PSS outperforms IPEA and DPEA in the both networks. The reason is that DPEA and IPEA tend to concentrate network load on nodes and links with high load levels. Hence, when network load is considerably high, some links become congested. Therefore, there will be a few less number of links available in order to compute a working or backup path for the newly arrived demand. In this situation, it is likely that al-

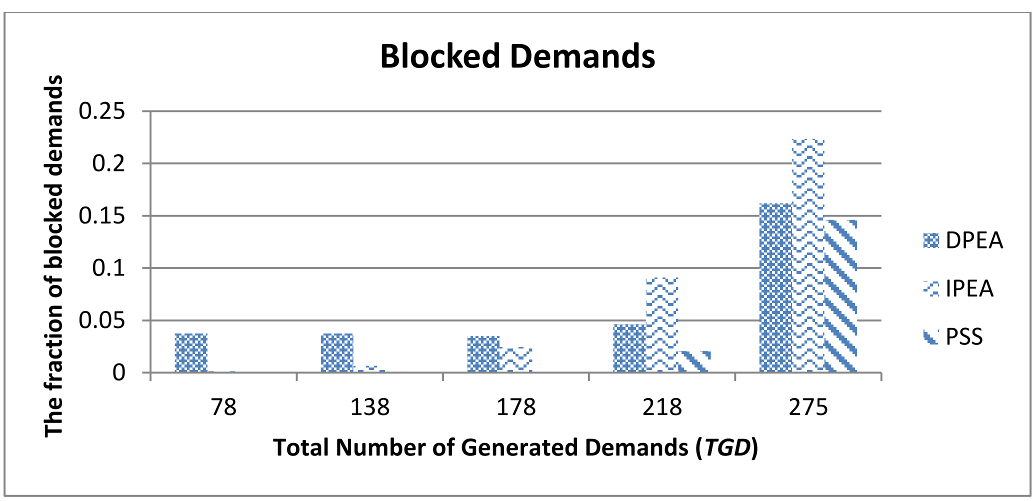

Figure 4.5 Total number of blocked demands in NSF network.

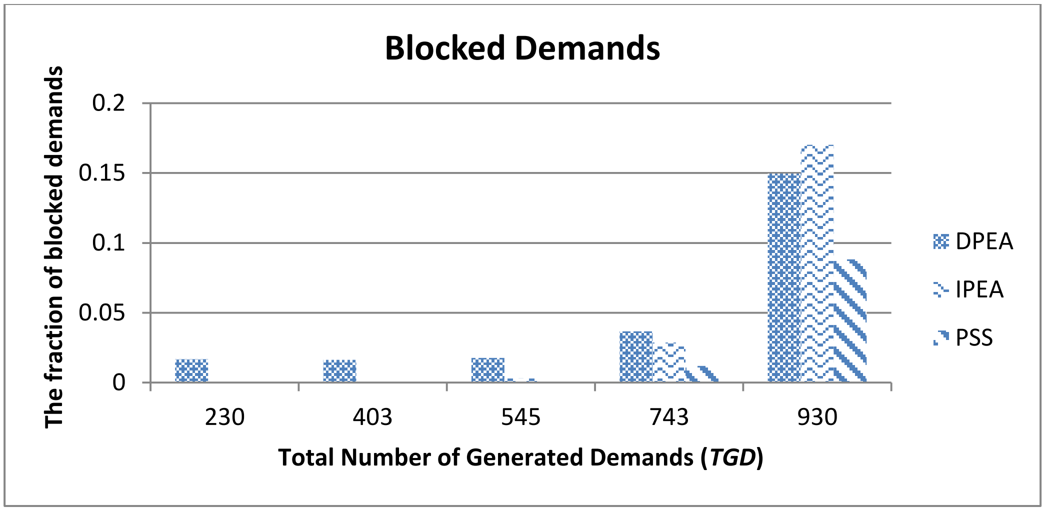

Figure 4.6 Total number of blocked demands in BT-Global network.

-gorithms fail to find a working or backup path for a demand and therefore block the demand. This is also the reason that at higher load level, IPEA blocks more demands than DPEA while for lower loads it is vice versa.

4.4.3 Links Load

A Link load is derived from proportion of load to the capacity of the link as described in section 4.2. Links capacities vary according to the topology of the network. Some links might have substantially more capacity than the others, particularly the links that terminate at nodes (cities) with large population and hence high generated demands. Generating more

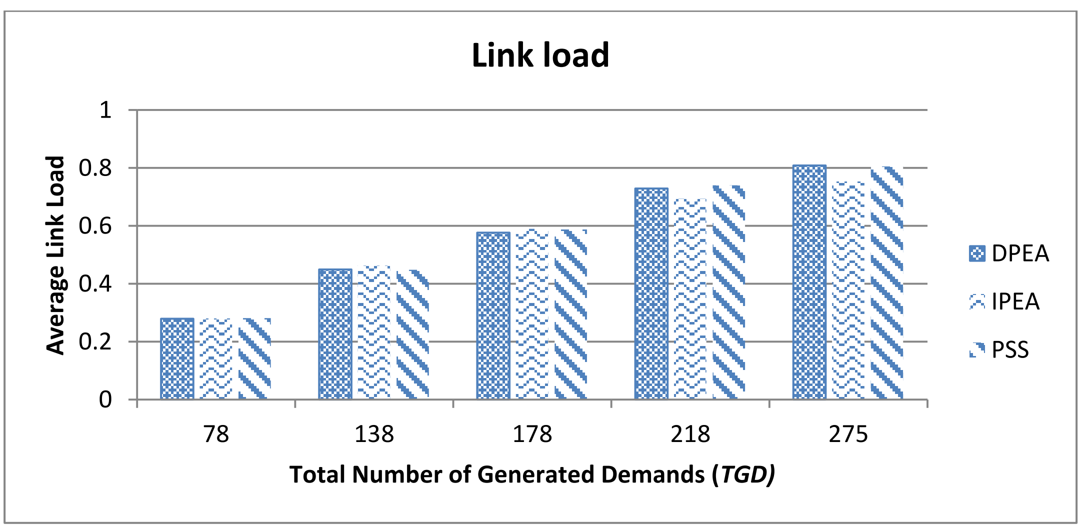

Figure 4.7 Average link load for NSF network.

demands requires high capacity links to support that. Therefore, a link load is dependent on the network topology to some extent. Consequently, simulation results may slightly vary on different networks due to dissimilar topologies.

To provide better insight into link load, Figure 4.7 and Figure 4.8 show the average link load for the NSF and the BT-Global networks, respectively. Similar to other diagrams when the total number of generated demands (*TGD)* increases, the average link load also increases.

In the NSF network, all the algorithms behave similarly in low and moderate loads (*TGD*=78), (*TGD*=138), and (*TGD*=178). At higher loads, IPEA slightly outperforms DPEA and PSS. This is due to the considerably more number of blocked demands in IPEA. Therefore, by taking into account the number of blocked demands, PSS tends to distribute traffic more evenly among links compared to than DPEA and IPEA.

In the BT-Global network, at low and moderate loads, (*TGD*=230), (*TGD*=403), and (*TGD*=545), DPEA and PSS behave similarly while IPEA outperforms them slightly. At higher loads, PSS outperforms IPEA and DPEA.

Overall, at low and moderate loads in both the networks, all the algorithms behave similarly. However, at high loads, links are becoming congested. Hence, algorithms have no choice except utilizing the links that have available capacity left. For instance, IPEA and DPEA tend to concentrate traffic on a certain set of links and nodes which results in more

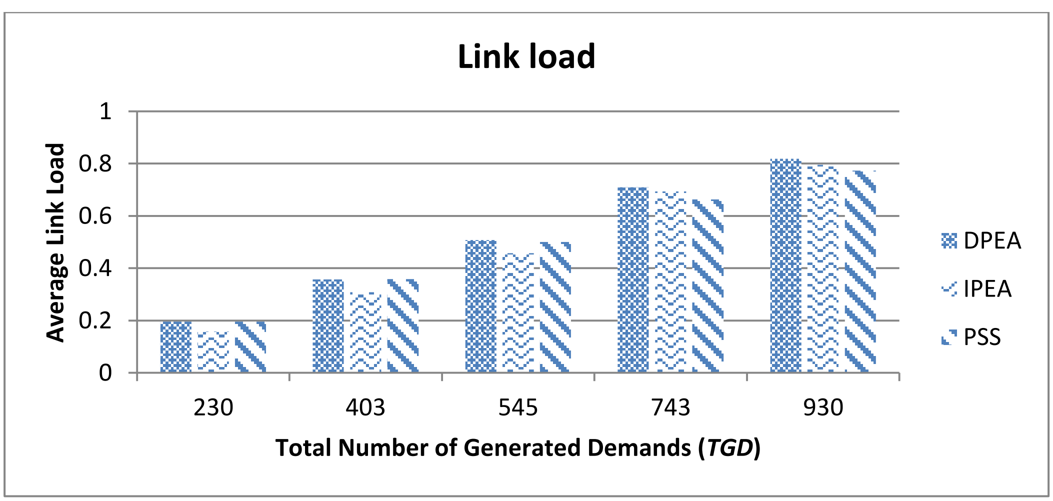

Figure 4.8 Average link load for BT-Global network.

blocked demands. Therefore, they process less number of demands than PSS and consequently less link loads. Furthermore, the slight difference in the performance of the algorithms in the two networks is due to the dissimilarity of their topologies and links capacities.

4.4.4 Total Reserved Wavelengths

In order to provide better insight into the capacity consumption of the proposed algorithms, the total capacity consumption (in terms of the number of wavelengths used) at the NSF and the BT-Global networks are illustrated in Figure 4.9, and Figure 4.10, respectively. At both networks and all the algorithms, when the total number of generated demands (*TGD*) increases, the capacity consumption also increases. As introduced in Section 4.2, capacity consumption is the sum of all the working and backup wavelengths reserved on each link. Therefore, lower amount of the total number of reserved capacity (*TR*) indicates better performance of an algorithm.

In the NSF network, for (*TGD*=78), (*TGD*=138), and (*TGD*=178) PSS and DPEA behave similarly and slightly outperform IPEA. At higher load levels, according to Figure 4.9 IPEA shows better performance, however, IPEA results in high ratio of blocked demands which indicates that IPEA processed less number of demands than DPEA and PSS. In the BT-Global network, according to Figure 4.10, PSS outperforms DPEA and IPEA slightly for

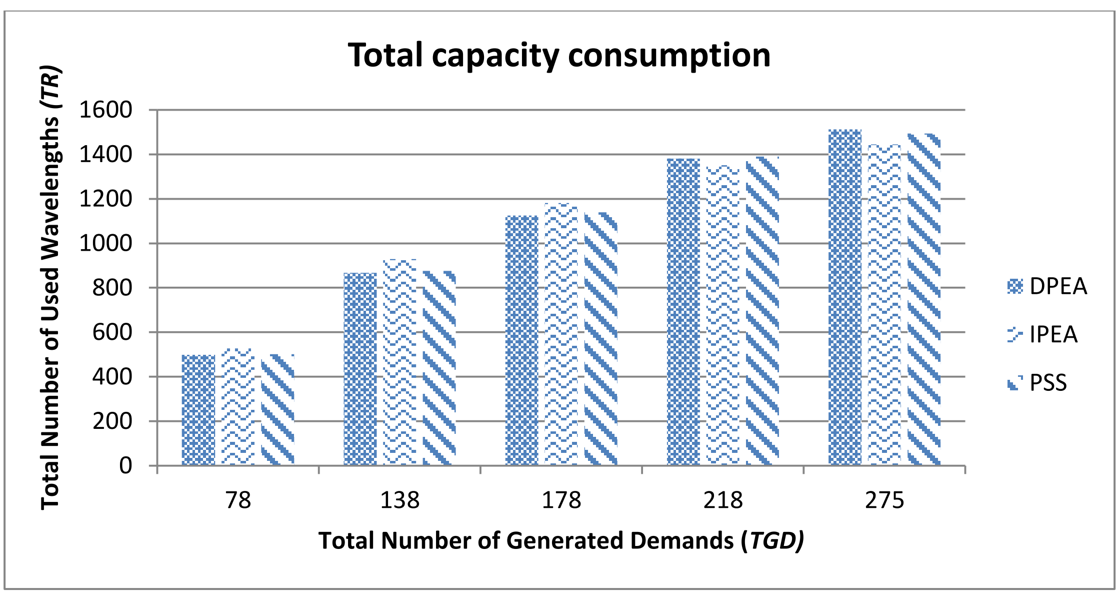

Figure 4.9 Total capacity consumption of NSF network.

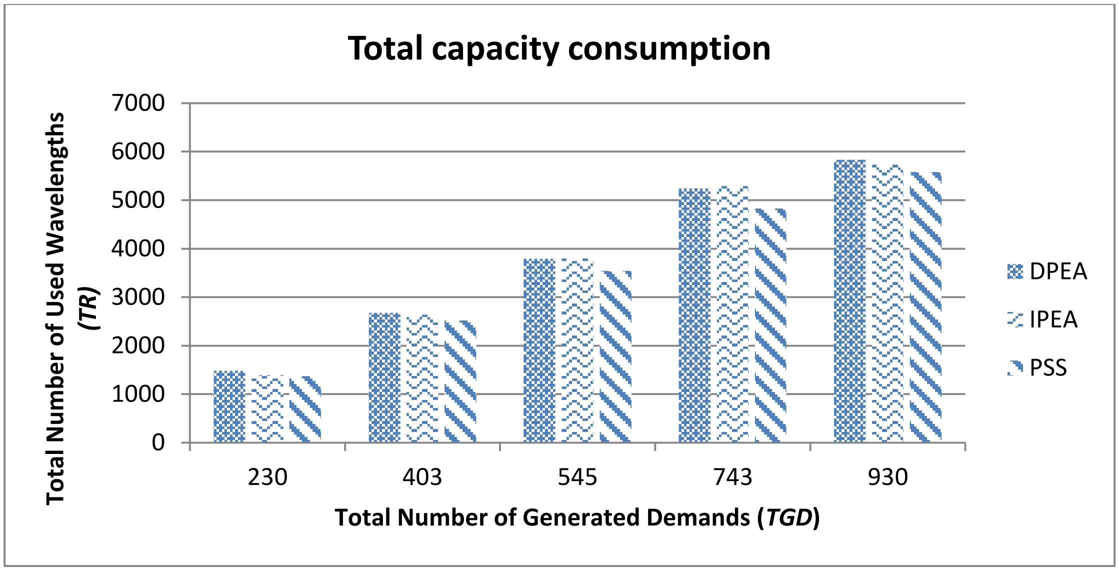

Figure 4.10 Total capacity consumption of BT-Global network.

any given *TGD*.

In conclusion, at low load levels, PSS outperforms DPEA and IPEA slightly in the both networks.

4.4.5 Links on Sleep Mode

One way to reduce power consumption in WDM networks is to put links on sleep mode. The power consumption of each link is dependent on the length of the link and whether or not it is underutilized. Since the length of each link is fixed, the only way to reduce power consumption at a link is by preventing traffic to traverse the link. In any network topologies, there are a number of links that are used for the purpose of protection. Furthermore, networks are designed in a way that they are able to operate at high traffic load. Hence, there is an opportunity to put some links on sleep mode when traffic load is low. This is feasible by routing traffic through the links with higher demand requests on them. Thus, this way of routing results in some links with no load on them.

Figure 4.11 and Figure 4.12 demonstrate the number of links on sleep mode for each algorithm in the NSF and BT-Global networks, respectively. Clearly, the number of links on sleep mode is decreased by increasing the traffic load. In the both networks, IPEA and DPEA outperform PSS significantly. This is due to the routing procedure of IPEA and DPEA. They tend to concentrate traffic on a set of links, while PSS scatters traffic among

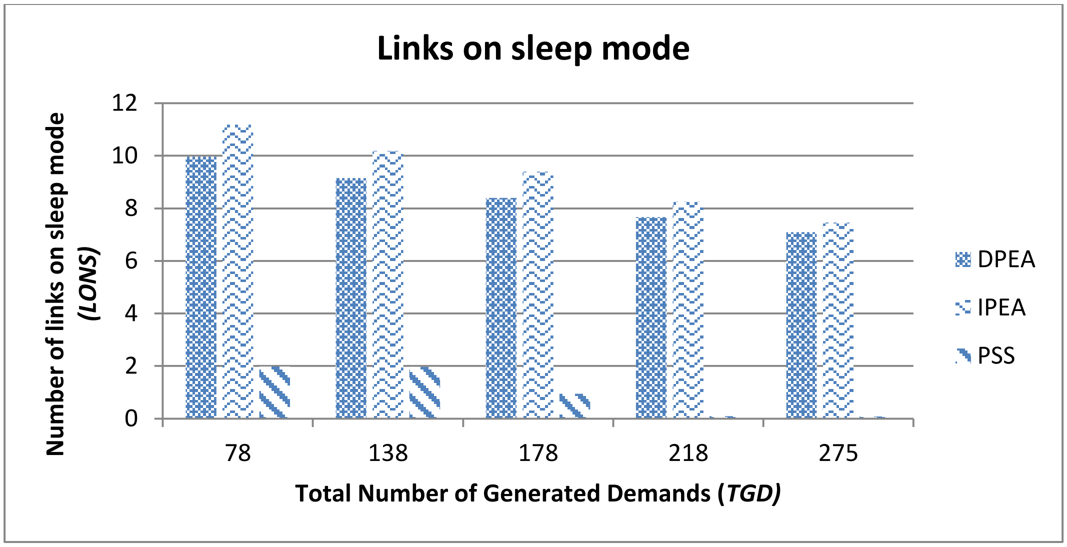

Figure 4.11 Number of links on sleep mode in NSF network.

the links on minimum-hop basis. Hence, IPEA and DPEA result in more links on sleep mode.

Moreover, in both networks, IPEA outperforms DPEA slightly while DPEA results in more power saving than IPEA. Since they perform similarly in terms of the number of nodes on sleep mode as will be shown in section 4.4.6, this means that DPEA put links with longer length on sleep modes as opposed to IPEA. According to the power model of links in Section 4.2, the power consumption at the link only depends on the number of amplifiers al-

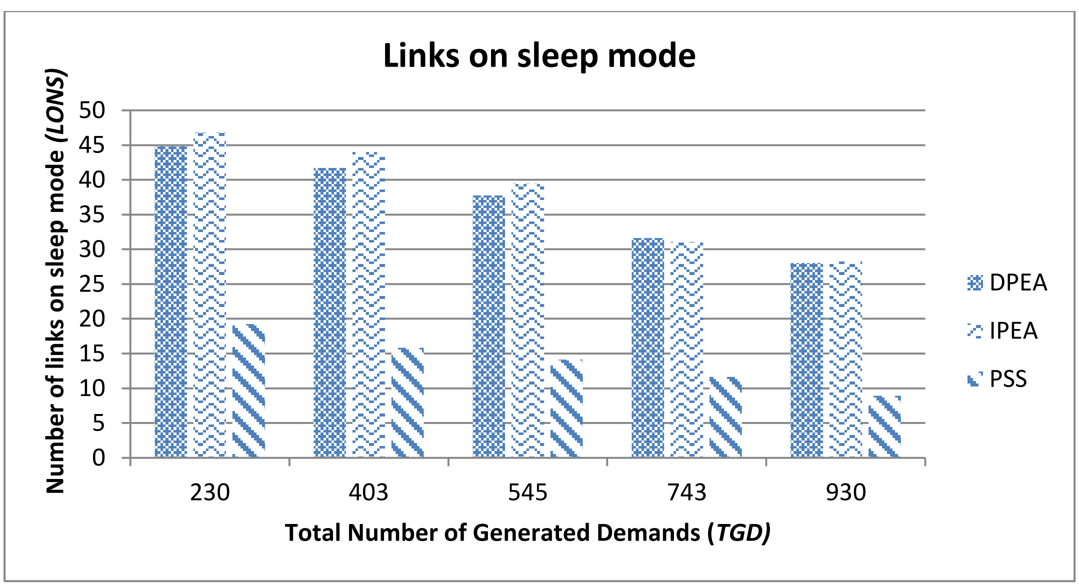

Figure 4.12 Number of links on sleep mode in BT-Global network.

-ong the link. Furthermore, links with longer length require more number of amplifiers than short links. Hence, they consume additional power due to the extra number of amplifiers. Consequently, having more number of links on sleep mode does not necessarily mean reducing more power consumption as opposed to put less number of links with longer lengths on sleep mode.

In the NSF network, PSS results in approximately zero number of links on sleep mode when traffic load is high, (*TGD*=218), (*TGD*=275). Indeed, since PSS spreads traffic through the links on minimum-hop basis, almost all the links become traversed in high traffic load. However, in the BT-Global network, PSS results in a number of links on sleep mode even at high load, (*TGD*=218), (*TGD*=275). Therefore, it can be concluded that there will always be some links that may not be used even at high traffic load.

4.4.6 Nodes on Sleep Mode

Putting nodes on sleep mode is another way to reduce power consumption in WDM networks. The power consumption of a node is dependent on the number of wavelengths generated, terminated, or passing through the node. Hence, it is feasible to reduce power consumption of a node by reducing the number of wavelengths of any type on the node. However, a node consumes a considerable amount of power regardless of traffic when it is

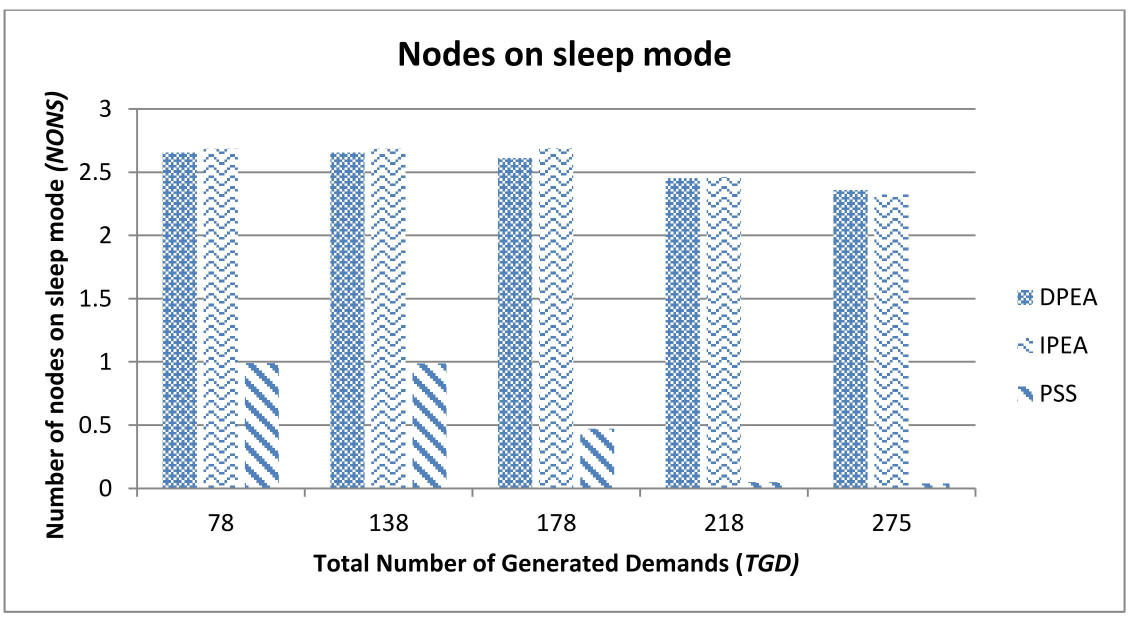

Figure 4.13 Number of nodes on sleep mode in NSF network.

active. The only way to prevent this is by putting the node on sleep mode which is only possible when no wavelength is generated, terminated, or passing through the node. Nodes which are used for the purpose of protection are good candidates to be put on sleep mode.

Figure 4.13, and Figure 4.14 illustrate the number of nodes on sleep mode for each algorithm in NSF and BT-Global networks, respectively. The number of nodes on sleep mode is only slightly decreased by increasing the traffic load when DPEA and IPEA are used. Therefore, it is feasible to put nodes on sleep mode even at high loads, although it may result in more number of blocked demands. For the similar reason in section 4.4.5, IPEA and DPEA outperform PSS significantly in both networks. Moreover, in both networks, IPEA and DPEA behave similarly.

In the NSF network, PSS results in approximately zero number of nodes on sleep mode when the traffic load is high, (*TGD*=218), (*TGD*=275). This leads to the conclusion that NSF topology is efficiently designed in that it utilizes network equipment even at high load. However, in the BT-Global network, PSS results in a number of nodes on sleep mode even at high loads, (*TGD*=218), (*TGD*=275). Therefore, similar to the argument made in section 4.4.5, it can be concluded that there will be a number of nodes that may not be used even at high traffic loads.

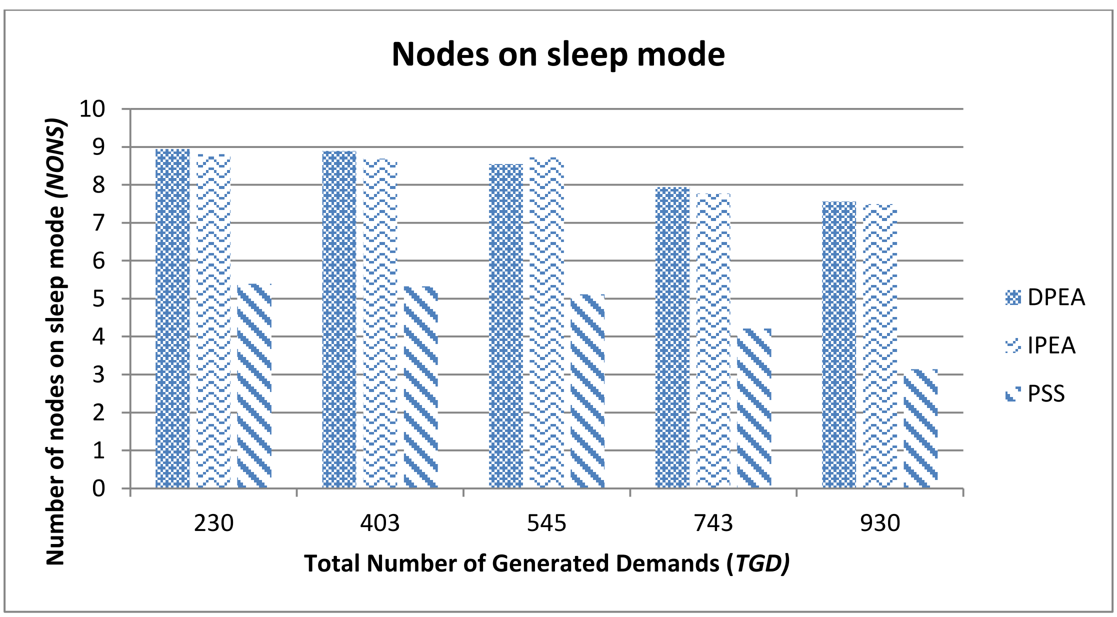

Figure 4.14 Number of nodes on sleep mode in BT-Global network.

4.4.7 Consumed Wavelengths for Working Paths

This section discusses the total number of wavelengths used for working paths. So far, it has been shown that DPEA and IPEA reduce power consumption of a network significantly when traffic load is low. Moreover, all the algorithms expressed similar performance in terms of the links load, total number of blocked demands, and capacity consumption when traffic load is low. In the following paragraphs we show how the proposed approaches perform in terms of the total number of working wavelengths.

To provide better insight into *TRW*, the total number of wavelengths used for working paths in the NSF and BT-Global networks are illustrated in Figure 4.15, and Figure 4.16, respectively. For both networks and all the algorithms, when the total number of generated demands (*TGD*) increases, the total number of reserved working wavelengths also increases. As introduced in section 4.2, *TRW* is the sum of all the working wavelengths reserved on each link. Therefore, lower amount of *TRW* indicates better performance of an algorithm.

In the NSF network, DPEA outperforms IPEA slightly for any given *TGD* while in BT-Global network DPEA and IPEA behave similarly. This is due to dissimilar network topologies. Nonetheless, PSS outperforms both DPEA and IPEA substantially in both networks as expected.

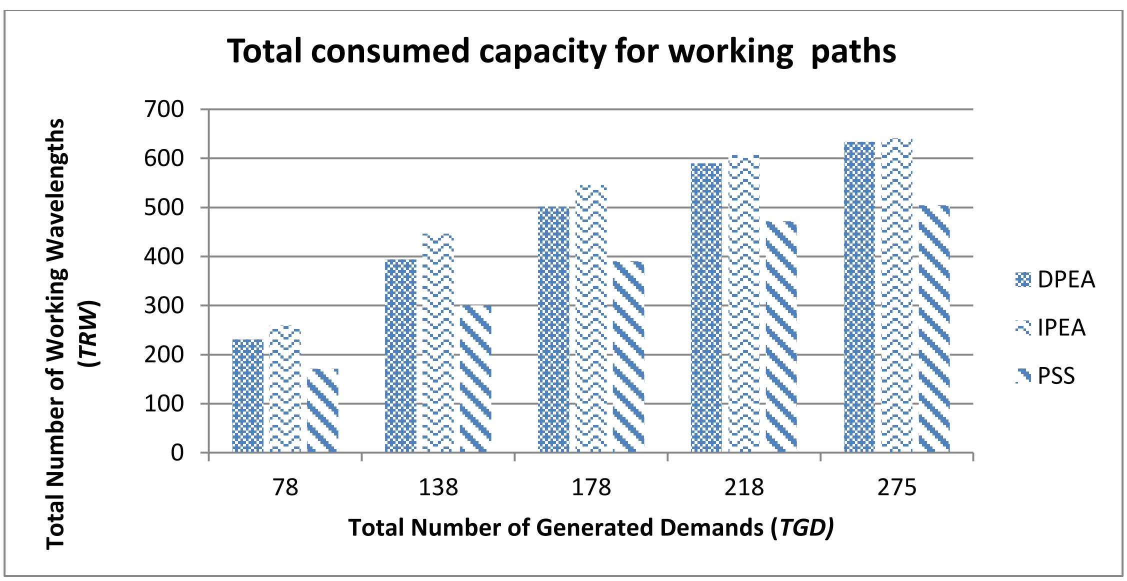

Figure 4.15 total number of wavelengths used for working paths in NSF network.

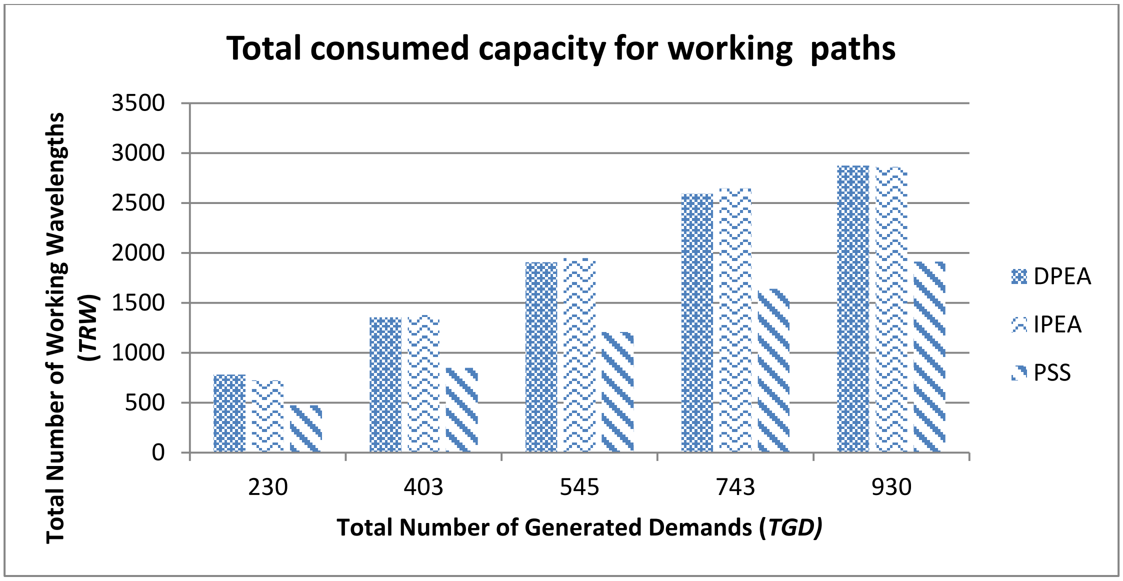

Figure 4.16 total number of wavelengths used for working paths in BT-Global network.

IPEA and DPEA avoid utilizing nodes and links with no reserved capacity for working paths. As a result, computed working paths by IPEA and DPEA are not necessarily the shortest paths. In contrary, PSS computes the shortest working paths, which is the reason for its better performance.

In conclusion, although IPEA and DPEA result in longer working paths, however, all the algorithms consume approximately the same total amount of capacities at low traffic load.

4.5 Summary

In this chapter we first described the simulation setup in which how we developed the simulation program. We also explained that how the networks were designed and what types of networks were utilized for the simulation. Finally, in the performance evaluation section, it was pointed out that IPEA, DPEA, and PSS behave similarly in terms of the total capacity consumption when the traffic load is low. In addition, DPEA outperforms IPEA marginally in terms of power saving. It reduces power consumption as much as to 35% at low traffic load in the BT-Global network, however, power saving decreases to 16% at high load level. In regard of NSF network, power saving is achievable as much as 24% at low traffic load while it reduces to 14% at high traffic load. This is due to the fact that NSF network has less nodal degree than the BT-Global network. Therefore, there is less opportunity to put network devices on sleep mode.

Chapter 5 Conclusions

Energy efficiency is arousing increasing interest in the past recent years. There is growing consensus on the necessity of investigating possible methods of energy efficiency as one of the most crucial current research issues. With this aim, energy efficiency has been explored in different aspects of networking in this thesis. Specifically in this thesis, we investigated energy efficiency in the context of network survivability with shared-path restoration.

Shared backup restoration scheme is a network survivability method which is used to find shared backup paths in order to reduce spare capacity consumption. Pool Sharing Scheme (PSS) is comprehensively used in the literature for the implementation of shared-path restoration scheme. PSS ensures that the amount of backup bandwidth required on a link to restore the failed connections will not be more than the total amount of backup bandwidth reserved on that link.

We presented a power model for network nodes in Wavelength Division Multiplexing (WDM) networks. It has been shown in the literature that the power consumption of a WDM node is modeled as sum of a fixed amount of power independent of their traffic and an additional amount of power proportional to their traffic load. We used this idea in this thesis in order to formulate the power consumption of a WDM node in our network topology. In our model, the proportional power is dependent on the number of working wavelengths, generated, terminated, or passing through the node.

Furthermore, we proposed two heuristic approaches with the objective of reducing power consumption at a given WDM networks with shared-path restoration. Indirect Power Efficient Approach (IPEA) is the first such approach that exploits properties of a math series in order to assign weight to the links. It attempts to concentrate traffic load on a set of links that makes it possible to switch off other nodes and links with no load. The second approach is Direct Power Efficient Approach (DPEA) which is aimed at dynamically routing traffic through nodes and links with high traffic load. Routing traffic on nodes and links with high load levels makes it possible for the links and nodes with no load to be set on sleep mode and, as a result, reducing the total power consumption at the network. Similar to the IPEA, the DPEA approach computes a pair of working and backup paths for every demand. The DPEA computes these paths for every new demand upon the arrival of that demand by comparing the power consumption of nodes and links in the network before the demand arrives with their potential power consumption if they are chosen along the paths of this demand.

Consequently, DPEA outperforms IPEA marginally in terms of power saving. It achieves up to 35% power savings at low traffic load in the BT-Global network, however, power saving reduces to 16% at high load level. Furthermore, less power saving (24% at low traffic load and 14% at high traffic load) has been obtained in the NSF network which has less nodal degree than the BT-Global network. Although DPEA and IPEA lead to significant power saving at the network, they result in longer working paths. In this regard, PSS outperforms DPEA and IPEA considerably. Regarding total capacity consumption, DPEA and IPEA behave similarly while PSS outperforms them slightly. All algorithms behave similarly in terms of the average link load at low traffic load; however, PSS outperforms them slightly at high traffic load. In terms of the ratio of block demands, as expected, PSS outperforms both DPEA and IPEA. It has also been shown that by increasing the total number of generated demand or the network load the number of links and nodes on sleep mode also decreases.

5.1 Future Work

This thesis has shown that concentrating traffic on a set of nodes and links in a network by taking into account their power consumption can eventually lead to reducing total power consumption of a network. However, links may become congested when traffic load is increases and consequently, demands can be blocked. One way to avoid blocking in a network could be to employ load-balancing technique when a certain amount of demands have been already processed. In this way, load balancing can be applied to only a set of links and nodes with high loads in order to prevent them from becoming congested.

Furthermore, there are numerous ways to assign weight to the links in a network in order to reduce total power consumption at the network. In this thesis, we proposed two functions to assign weights to the links and execute the Dijkstra algorithm for the given weights. However, it might be more effective to modify the Dijkstra algorithm such that it can compute the shortest path by taking into account not only the cost of the links but also the cost of the nodes. Hence, the current power consumption at each node can be incorporated into the path computation, similar to the links. Consequently, similar approach to DPEA can be used to compute shortest working path and its correspondent backup path for each demand by employing a modified Dijkstra algorithm. Therefore, the objective of the approach would be to avoid choosing links and nodes that do not consume any power.

Finally, we can also formulate the Integer Linear Programming (ILP) for the proposed approaches in this thesis. It has been proven in the literature that ILP formulation yields the optimal results. Hence, using ILP formulation can lead to the maximum possible power saving at the network based on the power model discussed earlier in this thesis.

Appendix A

Given the following series:

$$\sum_{n=0}^{\infty} \frac{1}{2^n}$$

by geometric series test we see that it converges to 2, so:

$$\sum_{n=0}^{\infty} \frac{1}{2^n} = 2 \qquad (1)$$

$$\sum_{n=0}^{\infty} \frac{1}{2^n} = \frac{1}{2^{-1}} \qquad (2)$$

By dividing the series on the left of (2) into increasing segments and subtracting them from the left we can observe the following pattern:

$$\sum_{n=1}^{\infty} \frac{1}{2^n} = \frac{1}{2^{-1}} - \frac{1}{2^0} = 1$$

$$\sum_{n=2}^{\infty} \frac{1}{2^n} = \frac{1}{2^0} - \frac{1}{2^1} = \frac{1}{2}$$

$$\sum_{n=3}^{\infty} \frac{1}{2^n} = \frac{1}{2^1} - \frac{1}{2^2} = \frac{1}{2^2} = \frac{1}{4}$$

$$\sum_{n=4}^{\infty} \frac{1}{2^n} = \frac{1}{2^2} - \frac{1}{2^3} = \frac{1}{2^3} = \frac{1}{8}$$

and in consequence

$$\sum_{n=x}^{\infty} \frac{1}{2^n} = \frac{1}{2^{x-1}}.$$

Finally, we can see that

$$\sum_{n=x}^{L} \frac{1}{2^n} = \frac{1}{2^{x-1}} - \sum_{n=L+1}^{\infty} \frac{1}{2^n} < \frac{1}{2^{x-1}}$$

this proves that each individual element of the series is always greater than the sum of all the remaining elements to the right, provided that L is finite.

Appendix B

The pseudo code for Dijkstra algorithm is presented below, [46]:

```
function Dijkstra(Graph, source):
    for each vertex v in Graph:                     // Initialization
        dist[v] := infinity                         // initial distance from source to vertex v is set to infinite
        previous[v] := undefined                    // Previous node in optimal path from source
    dist[source] := 0                               // Distance from source to source
    Q := the set of all nodes in Graph              // all nodes in the graph are unoptimized - thus are in Q
    while Q is not empty:                           // main loop
        u := node in Q with smallest dist[ ]
        remove u from Q
        for each neighbor v of u:                   // where v has not yet been removed from Q.
            alt := dist[u] + dist_between(u, v)
            if alt < dist[v]                        // Relax (u,v)
                dist[v] := alt
                previous[v] := u
    return previous[ ]
```

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