

DESIGN AND PERFORMANCE EVALUATION OF INTERNET PROTOCOL OVER DWDM-PROVINCIAL ELECTRICITY AUTHORITY CORE NETWORK

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การออกแบบและประเมินค่าประสิทธิภาพอินเตอร์เน็ตโปรโตคอล ในโครงข่ายหลัก DWDM ของการไฟฟ้าส่วนภูมิภาค

เชาวฤทธิ์ บุญตา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาปรัชญาดุษฎีบัณฑิต สาขาวิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์ มหาวิทยาลัยอุบลราชธานี ปีการศึกษา 2561 ลิขสิทธิ์เป็นของมหาวิทยาลัยอุบลราชธานี

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้ วิทยานิพนธ์ฉบับนี้มุ่งประเด็นการศึกษาและวิจัยในเรื่องการออกแบบและประเมินประสิทธิภาพ โครงข่ายอินเตอร์เน็ตโปรโตคอลบนโครงข่ายดีดับเบิลยูดีเอ็มในโครงข่ายหลักของ กฟภ. ส่วนของ การออกแบบแบ่งการพิจารณาออกเป็น 2 เลเยอร์ คือ ดีดับเบิลยูดีเอ็มหรือเลเยอร์เชิงแสง และ ้อินเตอร์เน็ตโปรโตคอลเลเยอร์หรือเลเยอร์ข้อมูล สำหรับการประเมินประสิทธิภาพของโครงข่าย ้ก็มีการแบ่งการศึกษาออกเป็น 2 เลเยอร์ เช่นกัน คือดีดับเบิลยูดีเอ็ม ใช้ค่าความน่าจะเป็นในการบล็อก ้ช่องสัญญาณเชิงแสงมาพิจารณา และนอกจากนี้ก็ยังมีการนำค่าเปอร์เซ็นต์ความพร้อมในการใช้งาน ของข่ายเชื่อมโยง ค่าความผิดเพี้ยนของช่องสัญญาณและค่าความเสถียรของโครงข่ายมาพิจารณาด้วย ้ส่วนในการประเมินประสิทธิภาพอินเตอร์เน็ตโปรโตคอลเลเยอร์ จะใช้ค่าคุณภาพการให้บริการ มาพิจารณา นอกจากนี้ยังได้ศึกษาและนำเสนอเทคนิคที่เหมาะสมสำหรับการป้องกันโครงข่าย เมื่อหนึ่งข่ายเขื่อมโยงได้รับความเสียหายไว้ในขั้นตอนการออกแบบและประเมินประสิทธิภาพ ในขั้นตอนการออกแบบเครือข่ายใช้การออกแบบหลายชั้นหรือมัลติเลเยอร์ โดยนำเสนอโครงข่าย แบบสามชั้น คืออินเตอร์เน็ตโปรโตคอลบนโครงข่ายโอทีเอ็นบนโครงข่ายดีดับเบิลยุดีเอ็ม ซึ่งยังไม่ได้ ้มีการนำเสนอแยกชั้นการพิจารณามาก่อน มีการนำเสนอเพิ่มเติมค่าตัวแปรต่าง ๆ ที่มีผลต่อต้นทุน ของโครงข่ายในแต่ละชั้น ได้แก่ ค่าขนาดความจุของอุปกรณ์ในแต่ละชั้น (ค่าพารามีเตอร์ A, M, Uk) เป็นต้น และเพื่อรองรับการเชื่อมต่อลำดับชั้นอินเตอร์เน็ตโปรโตคอลมีการเลือกใช้การมอดูเลต แบบ CP DQPSK (Coherent Polarization-Multiplexed Differential Quadrature Phase Shift Keying) และ FEC (Forward Error Corrections) ในชั้นดีดับเบิลยูดีเอ็ม โดยไม่มีการใช้อุปกรณ์ขยาย หรือการสร้างสัญญาณกลับ ส่งผลให้สามารถลดอุปกรณ์ชดเชยค่า dispersion

นอกจากนี้ ได้มีการนำเสนอต้นแบบสำหรับการหาค่าที่เหมาะสมที่สุดของความจุของอุปกรณ์ ในแต่ละชั้นเครือข่าย ซึ่งมีผลต่อต้นทุนของโครงข่ายในแต่ละชั้นและโครงข่ายโดยรวมทั้งหมด เป็นค่าขนาดของโมดูลในแต่ละลำดับชั้น เราสามารถลดค่าต้นทุนอุปกรณ์ในลำดับชั้นโอทีเอ็น โดยการเลือกค่าอัตราต้นทุนระหว่างลำดับชั้นอินเตอร์เน็ตโปรโตคอลและดีดับเบิลยูดีเอ็มที่ 14% หรือ ขนาดความจุโมดูลเท่ากับ 5 Gbps และเราสามารถหาค่าที่เหมาะสมสำหรับการลดต้นทุนโครงข่าย รวมทั้งสามลำดับชั้นได้โดยการเลือกค่าอัตราส่วนระหว่างอินเตอร์เน็ตโปรโตคอลต่อดีดับเบิลยูดีเอ็มที่ 3.5%

ABSTRACT

TITLE	: DESIGN AND PERFORMANCE EVALUATION OF INTERNER
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This thesis focuses on the issues design and performance evaluation of IP over DWDM network. We consider the network into DWDM layer and IP layer for designing phase and performance evaluation. We models the DWDM network based on physical parameters and the IP/MPLS layer based on traffics requirement of PEA. We evaluate the performance of DWDM layer with blocking probability and IP layer with QoS. We also consider the protection techniques in DWDM layer for against single link failure and equipment failure. In the process of the designing network of the multilayers, we introduce and study the explicit modeling of IP/MPLS over OTN over DWDM. This has not been proposed before. The parameters affecting on the cost of the network of each layer have also been introduced such as the equipment capacity (A, M, Uk). For interconnecting between the layers, we applied the Coherent Polarization-Multiplexed Differential Quadrature Phase Shift Keying (CP DQPSK) modulation and Forward Error Corrections (FEC) in the DWDM layer. This doesn't required dispersion compensation and regeneration units.

In addition, this study present the model for optimizing the equipment capacities of each network layers. This affects the cost of each network layers and the overall cost of the whole network to the module capacities of each layers. Finally, we present an explicit networking optimization model that aims to minimize the total capacity at the LSRs and the OXCs. We find that when M is above the average demand in the network is the best case that minimizes the cost of this layer, when the cost ratio of IP to W is 3.5%. On the other hand, the case when M is below the average demand is the

best case that minimizes the OTN layer cost when the cost ratio of IP to W is 14%. Our assessment shows that the different weight ratios of LSR to OXC nodes do not generally affect the overall required capacity of each layer. However, the weight ratios influence differently required node capacity at nodes in each layer.

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LIST OF ABBREVIATIONS

Symbol	Explain	
ADDC	Area Distribution Dispatching Centers	
ASE	Amplifier Spontaneous Emission	
AWG	Arrayed Waveguide Grating	
BER	Bit Error Rate	
BGP	Border Gateway Protocol	
BITS	Building Integrated Timing Supply	
BOM	Bill of Material	
CapEx	CapitalExpenditure	
CBWFQ	Class Based Weighted Fair Queuing	
CD	Chromatic Dispersion	
CE	Customer Edge	
CP-DQPSK	Coherent Polarization- Multiplexed Differential	
	Quadrature Phase Shift Keying	
СТР	Cisco Transport Planner	
DGEs	Dynamic Gain Equalizers	
DQPSK	Differential Quadrature Phase Shift Keying	
IGP	Interior Gateway Protocol	
ILA	In-line Amplifier	
IMS	IP Multimedia Subsyste m	
IP	Internet Protocol	
IS-IS	Intermediate System to Intermediate System	
ISP	Internet Service Provider	
KSP	K-Shortest Paths algorithm	
LCSs	Line Card Shelves	
LDP	Label Distribution Protocol	
LER	Label Edge Router	
LLDP	Link Layer Discovery Protocol	
LRMLF	Lightpath Routing and Maximum Load Factor	

LIST OF ABBREVIATIONS (CONTINUED)

Symbol	Explain	
LSP	Label switched path	
LSR	Label Switch Router	
MDRR	Modified Deficit Round Robin	
MEMSs	Micro Electro-Mechanical Systems	
MILP	Mixed Integer Linear Programming	
MLR	Mixed-Line Rate	
MPA	Modular Port Adapter	
MP-BGP	Multiprotocol Border Gateway Proto	
MPLS	Multiprotocol Label Switching	
MPLS TE	MPLS Traffic Engineering	
MPR	Multi Path Routing	
MXP	Muxponder	
NE	Network element	
NMS	Network Management System	
NOC	Network Operations Center	
OADM	Optical Add Drop Multiplexer	
OAM	Operations, Administration and maintenance	
OC	Optical Carrier	
OCH	Optical Channel	
ODB	Optical Duobinary	
ODU	Optical Data Unit	
OEO	Optical-Electrical-Optical	
OLA	Optical Line Amplifiers	
OpEx	Operational Expenditure	
OQPSK	Orthogonal Quadrature Phase Shift Keying	
OSC	Optical Service Channel	
OSNR	Optical Signal to Noise Ratio	
OSPF	Open Shortest Path First	
OTN	Optical Transport Network	

LIST OF ABBREVIATIONS (CONTINUED)

Symbol	Explain	
OTU	Optical Transport Unit	
OXCs	Optical Cross-Connects	
PE	Provide Edge	
PEA	Provincial Electricity Authority	
PHB	Per Hop Behavior	
PHP	Penultimate Hop Popping	
PLIs	Physical Layer Impairments	
PMD	Polarization Mode Dispersion	
PM-QPSK	QPSK Polarization Multiplexed Quadrature Ph	
	Shift Keying	
PQ	Priority Queuing	
PTP	Precision Timing Protocol	
QoS	Quality of Service	
RIP	Routing Information Protocol	
RSP	Route Switch Processor	
RSVP	Resource Reservation Protocol	
RWA	Routing and Wavelength Assignment	

CHAPTER 1 INTRODUCTION

1.1 Statement of the problems

More than three decades ago, the Provincial Electricity Authority (PEA), one of the state enterprise started to implement its IT system to support financial operation. At the present, PEA has been running many IT and communication technology systems, ranging from small in-house developed systems to large scale enterprise wide systems including extensive of optical fiber throughout the country for telecommunication and data communication purposes [1]. Many of the systems are vital to operating core business processes. (e.g. New video conferences, SAP, GIS, IMS, UC, SCADA/DMS, Smart Grid, Smart Substation IEC61850, cloud computing, etc.). They are the key drivers for the continuous growth of IP traffic. The architectures of today's IP and transport core networks are strained by the need to transport terabits of traffic with stringent latency and reliability constraints. Furthermore, as the price per bit decreases, this task must be achieved with the lowest capital and operational cost. Most of the applications driving this growth are based on TCP/IP.

The conditions and the problems in the PEA optical network at the present have to be listed as followings. First, the network size is a large scale and complex cause to hard implementation, operation and maintenance. Second, PEA optical network included many vendor of network equipment cause to some miss compatibles. Third, the network includes multilayers such as IP layer, DWDM layer, OTN layer and SDH layer made the hard implementation, operation and maintenance. They may cause the complexity for implementation, operation and maintenance. These affect the transformation of the PEA optical network. The conventional PEA optical network have implemented based on SDH technology. The traditional IP over optical network as PEA using is shown in Figure 1.1. The legacy SDH optical network of PEA has some disadvantages and limitations according to the SDH technology. Therefore, it cannot serve enough bandwidth requirement of IP traffic growth. The cards and spare parts of SDH equipments are also out of manufactured. At the present, the SDH network is still running and operating the existing service bandwidths until the IP over DWDM network is completely implemented on the year 2022. This has caused some effects and knock on effects on the transformation gap between SDH networks to IP network.



Figure 1.1 Traditional PEA IP over Optical Model

In this thesis, we address several fundamental issues of the grooming network design and operation to consider the CAPEX cost and reliability in the context of IP over DWDM also the methodology and experimental migration the PEA SDH optical network to IP over DWDM network. The survivability of each layer of the network depends on the standard of switching time according to IEEE standard. The network protection is set to prevent the single link failure in the DWDM layer for indicating the best link availability.

Optical networks have been evolving along with the advanced technologies and the social changes and needs. The first digital networks were asynchronous networks, where each network element's internal clock source timed its transmitted signal. Due to the fact that each clock has a certain amount of variation signals, arriving and transmitting could have a large variation in timing, which often results in bit errors. Furthermore, there are several vendors of equipments in the present PEA network, therefore, this causes some problems and difficulties for interconnecting those equipments.

Facing the challenges of increased service needs, fiber exhaust and layered bandwidth management, service providers need options to provide an economical solution. The first option is to alleviate the shortage of fiber is to lay more fibers. However, this solution is not always viable mainly due to the fact that the cost of laying new fibers is prohibitively high, especially, in densely populated metropolitan areas. Besides, this is too complicated and difficult to wire the added new fibers.

The second choice is to increase the network capacity using time division multiplexing (TDM) where TDM increases the fiber capacity by slicing time into smaller intervals for transmitting data per second. It allows flexible traffic: management on the fixed bandwidth but requires O-E-O and electrical multiplex/demultiplex function. Traditionally, this has been a method of choice (DS-1, DS-2, DS-3, etc.) in the industry. However, when service providers use this approach exclusively, they must make the leap to the higher bit rate in one jump, requiring the purchase of more capacity than they initially need. Based on the SDH hierarchy, the next incremental step from 10 Gbps TDM is 40 Gbps - a quantum leap that would not be possible for TDM technology in the present. TDM has also been used with transport networks that are based on either SONET or SDH.

The third choice for service providers is to use DWDM which increases the capacity of embedded fiber by first assigning incoming optical signals to specific frequencies (wavelength, lambda) within a designated frequency band and then multiplexing the resulting signals out onto the fiber. This wavelength special reuse reduces the cost of the expensive electrical multiplex/demultiplex function. Since incoming signals are never terminated in the optical layer, the interface can manage bit-rates and the formats of optical signals independently. This bit rate and protocol transparency allows service providers to easily integrate the DWDM technology with existing equipments in the network and access to the untapped capacity in the embedded fiber at the same time.



Figure 1.2 Increased network capacity using DWDM

DWDM combines multiple optical signals so that they can be amplified as a group and transported over a single fiber to increase capacity, as shown in Figure 1.2. Each signal carried can be at a different rate (STM-1, 4, 16, etc.) and in a different format (SDH, ATM, data, etc.). Using DWDM we can reduce the fiber requirement. Each channel can be transmitted on a different wavelength over a single fiber. So we have our 40 2.5 Gbps channels, each being transmitted as a different wavelength, that is, a different colour. They are multiplexed together and transmitted over a single fiber and at the far end demultiplexed. The multiplexer and demultilexer prevent channel interference and allows channels to be separated at the receiving end. One fiber is needed for the west-east direction, and another for the east-west. We can use only 2 fibers instead of using 80 fibers.

Optical Transport Network (OTN) has been emerging as promising for the next generation transport networks supporting large granular broadband service transmissions. OTN is designed and developed with the current and future Internet requirements. OTN offers efficient multiplexing and switching of high speed signals (around 100 Gbps) and cross connect dispatching of wavelengths and subwavelengths that lead to superior bandwidth utilization. OTN also defines a digital wrapper layer that is advantageous over SONET/SDH. It includes signal overhead to support up to six levels of tandem connection monitoring (TCM) and advanced forward error correction (FEC) making OTN performance monitoring and fault detection very powerful. Because of these benefits, the introduction of OTN explicitly in a multilayer architecture in which OTN interfaces are employed in DWDM systems has been identified as an important consideration for operational architecture. The advantages

of OTN over SONET/SDH can be exploited in multilayer architecture leading to superior service level performance monitoring to support for higher bit-rate client signal and efficient bandwidth utilization.

Two-layer networks, such as IP over DWDM, that are made of a traffic layer over a DWDM transport layer, have received much attention in the literature. In this architecture, the core routers are connected directly to the DWDM systems that provide point-to-point fiber links. One problem is that when a demand has to travel on multiple hops, an expensive O-E-O conversion is performed at intermediate routers that affects the network speeds. In addition, the transit traffic uses expensive IP router ports. Another problem is the inefficient capacity utilization in this architecture. That is approximately 60-70% of the core routers' capacity for forwarding services instead of processing local add/drop services on the nodes [2]. Another issue is that with DWDM being a purely analog form, a fiber failure in a network may only be recognized by the IP layer routing protocol based on its timer expiration, rather than being immediately observed through operations monitoring if a digital optimal layer were present. With OTN consisting of optical crossconnects (OXCs), DWDM allows migration from point-to- point to all-optical networks in which switching functions are performed in the optical domain. The OTN layer, as a middle layer between the IP/MPLS layer and the DWDM layer, separates the logical from the physical topologies. Core routers connect over the logical topology while OTN-over-DWDM provides connections based on the physical topology.

1.2 Objective of research

1.2.1 Introduce the evolution of PEA optical network architectures from SDH to DWDM. We describe the principle of routing and wavelength assignment in IP over DWDM networks and explain how wavelength continuity constrain and wavelength usage constraint affect network performance.

1.2.2 Develop a mathematical model to analyze the blocking performance of the optical networks with wavelength usage constrain. We conclude that in the practical DWDM networks with wavelength usage constrain, increasing the total number of available wavelengths in a fiber is an attractive alternative to employing wavelength conversion.

1.2.3 Make the network viable and cost effective for carrying IP centric traffic, it must be able to offer subwavelength level services and must have the capability to pack these services effectively onto a wavelength. This motivates the study of traffic grooming problems in the IP over DWDM framework

1.2.4 Study shared and dedicated protection against single link failure in DWDM grooming networks and develop an MILP formulation for each of them respectively.

1.2.5 Study and experiment the migration of PEA SDH optical network to IP over DWDM network

1.2.6 Use CTP (Cisco Transport Planner) plan, design and evaluate the performance of the modeled network.

1.2.7 Optimize the CAPEX network cost.

1.3 Scope of research

First, we provide an introduction to the evolution of optical network architectures from SDH to DWDM. We describe the principles of routing and wavelength assignment in IP over DWDM networks and explain how wavelength continuity constraint and wavelength usage constraint affecting network performance. We develop a mathematical model to analyze the blocking performance of the optical networks with wavelength usage constrain. We conclude that in the practical DWDM networks with wavelength usage constrain, increasing the total number of available wavelengths in a fiber is an attractive alternative to employing wavelength conversion.

Next, to make the network viable and cost effective for carrying IP centric traffic, it must be able to offer subwavelength level services and must have the capability to pack these services effectively onto a wavelength. This motivates the study of traffic grooming problems in the IP over DWDM framework. We investigate the traffic: grooming performed in IP layer where the subwavelength level IP packets are grouped together in electrical domain before they are sent to the DWDM layer. This refers the IP traffic grooming. Similarly, the grooming performed in DWDM layer is called DWDM wavelength grooming. We study IP traffic grooming problem with the objective to minimize the number of transmitters and receivers needed in the DWDM layer. The resulting topology is called the virtual topology. We also propose three routing strategies for allocating dynamic traffic requesting in the designed virtual topologies. Their blocking performance is studied and compared through simulations.

The third issue addressed in thesis is an optimization model for network planning of IP/MPLS over OTN over DWDM multilayer networks. An MILP is formulated for solving the light trail design problem with given static traffic requirement. Two heuristic approaches are also developed for obtaining fast solutions in large networks. In our numerical examples, our heuristic approaches give very fast and good solutions in comparison to the results obtained from solving the MILP formulations.

We finally address the issue of fault management in grooming networks. Although fault tolerance in DWDM network has been extensively studied in literature, the research on survivability issues in grooming networks is still a relatively new area. We study the shared and dedicated protection against single link failure in DWDM grooming networks and develop an MILP formulation for each of them, respectively.

We extend our research on the full protection design to partial protection where the backup capacity is smaller than the primary capacity. This problem is decomposed into two sub-problems, namely resource minimization and protection maximization. We present MILP formulations for each of the sub-problem and further design a dynamic routing strategy named shortest-available-least-congested routing. We mainly use CTP (Cisco Transport Planner) to plan, design and evaluate the performance of the modeled network.

1.4 EXPECTED CONTRIBUTION

We have expected several contributions in this thesis:

1.4.1 We present an integrated capacity optimization model for planning of a two-layer IP over DWDM.

1.4.2 The model of 4.1 is mixed integer linear programming problem that is difficult to solve with an MILP solver such as CPLEX and MATLAB except for small networks. We propose model theory to solve this model for large networks that introduces the notation of multilayer paths with modularity.

1.4.3 The model of 4.1 is mixed integer linear programming problem that is difficult to solve with an MILP solver such as CPLEX except for small networks.

We use the Cisco Transport Planner (CTP) to solve this model for large networks that introduce the notation of multilayer paths with modularity between layers for large network topologies. This gives us insight on how the cost of each layer influencing the overall network cost. Moreover, it provides us what resources are needed at each layer for a given set of network demands.

1.4.4 We present an optimization model for network planning of IP/MPLS over DWDM multilayer networks while the DWDM capacity is fixed.

1.4.5 We present a comprehensive study to quantify the interrelationship between layers through change in unit cost of elements and capacity modularity, coupled with network demand.

1.4.6 We develop an explicit networking optimization model with IP/MPLS over DWDM that aims to minimize the total capacity at the routing and switching nodes. We also present a brief assessment by considering a sample network topology.

1.4.7 We study the performance evaluation of network using the conceptual as shown in figure 1.3.



Figure 1.3 Related of research conceptual

1.5 Organization and content of this thesis

The thesis consists of seven chapters. Chapter 2 specifies the theory and literature surveys that we studied. Chapter 3 starts from a general description of the network environment for presenting the related questions that arise in design the performance analysis task. The approaches that can be applied in the studies are briefly presented. In Chapter 4 is the study of the performance evaluation of the network. The network performance is evaluated on both DWDM layer and IP layer. Chapter 5, we present an integrated capacity optimization model for planning of a three-layer network where modularity is explicitly considered. In addition, sublayer signals of OTN are also included. We present an optimization model for work planning of IP/MPLS over OTN over DWDM multilayer networks while the DWDM capacity is fixed. We present a comprehensive study to quantify the interrelationship between layers through change in unit cost of elements and capacity modularity, coupled with network demand. Chapter 6, we study the cost of the network and report it results. Finally, Chapter 7 includes conclusion and recommendation from the thesis, mentioning some possible directions of further studies and works.

CHAPTER 2 THEORY AND LITERATURE SURVEY

In this thesis, we assume a simplified IP over DWDM network model. For the IP network to be directly overlaid on the DWDM network, an enhanced IP layer and DWDM layer are necessary. The enhanced layers may be responsible for load balancing and reconfiguration, protection and restoration, optical flow switching, cross-layer optimization and network management [2]. The exact division of these functionalities between the IP and DWDM layers is an ongoing debate in the rest of this Chapter

2.1 DWDM

Optical technologies offer high capacities. This is achieved thanks to the DWDM technology, where multiple optical signals assigned to a unique wavelength are multiplexed into a single fiber. The anatomy of DWDM system as show in Figure 2.1. Each optical signal is generated by an optical transmitter (e.g. semiconductor diode laser or Fabry-Parot laser [3]) and received by a receiver (e.g. PN or PIN photodiodes [3]). Both the transmitter and the receiver are located in a transponder or a colored line card. The optical signals are added or dropped at the network nodes using Optical Cross-Connects (OXCs) (Functionality of Reconfigurable Optical Add-Drop Multiplexers (ROADMs) and OXCs is very similar. We also use both the term OXC, ROADM in this thesis.) An OXC has the ability to dynamically change its configuration. It can also pass the optical signal from its input to its output. It is composed of arrays of mirrors, which can be adjusted using Micro Electro-Mechanical Systems (MEMSs). The pre-amplifier and booster together with the multiplexer/ demultiplexer are often referred to as DWDM terminals, which provide the interface between fibers and OXCs. The optical signal traversing a fiber needs to be amplified every R kilometers by Optical Line Amplifiers (OLAs). Dynamic Gain Equalizers (DGEs) are placed at some OLAs (e.g. at every fourth OLA [3]) to compensate for any channel power tilt of lightpaths determine wavelengths used by the lightpaths. We assume that signal regeneration is done in the IP layer, and no dedicated regenerators are used.



Figure 2.1 DWDM system anatomy

The optical signals that traverse the same fiber installed on a fiber link are multiplexed together. A fiber can carry up to manies wavelength multiplexed optical signals. In order to overcome the attenuation, two amplifiers called pre-amplifier and booster are used at the ends of each fiber.

The optical DWDM channel originating and terminating in the transponders and traversing two or more OXCs is called a lightpath. A lightpath may span multiple fiber links and has capacity W bps. Each intermediate node traversed by the lightpath essentially provides an optical bypass facility [3]. The lightpath can be assigned a unique wavelength on all physical links that it traverses or wavelength converters can be used at intermediate nodes. The assignment of wavelength and choice of the set of physical links that a lightpath traverses is referred to as a Routing and Wavelength Assignment (RWA) problem.

The physical topology consists of physical nodes and fiber links. A fiber link consists of one or more fibers. The physical supply topology (in contrast to the physical topology) determines the nodes and links where network devices and fibers can be installed at the network design stage. The physical topology is the topology, where network devices and fibers have already been installed in the network design stage. All lightpaths between the same pair of nodes can traverse the same or different paths (set of physical links). Each wavelength can be used only once at each fiber.

2.2 IP

The IP is the basic protocol of networking today providing procedures to allow data to traverse multiple interconnected networks [4]. IP routers are installed in the nodes of the network. A router model proposed in [4] is presented in Figure 2.2. It consists of a basic node, slot cards and port cards. The basic node includes the control plane and data plane software, switch matrix power supply and cooling, as well as the physical and mechanical assembly. The basic node can be equipped with slot cards and port cards of different types. The port cards are interfaces from/to the lower hierarchy networks and to other nodes. One port card corresponding to each slot card is assumed in this work. A slot card equipped with port card (s) form a line card. The line cards can either be colored or gray [4]. A colored line card generates optical signals, which can be directly fed into the fiber towards the next network node and therefore does not require any transponder. A gray line card is a Short Reach (SR) interface and requires a transponder, which converts the SR signal into a Long Reach (LR) one. We assume the usage of colored line cards in this thesis, since they are more energy efficient than gray line cards combined with transponders. The advantage of using gray line cards with transponders is the flexibility of choosing solutions of different vendors in the IP and DWDM layers.



Figure 2.2 Router model with exemplary line cards and port cards [4]

The core IP routers usually have a modular structure, where the basic node consists of one or more Line Card Shelves (LCSs) interconnected by Fabric Card Shelves (FCSs) [4]. The modular structure allows proper choice of the router according to the required capacity. Lightpaths are transparent to the IP routers. All parallel lightpaths (regardless of their realization in the DWDM layer) between a pair of IP routers constitute a logical link (IP link). The IP routers correspond to logical nodes. Lightpaths are transparent to the IP routers. All parallel lightpaths (regardless of their realization in the DWDM layer) between a pair of IP routers constitute a logical link (IP link). The IP routers correspond to logical nodes. Source-target traffic demands arrive at the IP routers from the lower hierarchy networks (Figure 2.1). The traffic passes through several steps of aggregation when it goes from the end users through access and metro networks up to the core. The traffic has to be routed through the logical topology in order to get from its source node to its target node. There are different methods of routing of traffic demands. Ingeneral, Single Path Routing (SPR) and Multi Path Routing (MPR) can be distinguished. The SPR (such as the one computed with Dijkstra algorithm [5]) is simpler than the MPR (which can be computed using e.g. K-Shortest Paths (KSP) algorithm [5]), since no decision needs to be taken about what fraction of traffic should take which path. However, the MPR offers the potential of higher power savings, as the traffic can be split over multiple paths so that the logical links are filled to a high extent. Basic IP routing protocols are Open Shortest Path First (OSPF) and Intermediate System to Intermediate System (ISIS) [5]. Both of them are link state routing protocols. This means that the state of an IP link influences routing of traffic. The state of the link is advertised by the IP router attached to it. The advertisements are broadcasted to all IP routers in the network using flooding or spanning tree, i.e. each router must redistribute all the advertisements so that all routers Engineering Database (TED). Information about state of the links is exchanged using Link State Advertisements (LSAs) in OSPF. Dynamic changes in traffic routes can be made through modifications in network link metrics [5]. Changes in the link metrics can even result in the increased number of IP hops that traffic will traverse from its source node to its target node, which can however contribute to the lower power consumption of the network.

2.3 IP over DWDM



Figure 2.3 Model of the considered IP over DWDM network

Looking at both the IP and DWDM layers, line cards and OLAs respectively are the devices that can be targeted for switching off in the low-demand hours. The IP routers cannot usually be switched off because of the constantly present traffic originated from or targeted to them. The same way of reasoning makes switching off the whole OXCs difficult. Thanks to the modular structure of the IP routers, some arts of them (i.e. LCSs and FCSs) could be switched off. However, their boot times are expected to be much higher than the times needed to activate and deactivate line cards. Dynamic operation of OLAs is more difficult than dynamic operation of line cards due to transient (thermal) effect of optical transmission [6]. Routing is present in both the IP and the DWDM layers. Lightpaths need to be routed through the physical topology in order to provide connectivity between the IP routers. On the top of them, the IP traffic has to be routed over the logical topology in order to get from the source to the target node. Introducing flexibility of routing into one or both layers increases the complexity of the network operation, but offers potential of energy saving. Figure 2.4 shows a summarizing example of the network configuration given as input a traffic matrix visualized in the subfigure 2.4 (a). Note that the traffic units are normalized to the

capacity of a single lightpath. Going down through the layers, the traffic needs to be routed over the logical topology (Figure 2.4 (b)), where each logical link has a certain capacity in terms of number of lightpaths (Figure 2.4 (c)) and corresponding line cards located in IP routers. Traffic demands may be potentially split and traverse multiple logical paths (e.g. routing of the traffic demand between nodes A and D over the logical topology shown in Figure 2.4 (b)). The logical topology needs to be realized over the physical topology. This includes the routing of lightpaths over the physical topology. Figure 2.4 (d), where each fiber link has a certain capacity in terms of number of fibers (Figure 2.4 (e)). The fibers and their lengths determine the number of OLAs as well as the size of OXCs. Lightpaths connecting the same node pair may potentially traverse different physical paths.







(d) Realization logical over physical topolo (e) Physical topology (DWDM layer)

Figure 2.4 An Example showing different layer

2.4 OTN

The new generation transmission technology OTN was introduced, as an alternative route. The OTN technology resides at the physical layer in the open systems interconnect (OSI) communications model. OTN is a layer 1 network technology supporting physical media interfaces. That is, OTN is a new generation transmission layer technology that was conceived and developed after the SONET/SDH and DWDM systems. It offers viable solutions for the deficiencies typically found in traditional

DWDM networks such as, the lack of the subwavelength service capability, and poor networking and management capability. Moreover, it enhances the support for operation, administration, maintenance and provisioning functions of SONET/SDH in DWDM. TCM function in OTN is superior to that of SONET/SDH. TCM allows the user and its signal carriers to monitor the quality of the traffic that is transported between segments of connections in the network. SONET/SDH allowed a single level of TCM to be configured, while OTN enables six levels if TCM to be configured.

In addition, OTN support forward error connection (FEC) in the OTN frame and is the last part added to the frame before scrambling. FEC provide a method to significantly reduce the number of transmitted errors due to noise and other optical causes of errors that occur at high transmission speeds. This allows providers to support longer spans in between repeaters. The FEC uses a Reed-Solomon RS (255/239) coding technique. In this technique, 239 bytes are required to compute a 16-byte parity check. The FEC can correct up to eight (bytes) error per codeword or detect up to 16 bytes errors without correcting any. Combined with the byte interleaving capability, the FEC is more resilient to error burst, where up to 128 consecutive bytes can be corrected per OTN frame row.

Furthermore, OTN supports the adaptation of asynchronous and synchronous client services. OTN defines an operation channel carried within the signal's overhead bytes and used for OAM (Operation, Administration, and Maintenance) functions. It enables the transporting of any client service without interfering with the client OAM [7]. Applications for OTN can be a National backbone OTN, Intra provincial/regional backbone OTN and Metropolitan/local OTN.

The functionality of OTN is described from a network level viewpoint in [8]. The interfaces of OTN to be used within and between subnetworks of the optical networks are defined in [9]. To support network management and supervision functionalities, the OTN system is structured in layered networks consisting of several sublayers. Each sublayer is responsible for specific services and is activated at its termination points. For this thesis, we are interested in the Optical Data Unit (ODU) sublayer that provides TCM, end-to-end path supervision, and adaptation of client data that can be of diverse formats such as IP, Ethernet, SDH and so on. The ODU sublayer currently defines five bit-rate client signals, i.e., 1.25, 2.5, 10, 40 and 100 Gbps that are

referred to as ODU_k (k = 0, 1, 2, 3, 4) respectively (see Table 2.1 rates and how these fit into a wavelength assuming each wavelength is 100 Gbps).

Signal	Bit-Rate (Gbps)	Max. $U_k s$ in a wavelength
	1.25	80
U_1	2.5	40
U ₂	10	10
U ₃	40	20
U_4	100	1

Table 2.1 OTN Signals, Data Rates and Multiplexing

OTN also defines the ODU_k time division multiplexing sublayer. It supports the multiplexing and transporting of several lower bit-rate signals into a higher bit-rate signal and maintains an end-to-end trail for the lower bit-rate signals. This typically occurs when a client signal does not occupy an entire wavelength. The multiplexing of ODU_k signals is easy to visualize from the bit-rates shown in Table 2.1.

The multiplexing rules are defined as follows: $2 ODU_0$ can be multiplexed into an ODU_1 , up to $4 ODU_1$ can be multiplexed into an ODU_2 , up to $4 ODU_2$ can be multiplexed into an ODU_3 and $2 ODU_3$ can be multiplexed into an ODU_4 . Also, up to $80 ODU_0s$, $40 ODU_1s$, $10 ODU_2s$, or $2 ODU_3s$ can be multiplexed into an ODU_4 . It is possible to mix some lower rate signals into a higher rate signal. For instance, ODU_1s and ODU_2s can be multiplexed into an ODU_4 . It is possible to mix some lower rate signals into a higher rate signal. For instance, ODU_1s and ODU_2s can be multiplexed into an ODU_3 , but to reduce the overall network complexity only one stage multiplexing is allowed. For example, it is possible to perform the multiplexing of $(ODU_1 \rightarrow ODU_2)$ or $(ODU_1$ and $ODU_2 \rightarrow ODU_3)$, but not $(ODU_1 \rightarrow ODU_2 \rightarrow ODU_3)$. There are two additional specifications: ODU_{2e} and ODU_{flex} . For the purpose of capacity planning modeling, ODU_{2e} can be treated as ODU_2 , is not considered separately. ODU_{flex} is any rate over ODU_0 , which from

a model purpose can be treated as a real variable with lower bound 1 Gbps. Since in our model, any ODU modular variables can be relaxed to be real variables, thus, ODU_{flex} is not considered separately. In the rest of the dissertation, U_k denotes ODU_k for k = 0, 1, 2, 3, 4. Then for the multiplexing process we can write: $2U_0 = U_1$, $4U_1 = U_2$, $4U_2 = U_3$ and $2U_3 = U_4$. Furthermore, U_1 and U_2 can be multiplexed into a U_3 signal according to the following rule: $U_3 = j \times U_2 + (4-j) \times U_1$, where $(0 \le j \le 4)$.

To Summarize, OTN features the following advantages are more efficient multiplexing, provisioning and switching of high bandwidth (2.5 Gbps and up to 100 Gbps) services, leading to improved wavelength utilization. More efficient transport and switching of diverse traffic. And improved monitoring and management operations leading to superior transmission.

Recent work has considered the OTN as a new transmission layer technology. Carroll et al., in [10], present the OTN evolution from an operator's point of view, including the history of the transport network, the role of the OTN, and the motivations and requirements for OTN evolution. The paper also discusses the future of OTN. Gee et al., in [11], present an overview on OTN for use in multivendor/ operator environments and enactment in a fault management capability. The paper also highlights the G.709 enhancement in TCM and automatic protection switching technique and requirement. Jean et al., in [12], discuss the time aspect of OTN. The paper also presents work done since 2001 to support the evolution of ITU-T Recommendation G.709, which introduced new OTN mappings. Justesen et al., in [13], address forward error correction codes for 100Gbps optical transmission. The paper discusses the performance of hard decision decoding using product type codes that cover a single OTN frame or a small number of such frames. The authors argue that a three-error correcting BCH is the best 7 choice for the component code in such systems. Puglia, in [14], describes the tendency of shifting from an all-optical to a digital transport network concept.

2.5 Advance Modulation

To meet the growing data traffic demands in the telecommunication applications, the number of wavelengths is to be increased in a fiber optic backbone of the telecommunication network. The exponential growth of internet services, transmission capacity is a tremendous challenge to networks. Nowadays, 100 Gbps transmission systems are being used for commercial applications. At the same time, the nonlinear effects such as FWM, SRS, XPM, SPM and Dispersion are also increased, when the number of wavelengths passing through the single fiber is increased. In a DWDM optical network, the transmission systems design requires the balance between optical signal to noise ratio (OSNR) at the receiver and transmission margin allocation, where the margin is defined as the extra OSNR required at the receiver after transmission in order to get the same BER value as in back-to-back. Margins in DWDM transmission are usually dominated by multichannel impairments.

However, in a transparent optical network physical layer impairments (PLIs) have a major significance in achieving the better performance. PLIs occurs due to non-ideal nature of optical fiber which overall restricts the smooth flow of the traffic. PLIs such as amplifier spontaneous emission noise (ASE), and chromatic dispersion (CD) have greater role in better performance of the DWDM networks [17]. There are different modulation scheme for different data rates for better utilization of network resources. On-off keying or NRZ modulation format is commonly used at a data rate of 10 Gbps. Using advance modulation techniques, such as differential quadrature phase shift keying (DQPSK), polarization multiplexed quadrature phase shift keying (PM-QPSK) and orthogonal quadrature phase shift keying (OQPSK) are required for higher line rates 40/100 Gbps [18]. PLI aware routing and wavelength assignments (RWA) scheme needs to be formulated to achieve the required quality of transmission. DWDM is the backbone of communication networks which increases the data transmission up to 100 Gbps. A cost effective network can be designed with the implementation of MLR [19]. The wavelength of the channels vary in the range of 10/40/100 Gbps. In order to attach the capacities a high bit rates transceivers i.e. (40/100 Gbps) are required for large traffic demands. High bit rate lightpaths should be limited due to threshold signal quality i.e. BER. The different line rates can exist on the same fiber with different wavelengths, that can support 10/40/100 Gb/s [20]. An architecture can be built for both transparent and translucent optical networks. In view of the above literature survey, this paper presents the techniques of lightpath set up in MLR optical network with various modulation techniques.

The Reported on [15], show the experimental result of a DWDM transmission system with 70 channels on the 50 GHz grid, using single-carrier real time DSP implemented on an ASIC and real-time FEC performance including post-FEC measurements, over 2000 kms of uncompensated SMF, using a commercial DWDM system. The review recent trends and progress in the area of 100G module and subsystem development for long haul DWDM applications and explore how the 100 G market will likely differ from that experienced at 40 G was reported in [16]. Although much of the current research focuses on coherent systems, the differential detection schemes have significant benefits in terms of reduced receiver complexity and cost which make them attractive for commercialization in the short term. Polarization-Multiplexed QPSK has been widely recognized as the format of choice for commercial deployment of DWDM systems with 100 Gbps per channel. Modulation formats such as Optical Duobinary (ODB), Differential Phase Shift Keying (DPSK), Differential Quadrature Phase Shift Keying (DQPSK) and Polarization Multiplexed Quadrature Phase Shift Keying (PM-QPSK) have all been deployed in carrier networks. Other key requirements are Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) tolerance. There are additional performance and latency benefits to be gained by increasing CD tolerance further, allowing the elimination of optical dispersion compensation in the link. Meeting these requirements presents a significant challenge to system designers. One modulation format capable of broadly meeting these 100 GE LANPHY requirements is coherent polarization-multiplexed differential quadrature phase shift keying (CP-DQPSK) modulation scheme.

2.6 Multilayer Networks

2.6.1 Traffic Engineering

Androulidakis et al., in [21], propose an enhancement to the management plane IP/WDM model to introduce IP control plane awareness (TE and QoS) to the wavelength/LSP provisioning architecture. Retvari et al., in [22], review the challenges raised by the integrated routing and wavelength assignment problem in GMPLS-based IP over WDM networks. Vigoureux et al., in [23], discuss on the outline of the TE paradigms and a description of a strategy to improve the efficiency and robustness of the unified TE features of the GMPLS control plane for multilayer network architecture.
Cinkler et al., in [24], present a comparison study on protection scenarios when protection is performed jointly with TE and grooming in a multi-layer network.

2.6.2 Traffic Grooming/Multiplex Bundling

There is a huge gap between the bandwidth requirement of a single client demand and the capacity of a wavelength. A related problem is the multiplex bundling or traffic grooming in transmission network planning. Both terms are used for the same purpose. However, multiplex bundling is often used to imply grooming within the context of network optimization [25]. The goal of the traffic grooming problem is to minimize equipment required to multiplex lower rate signals into higher rate signals for routing over 8 transmission links. Modiano and Lin, in [26], present an overview of the traffic grooming problem and presents a survey on some representative work.

In a seminal work, Doverspike [27] presents a multiplex bundling algorithm in telecommunications transmission networks. However, the way OTN allows multiplexing is different than that of a digital telecommunications network where only limited pairs of rates can be multiplexed. (e.g. not common to multiplex 135 Mbps into 565 Mbps). Secondly, since we consider the capacity planning problem, we associate a signal multiplexing cost for each signal assuming multiplexing and de-multiplexing is possible at each OTN node. This makes each OTN node an OXC node with modular capacity on links connecting two adjacent nodes, allowing us to develop a less complex model for the capacity planning problem, yet consider all the sub-signals of the OTN layer.

Maesschalck et al., in [28] present an algorithm for traffic grooming in IP/MPLS over WDM that minimizes the overall network cost by using the resources in the network efficiently. Zhu and Mukherjee, in [29], present a study on the architecture of a node with grooming capability in WDM mesh networks. The authors develop an ILP model and a heuristic algorithm to solve the grooming problem with the objective of improving network throughput. They also provide a performance comparison of single-hop and multi hop grooming approach. Ou et al., in [30] extend the work of [29] by considering survivable traffic grooming in dynamic-provisioning context.

We observe that although these works assumed the presence of OXCs, the technological constrains of the OTN layer are not taking into account. In other words, what they did was a two-layer traffic grooming, IP/MPLS over DWDM.

2.6.3 Survivability

For multilayer network survivability, the problem is how to design a survivable multilayer network with two goals in mind: (1) to maximize the network protection and, (2) to reduce the cost of the network recourses. Several survivability mechanisms have been discussed in literature for two-layer networks [31, 32]. The most traditional approach is the redundant protection. In this case, the spare capacity of the upper layer is twice protected; once in the upper layer, and once in the lower layer. Clearly, this leads to a poor utilization of the expensive network recourse. A cost reduction can be achieved in this design if the protection (spare) capacity of the upper layer is left unprotected in the lower layer. Fumagalli and Valcarenghi, in [33], review the most common restoration and protection mechanisms available at the IP and WDM layers that can be implemented concurrently in the IP over WDM architecture. Sahasrabuddhe et al. address the problem of in which layer to provide the fault management technique (either the IP or WDM layer) in [34]. Kubilinskas and Pi'oro present two design problems providing protection in either the WDM layer or the IP layer in [35]. Zhang and Durresi investigate the necessity, methods, and advantages to coordinate multilayer survivability in IP over WDM networks in [36]. The joint multilayer survivability in IP/WDM networks is investigated and studied in [37, 38]. Bigos et al., in [39], present a comparison of single layer vs. multilayer survivability in MPLS over optical transport networks. We note however, in all previous work, that the OTN layer that imposes unique technological constraints is not explicitly considered.

2.7 Other related works

Koo et al. provide a study on the dynamic LSP provisioning problem for three different network models of the IP/MPLS over WDM networks (overlay, augmented, and peer models) in [40]. Br'ehon et al. develop a design of a virtual topology in a bus-LSP-capable network that aims to maximize the network utilization in [41]. The authors also show how their method can be used to reduced CAPEX and OPEX of a multilayer network. Belotti et al. present an MIP model and a heuristic algorithm for the problem that aims at optimizing the number and location of MPLS nodes in two layer networks in [42]. Gouveia et al., in [43], present a network design model and a heuristic that consider the joint determination of the MPLS network layout and the WDM optical

layout taking into account both packet level QoS constraints and lightpath constraints. Kaneda et al. in [44], propose a network design algorithm that minimizes the network cost for electrical and optical label switched multilayer Photonic IP networks. Palkopoulou et al. develop a generic multilayer model and a linear programming formulation enabling the calculation of the optimal network CAPEX in multi-homing design in [45]. A cost-based comparison study of IP/WDM vs. IP/OTN that shows that IP/OTN leads to significant decrease in network cost through reduction of expensive transit IP router ports and by exploiting more scalable and cheap OXC ports is presented in [46]. A heuristic algorithm for solving the cross-connects capacity management problem in OTN over DWDM is presented in [47]. The problem studied is that given a network topology and traffic statistics between the nodes, how to manage EXC resource such that the average blocking probability is optimized. Fingerhut et al., in [49] and [48], consider the problem of single layer topological design of ATM (and similar) communication networks. The problem is formulated from a worst-case point of view, seeking network designs that, subject to specified traffic constraints, are nonblocking for point-to-point and multicast virtual circuits. In addition, the authors present a discussion on how different elements of a network contribute to its cost and what this can mean in the context of a specific instance of the network design problem. The authors list the basic elements that contribute to the cost of ATM (and similar) networks as: (1) fiber plant (2) transmission electronics and (3) switching systems.

2.8 Remarks

In Table 2.2 we summarize the related work that mentions OTN in the context of multilayer networks. We note that all those works have embedded the OTN layer in the DWDM layer implicitly. We observe when OTN is mentioned, a reconfigurable optical backbone is defined that the core routers are connected through electro-optical cross-connects (OXCs) excluding limitations of the OTN as a distinct layer with its unique technological constraints. However, the functionalities each technology provide distinguishable prompt leading us to model each layers of network separately. From the reviews, we obtained the OTN sublayer technological constraints specifically in a multilayer network except the work in [26], [28] and [29]. Considering the OTN

sublayer constraints gives us more precise view of the layered architecture that captures OTN explicitly.

Paper	Topic	Approach	Objective	Study
			Min. cost of capacity	Compares 3 node
[42]	Nodes	ILP Model, Lagrangian	, Lagrangian and number and	
	Locations	Relaxation	location of MPLS	under 3 sets
			nodes	of demands
	Protection	ILP model close to	Min. cost of capacity	Compares
[39]	Design	ontimal results		protection methods
	Design	optimarresuits		under 3 cost ratio
			Design the IP/MPLS	Compares
[28]			logical topology	algorithm with
	Traffic	Algorithm	and the routing of	other algorithms
	Grooming	Aigonum	the capacity on the	under different
			physical topology	demands and given
				elements costs
[45]	Homing	I P Model	Min. network	Compares different
[43]	Architecture		equipment cost	homing architecture
	Architecture	Simulation	Compares cost of	Case study based
[46]	Comparison		IP/WDM vs. IP/OTN	on given network
	Comparison	(VPI Systems)		elements costs

 Table 2.2 Summary of Selected Related Work

CHAPTER 3 NETWORKS MODEL AND DESIGN

3.1 Introduction

PEA is a government enterprise that responsible for the generation, distribution, sales, and provision of electric energy services to business and industrial sectors as well as to general public in provincial areas, except of Bangkok, Nonthaburi and Samut Prakran provinces. PEA's vision is to be a leading organization of international standards, modernity and efficiency in energy, services and related businesses.

In order to achieve the vision and to strengthen the enterprise, PEA Information Communications Technology (ICT) infrastructure and the related services must be able to support its business strategies and the organization roadmap. These strategic services are as followed.

(1) Enterprise Resource Planning (ERP)

(2) IP Multimedia Subsystem (IMS)

(3) Supervisory Control and Data Acquisition (SCADA) and the Distribution Management System (DMS)

(4) Geographic Information System (GIS)

(5) Automatic Meter Reading System (AMR)

However, due to a very large and unrelenting growth in IP traffic in both the amount and the bandwidth demands, the large organization such as PEA, faces many challenges. While the organization and its ICT services demand increasingly stringent service-level agreements (SLAs), the underlying network infrastructure must maintain even higher levels of reliability. When traffic demands on the network core increase, the network must maintain flexibility to accommodate the changes based on the service demands. These challenges force PEA to consolidate its core networks and move toward more efficient ways to handle the increasing IP traffic. However, making the move to a consolidated environment presents a variety of business challenges such as, Inefficient transport: Network inefficiencies result from the way core transport networks are built out to support IP over SDH. Due to historically different business requirements, transport and IP networks have developed dissimilar and incompatible control schemes for directing the flow of traffic between endpoints. Complex network, to accommodate the congestion in the core transport network, intelligent ROADM DWDM solution will be pertinent to the ability to support the fast services creation for the ever-growing demand for capacity and bandwidth. And rapidly evolving solutions, service providers are being challenged to provide more sophisticated IP services at the network edge with greater levels of resiliency, security, and application intelligence.

3.2 PEA DWDM Network

The PEA DWDM network consists of 75 core and metro nodes, 1256 aggregation nodes and 1755 physical links. Part of the physical layer network is shown in Figure 3.1 as an example, as a picture of the complete network topology will give no details. The PEA DWDM core network consists of three types of node [50]. The RODAM/ Router node is include 24 ROADM equipment and a unit of the IP Core router at each node. The DWDM equipment connects to the IP Core router at 100 GE LANPHY and 10 GE LANPHY. It multiplexes the client signals into the 100 GE LANPHY channel using the TDM function. Accordingly, this type of node supports multiple types of client services up to 100 GE. The ROADM node is include 51 of nodes and installs the ROADM equipment. It supports client point-to-point services between the connected DWDM nodes up to 10 GE and 1 GE. And the ILA (The term "ILA" and "OLA" in this thesis are similar) node is include 173 of nodes and installs ILA without any service support. Its function is to optically amplify the DWDM signal using the Erbium Dope Fiber Amplifier (EDFA) equipment. All management of this type of node can be access through Optical Service Channel (OSC). Aggregation node connections were excluded from the topology variations in the IP-layer hence functional roles had to be assigned to a set of 97 IP-nodes, but all nodes and links are available in the physical layer for network optimization.



Figure 3.1 Part of PEA DWDM Network Diagram

3.2.1 DWDM Working and Protection

There are two types of DWDM links connecting the ROADM nodes, the 10 Gbps and the 100 Gbps links. The optical working links for connecting between ROADM nodes are shown in figure 2.2 (a) while the related optical protection links are shown figure 2.2 (b). GE User Network Interface (UNI) links are proposed at each node for local fan out connectivity. The types of connectivity between these nodes can be differentiated into three types as follow, first is a 10 Gigabit Ethernet with 100 Gigabit trunk port (OTU-4) installed on almost all links connecting to HQ and

SMC, second is a 10 Gigabit Ethernet (OTU-2) used as the core trunks for interconnect the rest of topology for backbone router connectivity the nodes apart from what are connected to the HQ and SMC node. And the third, is the Gigabit Ethernet with 10 Gigabit trunk port (OTU-2) for intra-region connectivity.



(a) Working Link

(b) Protection Link

Figure 3.2 DWDM Connectivity Diagram

3.2.2 DWDM Network Equipment

The DWDM Network Equipment used in designing for the PEA DWDM Network used the main network equipment following theses.

3.2.2.1 Chassis

The chassis has two slots for redundant control cards and six slots for service cards. These six line-card slots provide increased power and cooling capability over the original chassis, and a usable high-speed backplane for future applications.

3.2.2.2 Add/Drop Multiplexer Modules

Mux/Demux 40-Channel Patch Panel is a standalone unit that contains both a 40-channel optical multiplexer and a 40-channel optical demultiplexer,

precabled within the unit housing. Two models are includes the odd-numbered and even-numbered frequencies as defined by ITU G.694.2

3.2.2.3 TNCE/TSCE Controller Card Module

The Transport Node Controller Enhanced (TNCE) and Transport Shelf Controller Enhanced (TSCE) card perform system initialization, provisioning, alarm reporting, maintenance, diagnostics, IP address detection and resolution, SONET and SDH data- communications-channel (DCC) termination, etc.

3.2.2.4 ROADM Module - Single Module ROADM

The single-module ROADM (SMR) cards are so compact by integrating multiple features on the same card (OSC, amplification and ROADM). This next generation 40-channel single-module ROADM with integrated optical pre-amplifier combines the OSC add/drop filter, a pre-amplifier, and a 2x1 wavelength selective switch (WSS)-based ROADM core into a single-slot unit. The SMR-1c unit is optimized for Degree-2 reconfigurable nodes. And the other is the 40-SMR2-C, ROADM with integrated optical pre-amplifier and boost amplifier also includes the OSC add/drop filter, pre- and boost amplifiers, and a 4x1 WSS-based ROADM core. The SMR-2c unit provides an effective way to support multi-degree nodes up to Degree-4.

3.2.2.5 ROADM Module - 80 Wavelength Cross Connect (WXC) Module

The 80-channel wavelength cross-connect card (80-WXC-C) is provides multi-degree switching capabilities at the individual wavelength level. Mesh and multi-ring network topologies can now be extended to 50-GHz, 80-channel DWDM systems, with complete flexibility of service routing at all nodes in the network. In planning design we used in the core of the network to build 50-GHz ROADM nodes. The 80-WXC-C is the primary unit for the 80-channel ROADM solution operating in the C band. The advantage is allows the possibility to remotely and automatically control a wavelength to be routed to any direction of a ROADM node. Embedded automatic power control mechanisms allow interfacing with different types of DWDM units without requiring external attenuators. Used in conjunction with multiplexers and demultiplexers, these mechanisms allow the management of local add/drop traffic in the specific direction supported by the 80-WXC-C unit. The 80-WXC-C card operates on the ITU 50-GHz wavelength plan.

3.2.2.6 10x 10 G Muxponder Card

The 10-Port 10 Gbps Line Card consists of 10 Enhanced Small Form-Factor Pluggable (SFP+) based ports and one 100-Gbps Channel Express (CXP) based port. Each of the 10 Gbps SFP+ based ports can support the following services OC-192/STM-64 (9.95328 Gbps), 10 Gigabit Ethernet LAN PHY (10.3125 Gbps), etc. Client ports can be equipped with a large variety of pluggable SFP+ transceivers, including grey or coloured

3.2.2.7 100 G Coherent Trunk Line Card

The trunk card that delivers DWDM transmission using a coherent polarization-multiplexed differential quadrature phase shift keying (CP-DQPSK) modulation scheme. The 100 Gbps Coherent DWDM Trunk Card is integration and transport of 100 Gigabit Ethernet and Optical Transport Unit Level 4 (OTU-4) interfaces and services into enterprises and service provider optical networks. With advanced modulation schemes, the ability to transmit 100 Gbps wavelengths on existing or new DWDM systems improves return on investment by increasing the overall capacity per fiber pair without impacting the unregenerate transmission distance supported by the system. Scaling from 10 Gbps to 40 Gbps and now 100 Gbps increases by a factor of 10 the bandwidth that can be transported over existing fiber networks. The new CP-DQPSK modulation supports 9.6 Tbps capacity transmission over Ultra-Long-Haul (ULH) networks of up to 3000 km of unregenerate optical spans.

3.2.2.8 OTU2-XPonder Card

This OTU2 XPonder is the primary service card type used to design for the PEA DWDN network requirement for 20 GE LAN PHY client interconnection services. This card provides internal protection mechanism (fiber switched protection) which allows the switchover to the protection trunk path in the event of the working path failure.

The 4-port 10 Gigabit Small Form-Factor Pluggable (XFP) based 10 Gigabit Ethernet transponder card for the integration and transport of OTU2, 10 Gigabit Ethernet (10GE), 10 Gigabit Fiber Channel (10G FC) and OC-192/STM-64 interfaces and services into enterprises or metropolitan-area (metro) and regional service provider networks. This card have the advantages of the Forward Error Correction/Enhanced Forward Error Correction (FEC/E-FEC) to regenerate the longer distance.

3.2.2.9 AnyRate XPonder Card

The Any Rate Enhanced Xponder Card provides an 8-port Small Form-Factor Pluggable (SFP) muxponder with two 10-Gigabit XFP ports. The card supports the following services include SDH level STM-1 /4/16, OTN level OTU-1 /OTU-2, Ethernet level Fast Ethernet (FE) and Gigabit Ethernet (GE).

3.2.2.10 Optical Amplifiers

The enhanced optical amplifier card operating in the C-band region of the optical spectrum to extend the reach and capacity of a metro, regional, or long-haul network. The network configuration utilizes five types of amplifiers in the entire system design. [50]

3.2.3 PEA DWDM Network Requirements

The number of the ROADM node is 54 nodes while the ILA node used in the expect design is 173 nodes. Accordingly, the total number of the DWDM nodes is 227 nodes. They can be classified by the type of the node as ROADM with Router. This type include 24 nodes are installs the ROADM equipment and one unit of Core Router as IP core router. The point-to-point service connection between nodes intra section is DWDM 10 GE and 1 GE service, while the connection between inter region core routers to support IP networking is DWDM 100GE and 10 GE service. This type of node can be further divided into the Area Distribution Dispatching Centers (ADDCs) 12 nodes and the Electrical Office/Substation (EO/ES) 12 nodes. The second type is ROADM node, this type of node are installs 30 ROADM nodes. It can support services up to 10 Gigabit Ethernet. This is for the service connection between nodes in the intra section. And Finally, ILA node without any service support. All management can be access through OSC. There is no add/drop traffic running on these nodes, their function is to only amplify DWDM signal. Reference to the overall requirements for the DWDM network system design and configuration is based on the sets of the optical fiber infrastructure information according to the table 3.1. The following information is the provided equations and the parameters.

Total Loss(dB) = Fiber Attenuation(dB) + Splice Loss(dB) + Connector Loss(dB)

Power Budget(dB) = Minimum Transmit Power(dBm) - Minimum Receiver Sensitivity(dBm)Operation Margin(dB) = Power Budget(dB) - Total Loss(dB) - Attenuator Loss(dB)

Parameters	Values
Spice Loss	0.15dB/Point
Connector Loss	0.40dB/Point
G.652 Attenuation	0.25dB/km at 1550 nm
G.655 Attenuation	0.25dB/km at 1550 nm
G.652 Chromatic Dispersion(CD) Coefficient	20 ρ s (nm × km)
G.655 Chromatic Dispersion(CD) Coefficient	6 ρ s (nm × km)
G.652 Polarized Mode Dispersion (PMD) Coefficient	0.2 ρ s / (km) ^{1/2}
G.655 Polarized Mode Dispersion (PMD) Coefficient	0.5 ρ s / (km) ^{1/2}
Operation Margin for each span	= 3 dB

 Table 3.1 PEA Optical Fiber Infrastructure Parameters [50]

3.3 PEA IP/MPLS Core Network

The Core Routers are designed to simplify and enhance the operational and deployment aspects of service delivery networks. The PEA IP/MPLS core network uses the IS-IS protocol as the IGP. In order to design the MPLS label mapping and exchange capability, the LDP is used along with the IS-IS. The services that can be provided by the PEA IP/MPLS core network are such as L2VPN (i.e. pseudowire), L3VPN (i.e VRF), MPLS-TE and etc. This design uses 24 Core Routers to support PEA departments (e.g. IT, IMS and SCADA). The services that are provided to these departments are such as L2VPN and L3VPN as mentioned above. This equates to all packet forwarding decisions and actions taking place on individual line cards. The Core Router provides an in place upgrade roadmap to a higher density of 10 GE, 40 GE and 100 GE ports without the need for a complete chassis replacement. These line cards, offered in base and extended-scale configurations, are complemented by the nonblocking fabric. The chassis components include two RSP cards and Up to eight Ethernet line cards. Figure 3.4 show the Core Router.



Figure 3.3 Core Router Connectivity Diagram

3.3.1 IP/MPLS Network Requirements

The overall requirements for network system design and configuration is based on these sets of "Traffic Matrix Demand and Lambda Connectivity". The overall network topology diagram shown in figure 3.3.

Core Router connectivity diagram shows the connections between the IP core router nodes, the hostname of the nodes and the lambda connectivity ID according to the planning as show in figure 3.5. The IP core router connectivity is used to provide the IP services such as IGP, MP-BGP, MPLS, Virtual Private Network (L2/L3 VPN).



Figure 3.4 Core Router



Figure 3.5 lambda connectivity ID

3.4 PEA IP over DWDM NETWORK

We introduced the concepts physical and logical topologies to design IP over DWDM in previous chapter. The physical topology is the network seen by the DWDM layer (optical layer). The logical topology seen by the IP layer (data layer). The node in topology corresponding to the IP router and a link in this topology represents and IP link realized by a lightpaths that has been established between the corresponding nodes. In the logical topology, the lightpath not only carries the direct traffic between the nodes it interconnects but also the traffic between the nodes that are not directly connected in the logical topology using electronic packet switching at the intermediate nodes [3]. The electronic packet switching functionality is provided by the IP routers.

To support the PEA IP/MPLS Core Network requirements, the IP/MPLS core network infrastructure using the Core Routers that are connected together through the DWDM equipment are designed. The transforming network will deliver the countrywide IP/MPLS network for connecting PEA sites. The Core Routers design will permit PEA network to profit from new aggregation services to its departments, enhance network operation and the efficiency of PEA network, decrease performance costs and the complexity of network configurations, and optimize end user experiences.

3.5 Design the network

For convenience, we define some general notations and assumptions that are used throughout the rest of the thesis.

Let (N_P, E_P) denote the physical topology, which consists of a set of nodes $N_P = \{1...|N_P|\}$ and a set of links E_P where link (i, j) is in E_P if a fiber link exists between node i and j. We assume a bidirectional physical topology, where if link (i, j) is in E_p so is link (j, i). Furthermore, we assume that a failure (fiber cut) of link (i, j) will also result in a failure of link (j, i). This assumption stems from the fact that the physical fiber carrying the link from i to j is typically bundled together with that from j to i. In some systems, the same fiber is used for communicating in both directions. Let $E_p = \{(i, j) \in E_p > j\}$ denote the set of bidirectional physical links. Lastly, we assume that each physical link is capable of supporting W wavelengths. Let (N_L, E_L) denote the logical topology. The logical topology can be described by a set of nodes N_L and a set of links E_L , where N_L is a subset of N_P and link (s,t) is in E_L if both s and t are in N_L and there exists a logical link, or a lightpath, between them. We also assume a bidirectional logical topology, where if link (s,t) is in E_L so is link (s,t). Given a logical topology, we want to route every logical link on the physical topology. We refer to this process as the routing of the logical topology. In order to route logical link (s,t) on the physical topology, we must establish a corresponding lightpath on the physical topology between node s and t Such a lightpath consists of a set of physical links connecting nodes s and t as well as wavelengths along those links. If wavelengths converters are available then any wavelength can be used on any link. However, without wavelength converters, the same wavelength must be used along the route. We assume that either wavelength converters are available or that the number of wavelengths available exceeds the number of lightpaths. Let $f_{i,j}^{s,t} = 1$ if logical link (s,t) is routed on physical link (i, j)

and 0 otherwise. We denote the routing of the logical topology by the assignment of values to the variables $f_{i,j}^{s,t}$ for all physical links (i, j) and logical links (s,t). We assume that logical link (s,t) will not be routed on both physical links (i, j) and (j,i), thus $f_{i,j}^{s,t} + f_{j,i}^{s,t} \leq 1$. Every logical link (s,t) is associated with a capacity denoted C_s . The capacity of each logical link (s,t) is divided into working capacity and spare capacity denoted by $\beta_{s,t}$ and $\mu_{s,t}$ respectively. The working capacity is dedicated to carry working traffic, while the spare capacity is dedicated to carry rerouted traffic in case of failures. We define the total working capacity as the sum of working capacity on all logical links. Similarly, we define the total spare capacity as the sum of total working capacity and total spare capacity.

The traffic demand for source-destination pair (u, v) is the amount of traffic that must be delivered from node u to v, where both u and v are in N_L . We assume a multi-hop network, where a traffic demand may have to hop through zero or more intermediate logical nodes. Lastly, we assume the IP routers can perform load sharing. If there are multiple routes from a source to a destination, traffic can be bifurcated over these multiple routes.

3.5.1 Mixed Integer Linear Programming Formulation

Given the physical topology and the logical topology, we want to develop a criterion for routing the logical topology. We associate a routing with a quantity between 0 and 1, called the load factor. Assume each logical link has capacity C. Given the routing and the corresponding load factor denoted by a network survivability is guaranteed if the traffic on every logical link does not exceed αC . The spare capacity on every logical link required for carrying disrupted traffic in the event of any physical link failure is at most $C(1-\alpha)$. Consequently, we want to find a routing that maximizes the load factor. We call this the lightpath routing and maximum load factor (LRMLF) problem. We will show that the load factor is indeed a good criterion for routing the logical topology and present a method to solve this problem. Based on the criteria established. We now formulate the LRMLF problem as a mixed integer linear program (MILP). Given a physical topology and a logical topology, we want to find a routing of the logical topology on the physical topology that maximizes the load factor.

We first develop a set of constraints which must be satisfied by every routing of the logical topology. To route logical link (s,t) on the physical topology, we must find a corresponding path on the physical topology between nodes *s* and t. When the logical links are bidirectional, finding a route from *s* to t also implicitly gives a route from *t* to *s* that follows the same physical links in the opposite direction. Let if $f_{i,j}^{s,t} = 1$ logical link (s,t) is routed on physical link (i, j) and 0 otherwise. Using the standard network flow formulation, finding a route from *s* to *t* equivalent to routing one unit of flow from node *s* to node t [27]. This can be expressed by the following set of constraints on variables $f_{i,j}^{s,t}$ associated with logical link (s,t):

$$\sum_{js.t.(i,j)\in E_p} f_{ij}^{st} - \sum_{js.t.(i,j)\in E_p} f_{ji}^{st} = \begin{cases} 1, & \text{if } s = i \\ -1, & \text{if } t = i \\ 0, & \text{otherwise} \end{cases}$$
(3.1)

The set of constraints above are the flow conservation constraints for routing one unit of flow from node s to node t. Equation (3.1) requires that equal amounts of flow due to lightpath (s,t) enter and leave each node that is not the source or destination of (s,t). Furthermore, node s has an exogenous input of one unit of flow that has to find its way to node t. There are many possible combinations of values that can satisfy Eq. (3.1). Any feasible solution has a route from s to embed in it. To find a routing of the logical topology, we must find a route for every logical link (s,t) in E_L

If the number of wavelengths on a fiber is limited to W, a wavelength capacity constraint can be imposed as follows:

$$\sum_{(s,t)\in E_L} f_{ij}^{st} \le W, \qquad \forall (i,j)\in E_P$$
(3.2)

The routing of logical topology, denoted by $\{f_{i,j}^{s,t}\}^*$, that maximizes the load factor must satisfy the following condition established in the previous section:

$$\left\{f_{i,j}^{s,t}\right\}^{*} = \underset{\left\{f_{ij}^{st}\right\}\in RS}{\arg\min} \max_{\substack{S \subset N_{L} \\ (i,j) \in E_{P}}} \frac{\sum_{(s,t) \in CS(S,N_{L}-S)} f_{ij}^{st} + f_{ji}^{st}}{\left|CS(S,N_{L}-S)\right|}$$
(3.3)

This directly translates to the following objective function, which must be minimized:

$$\max_{\substack{S \subset N_{L} \\ (i,j) \in E_{P}}} \frac{\sum_{(s,t) \in CS(S,N_{L}-S)} f_{ij}^{st} + f_{ji}^{st}}{\left| CS(S,N_{L}-S) \right|}$$
(3.4)

The objective function has the form $\max_{i=1,\dots,m} c_i x$. It is piecewise linear and convex rather than linear [27]. Mixed integer linear programming does not allow such objective functions. Problems with piecewise linear convex objective functions can be solved by solving an equivalent MILP problem. Note that $\max_{i=1,\dots,m} c_i x$ is equal to the smallest number f that satisfies $f = c_i x$ for all f. For this reason, the LRMLF problem is equivalent to the following MILP problem:

3.5.1.1 LRMLF

Minimize fSubject to:

1) Load factor constraints:

$$f \ge \frac{\sum_{(s,t)\in CS(S,N_L-S)} f_{ij}^{st} + f_{ji}^{st}}{\left| CS(S,N_L-S) \right|}, \qquad \forall S \subset N_L, \forall (i,j) \in E_P$$

2) Connectivity constraints:

$$\sum_{js.t.(i,j)\in E_P} f_{ij}^{st} - \sum_{js.t.(i,j)\in E_P} f_{ji}^{st} = \begin{cases} 1, & \text{if } s = i \\ -1, & \text{if } t = i \\ 0, & \text{otherwise} \end{cases}, \forall_i \in N_P, \forall (s,t) \in E_L \end{cases}$$

3) Wavelength capacity constraints:

$$\sum_{(s,t)\in E_L} f_{ij}^{st} \le W, \qquad \forall (i,j) \in E_P$$

4) Integer flow constraints: $f_{ij}^{st} \in \{0,1\}$

Let f^* and $\{f_{ij}^{st}\}^*$ be the optimal solution to the MILP problem assuming the problem is feasible. Using the maximum load factor. Furthermore, $f^* \ge \max_{k \in N_L} \frac{\left[\frac{L_k}{P_k}\right]}{L_k}$. The corresponding routing of the logical topology for the load factor is embedded in $\{f_{ij}^{st}\}^*$. The set of physical links used to route each logical link (s,t) is given by $\{(i,j) \in E_p : f_{ij}^{st} = 1\}$. The route may contain cycles because $\{f_{ij}^{st}\}^*$ with cycles always satisfy the connectivity constraints (i.e. flow conservation constraints) [27]. Cycles can be avoided by modifying the original objective function to the following, where c is a large constant:

$$\begin{array}{ll} \text{Minimize} \quad cf + \sum_{\substack{(s,t) \in L_L \\ (i,j) \in E_P}} f_{ij}^{st} \end{array}$$

Changing the objective function does not affect the feasibility of the original optimal solution f^* and $\{f_{ij}^{st}\}^*$ because the constraints are not

changed. Thus f^* and $\{f_{ij}^{st}\}^*$ remain feasible in the modified problem. Let f and $\{f_{ij}^{st}\}^{'}$ be the optimal solution to the modified problem. We show by contradiction that if c is sufficiently large (i.e. $c \gg |E_p| |E_L| \ge \sum_{\substack{(s,t) \in E_L \\ (i,j) \in E_P}} f_{ij}^{st}$), then $f' = f^*$

Proof Let C' be the objective value associated with f', $\{f_{ij}^{st}\}'$

and C' be the objective value associated with f^* and $\{f_{ij}^{st}\}^*$. Assume $f' > f^*$, we must show that $C' > C^*$ which would contradict the assumption that C' is the optimal objective value in the modified problem. Using the modified objective function, we can express $C' > C^*$ as

$$cf' + \sum_{\substack{(s,t) \in L_{L} \\ (i,j) \in E_{p}}} f_{ij}^{st'} > cf^{*} + \sum_{\substack{(s,t) \in L_{L} \\ (i,j) \in E_{p}}} f_{ij}^{st'}$$
$$c(f' - f^{*}) > \sum_{\substack{(s,t) \in L_{L} \\ (i,j) \in E_{p}}} f_{ij}^{st*} - f_{ij}^{st'}$$

Since $|E_p||E_L| > \sum_{\substack{(i,j)\in E_L\\(i,j)\in E_P}} f_{ij}^{sr^*} - f_{ij}^{sr'}$ it is sufficient to show $c(f'-f^*)|E_p||E_L|$. According to Eq. (3.4), both f' and f^* can only take on values from a finite set of rational numbers, which is a subset of $\left\{\frac{m}{n}; 0 \le m \le n \le K\right\}$ where m and n are integers and $K = \max_{s \in N_L} |CS(S, N_L - S)|$. Since f' and f^* are rational, $f'-f^*$ must also be rational. Because we assumed $f' > f^*$, the minimum nonzero difference is $f'-f^* \ge \frac{1}{K(K-1)}$: If c is sufficiently large such that $\frac{c}{K(K-1)} > |E_p||E_L|$, then $C' > C^*$. This would contradict the assumption that C' is the optimal objective value. Therefore, for this reason, we can add the term $\sum_{\substack{(s,t)\in E_L\\(i,j)\in E_P}} f_{ij}^{st}$ to the objective function, which can be considered as the cost of total flows associated

with routing the logical topology. Since any unnecessary flow will be avoided with the new objective, the routing embedded in variables $\{f_{ij}^{st}\}$ must not contain any cycles.

The above MILP can now be solved using a variety of techniques. We use the MATLAB language to implement the MILP and the CPLEX solver to solve it. The CPLEX solver uses the simplex method along with branch and bound techniques for solving MILPs [29]. However, the CPLEX solver takes a very long time to optimally solve our MILP. We find that if we use $minimize \sum_{\substack{(s,t) \in E_L \\ (i,j) \in E_P}} f_{ij}^{st}$ as the objective function, the solver can quickly find a feasible solution for a given value of f. Let MILP-LF(f) denote this modified MILP. By solving MILP-LF(f) for different values of f, we can obtain the minimum value of f for which MILP-LF(f) generates a feasible solution.

We now present an iterative algorithm that finds a routing with f arbitrarily close to the optimal value f^* . Let f and $\{f_{ij}^{st}\}$ denote the solution returned by the algorithm. Let $\{f_{ij}^{st}\}$ denote the optimal solution to MILP-LF(f) for a given value of f. Let δ be a small number (~ 0.01). Let ε be the maximum allowed gap between f and f^* .

3.5.1.2 Algorithm

Given the physical topology (N_P, E_P) and the logical topology (N_L, E_L) , we obtain an ε -close optimal solution to the LRMLF problem using the following procedures:

1) If MILP-LF(f) with f =1 - δ is infeasible, then return no survivable routing exists.

2) Set
$$f_{lb} = \max_{k \in N_L} \frac{\left[\frac{L_k}{P_k}\right]}{L_k}, f_{ub} = \max_{\substack{S \subset N_L \\ (i,j) \in E_P^{-}}} \frac{\sum_{(s,t) \in CS(S,N_L-S)} f_{ij}^{st} + f_{ji}^{st}}{\left|CS(S,N_L-S)\right|}$$

3) Repeat

If MILP-LF(f) with
$$\frac{f_{lb} + f_{ub}}{2}$$
 is feasible, then

Set
$$f_{ub} = \max_{\substack{S \subset N_L \\ (i,j) \in E_P}} \frac{\sum_{(s,t) \in CS(S,N_L - S)} f_{ij}^{st} + f_{ji}^{st}}{|CS(S,N_L - S)|}, \{f_{ij}^{st}\} := \{f_{ij}^{st}\} f_{ub} = f'$$

Else: Set $f_{lb} = f$

- 4) Until $f_{ub} f_{lb} \leq \varepsilon$
- 5) Return f' and $\{f_{ij}^{st}\}'$.

Algorithm 3.5.1.2 first determines whether or not any survivable routing exists for the given physical and logical topologies (step 1). Note that MLP-LF (f) with $f = 1 - \delta$ is precisely the ILP formulation of the survivable routing problem presented in [14]. If no survivable routing exists, the load factor can only be zero. Otherwise, the algorithm iteratively searches for the routing that minimizes f'. The optimal value f^* must be bounded between f_{lb} and f_{ub} (step 2). The key to finding the optimal value is to squeeze the two bounds as tightly as possible. During each iteration (step 3), we solve an instance of MILP-LF (f) by choosing f as the middle point between f_{ub} and f_{ub} If the chosen f yields a feasible solution, we use Eq. (3.4) to compute f' associated with the routing $\{f_{ij}^{st}\}$. Note that f' will be always be less than f. We also lower f_{ub} to f' because any feasible f' is an upper bound on the optimal value f^* . If the instance of MILP-LF (f) for the chosen f is infeasible, we increase $f_{lb} to f$. The gap between the two bounds strictly decreases after every iteration. The algorithm terminates when the gap is less than c (step 4). At this point,

f' is at most *c* away from f^* and the corresponding routing is given by $\{f_{ij}^{st}\}'$ (step 5).

3.5.2 Cisco Transport Planner (CTP)

Cisco Transport Planner software provides a simple tool set for designing optical networks with Cisco ONS 15454 MSTP products. We enter all network parameters, or minimal information, such as site distance and CTP models the network we need to build and generate a detailed BOM with ordering information. Designing optical networks requires the verification of multiple constraints such, as optical budget limitations and platform architectural restrictions. It provides a way to model and test DWDM optical networks in a graphical environment. The primary purpose of it is to help design and validate networks. We can create multiple instances of a network to modify different parameters in each instance for comparison also generates a shelf view of all the sites deployed in the optical network and provides a complete bill of materials (BoM) for the network and the differences between instances of a network. CTP able to design, analyze, and optimize new or existing network, searches for the best solution to a designed network using an optimization algorithm. A network design must meet the optical budget and receiver overload criteria to operate efficiently. An analysis of the optical budget and receiver overload evaluates the strength of the signal traversing the topology. If a design solution satisfies the constraints, it is a valid design. The optimization algorithms generate multiple solutions and verifies the constraints against those solutions. If the constraints are satisfied, the solution with the lowest "cost-to-utilization ratio" is selected as the optimal solution. If the network design solution fails to satisfy all the constraints, we makes adjustments to parameters such as signal attenuation and amplification. Amplification is achieved using an EDFA. Attenuation is achieved using the VOA modules integrated into the platform. We corrects the optical budget using an algorithm that includes automatic placement of EDFAs and VOA regulation.

The CTP process flow shown below provides network designer a high level engineering design workflow standard. To generate a DWDM network design, in general, we enter the following parameters into the CTP [51]:

3.5.2.1 The topology of the network: ring, linear, or meshed.

3.5.2.2 The number of network nodes.

3.5.2.3 The distance separating the nodes, the type of fiber connecting the nodes, the losses for each span, and the required End of Life (EOL) margin as per customer.

3.5.2.4 Service demands, including the service type, the protection type, and the number of channels between nodes.

3.5.2.5 The type of equipments used at each node.

The CTP optimization algorithms generate multiple solutions and verify the constraints against those solutions. If the constraints are satisfy, the solution with the lowest "cost-to-utilization ratio" is selected as the optimal solution. Using the optimization algorithms, its find the best routing, defines the required add/drop filters, and places optical amplifiers with DCUs.

Finally, CTP generates a BOM, the quantities, and pricing information. In addition, it creates other reports, such shelf-level vide of the configuration. This information helps we understand how to shelf is built and helps to avoid confusion and errors during the actual deployment.



Figure 3.6 The High-Level Engineering Design Workflow

3.6 Experimental results

Using the CTP, the network topology, traffic client interfaces, working and protection paths, fiber types, fiber losses and EOL margin are mapped according to the PEA's Network requirements. All required parameters are encoded into the design tool. The topology type of the network is mesh because we requires some specific working and protection path. The types of equipment used at each node are specified in [16]. It is matched with PEA's Network requirement at each node. The type of fiber connecting the nodes, the losses for each span (e.g., Fiber type, Total Span Loss and etc.) and the distance separating the nodes are specified in table 2.1. The required End of Life (EOL) margin as per customer is 3 dB EOL aging loss. All ducts as service demands, including the service type, the protection type, and the number of channels between nodes (i.e., 40-Channel P2P 10 GE or 100 GE). The initial design, all ROADM node build top support full 40-channel of 10 GE and 100 GE point-to-point demand. But for this design, the transponder card are proposed based on Traffic

Matrix Demand and Lambda Connectivity. The network topology, which include 54 ROADM and 173 ILA nodes are show (partly, due to limit of page) figure 3.7.

The PEA DWDM network design results are present and discuses on this paper, include the optical summary design results as show in table 3.2-3.3, the traffic matrix design result as show in table 3.4, and the link availability as show in the table 3.5. The optical summary design result show the detail of parameter and performance of the wavelength service. In the table is the service of point to point between UBN_ADDC and NMA_ADDC with the wavelength channel carried 10 GE LAN PHY service between NMA_ADDC and SMC.

The service of point to point between UBN_ADDC and NMA_ADD the design result selected the wavelength channel No. 37 (λ_{37}) 1558.98 nm or 192.30Thz C-band DWDM 50 GHz ITU-T grid. The traffic matrix design result as show in table 3.2. The traspoder card is seleted OTU2-XP with the FEC function to enhance the BER and impove more long distance approximately 431.60 km. with unregenerate. The perforemance evaluate as BER target at 10⁻¹⁵ passed. The OSNR value at source node are 15.77 dB and 15.40 dB, at the destination node are 13.34 dB and 13.14 dB the performance of OSNR values all are passed the margin and the definition of ITU-T G.692 stanndard, which make the wavelength chanel can carrried the traffics and able to decode. With the protection type, the design selected Fiber-Switched with the link availability of 0.999987% or 99.9987% as show in table 3.3. The latency network performance of this wavelength are aproximately 2.59 msec. for working path and 3.36 msec. for protection path.

The second service is, point to point between NMA_ADDC and SMC (HQ) the design result selected the wavelength channel No. 1 (λ_1). The traspoder card is seleted 100 G-LC-C + 10X10G-LC, w/HG-FEC(ClASS: AL) with the FEC function to enhance the BER and impove more long distance approximately 350.99 km. with unregenerate. The perforemance evaluate as BER target at 10⁻² passed. The OSNR value at source node are 15.90 dB and 16.35 dB, at the destination node are 14.44 dB and 14.80 dB the performance of OSNR values all are passed the margin and the definition of ITU-T G.692 stanndard, which make the wavelength chanel can carried

the traffics and able to decode. With the protection type, the design selected Y-Cable with the link availability of 0.9999999 or 99.99999 % as show in table 3.3 The latency network performance of this wavelength are aproximately 2.50 msec. for working path and 1.90 msec. for protection path.

Additional designed results in table 3.1 can be describe following, BER target displays the bit error rate (BER) target for this channel based on the capability of the channel's optical interface. It is 10^{-15} for the interfaces using forward error correction (FEC) and 10^{-12} for interfaces without FEC. SOL OSNR (dB) and EOL OSNR (dB) displays the start of life and end of life average OSNR value at the receiver respectively. SOL OSNR Margin (dB) and EOL OSNR Margin (dB) displays the SOL OSNR and EOL OSNR margin calculation, which is the difference between the OSNR value at a certain power of the working point of the receiver client and the working area boundary. SOL RX (dBm) and EOL RX (dBm) displays the SOL and EOL received average power at the destination node in dBm. SOL and EOL Power margin (dB) displays the SOL and EOL power budget margin at the receiver in decibels. It is defined as the offset between the receiver working point and the BER curve with margin. A positive value indicates no power problems. SOL and EOL Overload (dB) displays the SOL and EOL overload margin at the receiver in decibels. A positive value indicates no overload problems. Residual CD [ps/nm] displays the total dispersion value of the circuit. This total is the difference between the sum of CD robustness of the source and destination transponders, and the sum of fiber dispersion and dispersion compensation due to DCU units in the circuit. CD Robustness [ps/nm] displays the chromatic dispersion robustness of the receiver.

In Y-cable protection, one transponder card is designated as active and the other as standby. The standby transponder card has the client-side laser turned off to avoid corrupting the signal transmitted back to the client. The active transponder monitors the signal from the trunk side and in the event of loss or signal failure, the system switches to the standby path. This specific protection mechanism is used for the 10 GE traffic demand running over the 100 G trunk cards (15454-M-10X10G-LC card and 15454-M-100G-LC-C card). After they use protection path for send data, the protection path will promote to working path and still use it until path is broken.

Fiber-switched protection, the single client signal is injected into the client receive (Rx) port. It is then split into two separate signals on the two trunk transmit (Tx) ports. The two signals are transmitted over diverse paths. The far-end card chooses one of the two trunk Rx port signals and injects it into the Tx client port. This specific protection mechanism is used for the 10 GE traffic demand for the case of OTU2 Xponder card and GE for the case of AnyRate Xponder/Transponder cards (15454-OTU2-XP card and 15454-AR-MXP card). After they use protection path for send data, the protection path will promote to working path and still use it until path is broken.

With the benefit of coherent CP-DQPSK aimed to results of high CD robustness, PMD robustness and low OSNR needed as the results in table 3. As the result we can avoid the DCUs, no need the precise the fiber characterization and can reach more distance without E-O-E regeneration.

To verify the benefit of coherent CP-DQPSK in simultion phase ,in Figure 3.7 illustrates that Coherent DQPSK offers approximately 4dB improvement in OSNR sensitivity compared to Noncoherent DQPSK.



Figure 3.7 Comparison of Coherent and Noncoherent of DQPSK 100 GE transponder in AWGN

Finally, we can measure the spectrum of 100 GE transponder by use the OSA to verify the optical signal and noise. We measured it at the point of demultiplexer card where the ROAMD site as show in Figure 3.2. The measurement result show the spectrum of the three 100 GE transponders and one supervisory channel, each wavelength channel flat and OSNR value meet the requirement value according to ITU-T G.698



(c) Optical Spectrum Analyzer

Figure 3.8 Optical spectrum of 100 GE transponder experimental measurement



Figure 3.9 PEA DWDM designed topology

Table 3.2	Optical Summary Design Result of UBN_ADDC-NMA_ADDC/10GE
	LAN PHY

Parameter	Value/Results
Protect Type	Fiber-Switched
SOL	ОК
EOL	ОК
SE	OK
Wavelength (No.)	58.98 (O-37)
Src Tx Type	OTU2-XP - w/EFEC
Dst Tx Type	OTU2-XP - w/EFEC
Span [Km]	431.6
BER target	1.0E-15
	1.0E-15

Table 3.2 Optical Summary Design Result of UBN_ADDC-NMA_ADDC/10GE LAN PHY (Continued)

Parameter	Value/Results
SOL OSNR [dB]	15.77
	15.50
EOL OSNR [dB]	13.34
	13.14
SOL OSNR margin [dB]	6.30031
	5.91255
EOL OSNR margin [dB]	3.87031
	3.52445
SOL RX [dBm]	-13.70
	-13.46
SOL Overload [dB]	4.35929
	4.49704
EOL Overload [dB]	4.35929
	4.49704
Residual CD [ps/nm]	174.40
	1,021.40
CD Robustness [ps/nm]	[-350.0, 1300.0]
	[-350.0, 1300.0]

Table 3.3 Optical Summary Design Results of PointToPoint/NakhonRatchasima ADDC-SMC/10GE LAN PHY (1/1)

Parameter	Value/Results
Protect Type	Y-Cable
SOL	ОК
EOL	ОК
SE	ОК
Wavelength (No.)	30.33 (O-01)
Src Tx Type	100G-LC-C + 10X10G-LC,w/HG-FEC
Dst Tx Type	100G-LC-C + 10X10G-LC,w/HG-FEC
Span [Km]	350.99
BER target	0.01
	0.01
SOL OSNR [dB]	15.9
	16.35
	14.44
EOL OSNR [dB]	14.8
SOL OSNR margin [dB]	4.08572
	4.62162
EOL OSNR margin [dB]	2.58879
	2.95719
SOL RX [dBm]	-12.52
	-11.82
CD Robustness [ps/nm]	[-37000.0, 37000.0]
	[-37000.0, 37000.0]

								Cl.			Max.
			Src.	Src. T/C		Dst.	Dst. T/C	Serv.	Protection		Latency
Demand		Src. Site	Card	OpMode	Dst. Site	Card	OpMode	Type	Type	Wavelength	(µs)
UBN - NRM	•	•	•			•		10GE LAN PHY	Fiber- Switched		
	Service_1			-							
	OCH-CC- W	UBN_ADDC	OTU2- XP OTU2-	Splitter Mode	NRM_ADDC	OTU2- XP OTU2-	Splitter Mode				2,587.5708
	Trail-W	UBN_ADDC	XP OTU2-	w/EFEC	NRM_ADDC	XP OTU2-	w/EFEC				
		UBN_ADDC	XP OTU2-	w/EFEC	NRM_ADDC	XP OTU2-	w/EFEC			58.98 (O-37)	2,587.5708
		NRM_ADDC	XP OTU2-	w/EFEC	UBN_ADDC	XP OTU2-	w/EFEC				2,564.25
	Trail-P	UBN_ADDC	XP OTU2-	w/EFEC	NRM_ADDC	XP OTU2-	w/EFEC				
		UBN_ADDC	XP OTU2-	w/EFEC	NRM_ADDC	XP OTU2-	w/EFEC			58.98 (O-37)	3,354.3545
		NRM_ADDC	XP	w/EFEC	UBN_ADDC	XP	w/EFEC	10GE			3,362.8347
NRM- HO								LAN PHY	Y-Cable		
	Service 1										
	OCH-CC-		100G-			100G-					
	W	NRM_ADDC	LC-C 100G-	w/EFEC	HQ_EO	LC-C 100G-	w/EFEC				2,476.7334
	Trail	NRM_ADDC	LC-C 100G-	w/EFEC	HQ_EO	LC-C 100G-	w/EFEC				
		NRM_ADDC	LC-C 100G-	w/EFEC	HQ_EO	LC-C 100G-	w/EFEC			32.68 (O-04)	2,476.7334
	OCH-CC-	HQ_EO	LC-C 100G-	w/EFEC	NRM_ADDC	LC-C 100G-	w/EFEC				2,433.2048
	Р	NRM_ADDC	LC-C 100G-	w/EFEC	HQ_EO	LC-C 100G-	w/EFEC				1,944.0978
	Trail	NRM_ADDC	LC-C 100G-	w/EFEC	HQ_EO	LC-C 100G-	w/EFEC				
		NRM_ADDC	LC-C 100G-	w/EFEC	HQ_EO	LC-C 100G-	w/EFEC			32.68 (O-04)	1,944.0978
		HQ_EO	LC-C	w/EFEC	NRM_ADDC	LC-C	w/EFEC				1,895.3359

Table 3.4 Traffic Matrix Design Result

Source - Destination	Serv. Circuit	DWDM Card	Protection	Cl. Serv. Type	Link Availability
NMA - HQ	Service_1	100G-LC	Y-Cable	10GE LAN PHY	0.999999
NMA - SMC	Service_1	100G-LC	Y-Cable	10GE LAN PHY	0.999999
UDN - UBN	Service_1	OTU2-XP	Fiber-Switched	10GE LAN PHY	0.999987
UBN - NMA	Service_1	OTU2-XP	Fiber-Switched	10GE LAN PHY	0.999987
UBN - MDH	Service_1	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
UBN - MDH	Service_2	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
UBN - MDH	Service_3	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
UBN - MDH	Service_4	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
UBN - MDH	Service_5	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
UBN - MDH	Service_6	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
UBN - MDH	Service_7	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
UBN - MDH	Service_8	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_1	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_2	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_3	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_4	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_5	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_6	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_7	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981
NMA - MHK	Service_8	AR-XP	Fiber-Switched	Gigabit Ethernet	0.999981

Table 3.5 Link availability results

3.7 Conclusions

In this Chapter, we studies on the overview of the network and models. First, we introduce the theory and concept of the MILP call this the lightpath routing and maximum load factor (LRMLF) for using in the designing phase.

Second, we study the PEA DWDM network includes the environment, parameter of optical fiber and the network equipment of DWDM system for designing the network according to requirements of bandwidths. The designing phase considering the impairment of physicals (include the DWDM equipment and optical fiber cable). We find the observation on the designing based on CTP program are follows: (1) Using different of the modulation formats of transponder card are effect to performance for transport the wavelength channel on the signal rate 1 GE, 10 GE and 100 GE. The experimental results show using modulation format of coherent CP-DQPSK aimed to results of high CD robustness, PMD robustness and low OSNR needed. As the result we can avoid the DCUs, no need the precise the fiber characterization and can reach more distance without E-O-E regeneration. (2) FEC, EFEC, HG-FEC aimed to improve the limite of distance, we can transport wavelength channel across the network without generation, especially 100 GE signal. (3) Protection type of Y-cable give well link availability more than fiber switched. Third, we verify the benefit of coherent CP-DQPSK in simultion phase, illustrates that Coherent DQPSK offers approximately 4 dB improvement in OSNR sensitivity compared to noncoherent DQPSK.

And finally, we study on IP/MPLS core netwok with the concepts to connect on DWDM layer ,what we designed. The design results, give we the concepts with connect the IP/MPLS Core router at the ROADM node with 1GE, for intra region, 10GE for inter region and the high capacity 100 GE for HQ to inter region. For the performance of network, which we desiged will discus in next chapter.
CHAPTER 4 NETWORK PERFORMANCE EVALUATION

In the previous chapter we presented the network model and requirements of network that lead us to examine the general routing issues in networks from the performance point of views. Now we define more precisely the performance evaluation in the DWDM layer (optical layer) and IP layer (data layer). We also list and classify the methods that can be applied in the analysis in the both layers.

4.1 Introduction

We study IP over DWDM in the core segment of the network. According to the network model presented in Chapter 3 and with specifying the service trail we define two layers, which are the optical layer provides high capacity connectivity by establishing optical connections that may span large physical distances, and the data layer providing resources and networking functions to the user with applications that can use several transport protocols (or "IP layer"). The optical layer can be interpreted as a network that consists of optical links and switching nodes (or "DWDM layer"). The optical links contain several fibers, their number can go up to hundreds in one link. Each fiber can transport data on several wavelengths. A wavelength realizes a high capacity optical channel on the link. The theory and related work of grooming were described in Chapter 2.

4.1.1 General model of the network structure

Let us follow the whole route of an IP data unit in the network shown on Figure 4.1. It presents the data planes of the two layers and the connection between them. Control plane details are neglected in this abstraction of IP over DWDM networks and we assume a single domain environment in both layers. The data is sent from router C_D to router E_D . We assume that the routing of the data layer assigned to this communication the route $C_D - A_D - E_D$, i.e. a two-hop path in the virtual topology. In the reality the data will be groomed into lightpaths and passes through the optical layer. First it takes interlayer channel $C_D - C_O$, lightpath $C_O - A_O$ and interlayer channel $A_O - A_D$ which series realizes the virtual link $C_D - A_D$ and then another interlayer channel $A_D - A_O$, lightpath $A_O - E_O$ and interlayer channel $E_O - E_D$ that realizes the virtual link $A_D - E_D$. The real route passed even the optical equipment of node *B* but this remains hidden from the data layer.



Figure 4.1 General multilayer network model

4.1.2 Decomposition of the analysis task

The main objectives of the studies presented in the Chapter is to find the right performance measures that characterize the modelled networks and to evaluate them considering general routing problem solutions. The optimal solution would be the compound analysis of the multilayer network architecture, but besides the very complex modelling task, this meets with other difficulties too. On the one hand the different layers imply different characteristics to observe. The different issues may require also different methods to apply in the analysis. On the other hand the general routing problem may include multiple functions, thus enlarges also the solution space to study. Using a compound model the separation of the effects caused by each cooperating function becomes rather complex. For instance, the effects of the current IP network routing may

blend with that of the applied wavelength assignment and lead to a confusion in the analysis. We focus the analysis on the special issues in a more effective way by decomposing the network and observing the layers separately. The performance of not compound routing functions can be analyzed easier this way, since it remains tractable how the algorithm settings affect the behavior of the network. However, there are questions that refer the issues of the cooperation of the layers and the compound analysis is surely indispensable, e.g. the performance of a given grooming solution. Figure 4.2 illustrates the decomposition of the IP over DWDM architecture. In the compound model data transfer requests arrive from the IP users to the network. The changes of the traffic generated by the service of the user requests implies requests to opening or closing optical connections, i.e. lightpaths, according to the decisions of the grooming policy.



Figure 4.2 Separation of network layers

If we separate the layers, only the relating requests and functions need to be considered in their models. This simplifies the analysis. The decomposition of our general analysis task results in three subproblems:

(1) Analysis of the optical layer as a DWDM network with fix topology,

(2) Analysis of the data layer as an IP network with fix topology,

(3) Analysis of the IP over DWDM network with fix topology in the optical layer but with variable topology in the data layer.

4.2 Performance of the optical layer

Though there are some relevant differences, the obvious similarities with classic circuit switched networks suggest us to study similar performance measures as in that research field. The measurement of the performance are the utilization of the total network transfer capacity of the individual links and blocking probability, i.e. the ratio of refused optical connection requests. These quantities represent the cost efficiency and availability of services provided by the dynamically switched optical network, thus our studies focus on the analysis of these measures. We dealt mainly with the blocking probability and the impact of the following special properties:

(1) Wavelength conversion constraints in nodes,

(2) Links consisting of several fibers,

Recently the performance analysis of RWA in dynamic DWDM, i.e. automatic switched optical networks received a lot of interest. Many algorithms on this topic were presented and analyzed, summaries on this research area can be found for instance in [52-54]. Several previous work were presented in recent years on parts of the theoretical models of dynamic DWDM networks. However, most of these models can be applied only among very strict conditions. In nearly all related models we find the constraint, that the requests arrive according to a very realistic scenario. As it was discussed in chapter 3.

4.2.1 Theoretical analysis of dynamic DWDM networks

We assume that the all optical communication network consists of a set of switching nodes modelling ROADMs and optical links connecting them. A continuous series of adjoint links is called path or route. According to the multifiber option a link consists of one or more fibers. An identical wavelength set is assumed on each fiber. A wavelength realizes one optical channel with a bandwidth that depends on the technology. As discussed about the network model in chapter 3

Approaching the study of performance evaluation of DWDM networks, we applied and devised Wavelength Dependent Multifiber Model (WDMM). We define the

WDMM in our term is the capable of ROADM, its make we except the condition of wavelength continuities constrain.

The model is define that a wavelength is free on a link when there is at least one fiber of the link where the wavelength is currently not occupied. This term can be extended for routes, a wavelength is free on a route if it is free on each link of the route.

We illustrate the concept of wavelength trunks on Figure 4.3. The wavelength trunk T_j^w is the set of optical channels in link *j* that are assigned to wavelengthw. The possibly different number of fibers on the links imply that T_i^w and T_j^w on different links can have different sizes. On the other hand, since fibers are identical, the trunk sizes T_j^w and T_j^v are equal for each *w* and *v*. The channels in trunks with the same wavelength can be connected in the nodes without restrictions since no wavelength conversion constrain among them. A trunk is free on a link when at least one of its channels is free, i.e. the corresponding wavelength is free on the link according to the above defined term.



Figure 4.3 Wavelength trunks on joint links

Connection requests arrive in dynamic fashion according to a stochastic process and their duration is stochastically distributed. The routing and wavelength assignment task is performed every time a request arrives. The pairs of nodes can be referred by their assigned route and vice versa, since a single, predefined path is selected for each connection between a given source-destination pair. Thus our model considers fix routes that can be determined with any algorithm.

If there are one or more free wavelengths on the selected route, a lightpath can be established for the communication. The selection of the wavelength is realized by a weighted random choice. To achieve a uniform distribution of their usage, the current weight for wavelength w is set to the current minimum of the available optical channels of w on the links of the route. This is equal to the number of lightpaths that could be set up concurrently using w at the instant of the arrival.

The connection occupies one optical channel of the chosen wavelength w on each link of the route and it is called a connection of color w. If there are no free wavelengths on the route assigned to the source-destination pair, the connection request will be refused and a blocking event has to be registered. Blocked requests are not repeated.

We used the following notation:

J : number of network links

R: route, that consists of |R| links

 M_i : number of fibers on link j

M : maximum value of M_i

C: number of different wavelengths on one fiber

 C_i : capacity of link j, it can be calculated as $M_i \cdot C$ and it is given in optical

channel

H : maximum number of hops in the predefined routes of the network.

According to the definitions the number of trunks is C on every link and the size of T_i^w is M_j .

The analysis is performed by an iterative algorithm equipped with a feedback on the offered load level. The main steps are as follows:

(1) Initialize the input values.

(2) Compute link loads considering the blocking effects originating from other links.

(3) Calculate the probability that a set of wavelengths is free on a single link,

(4) Extend the analysis to whole routes using an iterative method considering the mutual impact of adjacent links.

(5) Calculate total network blocking probability considering the offered traffic pattern.

(6) If the required precision is reached then stop, else start again from step 2.

4.2.1.1 Traffic model and single link analysis

We model the DWDM network considering all types of traffic that can be described by a memoryless arrival process with a possibly varying intensity and exponential holding times. From these traffic models we can derive the process that describes the number of occupied optical channels on a link as a birth-death process. Let $\alpha_j(m)$ be the intensity of connection request arrival on link j, given exactly mfree optical channels on it. At the calculation of this intensity we have to consider the characteristics of all the traffic that meets link j. According to the arrival model $\alpha_j(m)$ can depend on the current state of link j and it is also affected by the traffic arriving to other network links. We do not loose generality assuming normalized intensities by setting the mean connection holding time to 1.

From the steady state analysis of the birth-death process we can easily get the probability of being exactly m free channels on link j:

$$q_{j}(m) = \frac{C_{j}(C_{j}-1)\cdots(C_{j}-m+1)}{\alpha_{i}(1) + \alpha_{i}(2)\cdots\alpha_{i}(m)}q_{j}(0)$$
(4.1)

Where $q_i(0)$ has to be calculated via normalization, i.e. according to

the fact, that $q_j(m)$ is a distribution on m. All the following calculations use this distribution regardless of how the $q_j(m)$ values were obtained. Thus, WDMM works in the case of any traffic model, for which these values can be calculated. A wavelength set is available by definition if each wavelength in the set is free. The probability that a set I with cardinality i is available on link j can be derived according to the application of the random wavelength assignment algorithm:

$$\beta_{I,j}^{mul} = \sum_{m=i}^{C_j} q_j(m) \frac{\sum_{k=0}^{\min\left(\left\lfloor i, \frac{C_j - m}{M_j} \right\rfloor\right)} (-1)^k \binom{i}{k} \binom{C_j - M_j k}{m}}{\binom{C_j}{m}}$$
(4.2)

The sum in the nominator of Equation 4.2 describes the number of cases when the wavelengths of set I are free, given that there are m free channels on link j. We can get it as the number of all cases $\binom{C_j}{m}$ less the number of cases when at least one wavelength of I is not free. The latter is calculated using the inclusion-exclusion rule for the members of set I.

4.2.1.2 Analysis of multihop routes

Let us observe now the mutual effect of links that can be derived from the traffic correlation and from the lack of wavelength conversion assumed in our all optical network model. As it is mentioned in [55] too, this effect is not negligible if there are several routes that contain some common multihop sections.

To simplify the problem we introduce some assumptions applied to each route R:

1) On adjacent links j and j+1 of route R we consider only the dependencies of the trunks with the same wavelength, i.e. T_j^w and T_{j+1}^w ,

2) The dependencies of trunks with the same wavelength is considered only on the adjacent links of route R,

3) We do not consider the dependencies between the traffic on link j and any other traffic relation in the network that uses a route R not containing j.

Now we can estimate the probability that a set I is available on the two-hop route consisting of links A and B:

$$g_{I}^{A,B} \approx \beta_{I,B}^{mul} \prod_{k=1}^{i} \frac{\beta_{I_{k},A}^{mul} - \beta_{I_{k-1},A}^{mul} \gamma_{k,AB}^{0}}{\beta_{I_{k-1},A}^{mul} (1 - \gamma_{k,AB}^{0} - \gamma_{k,AB}^{1})}$$
(4.3)

where $\gamma_{k,AB}^0$ is the probability that wavelength k is free on link A,

but not free on link B, while the $\gamma_{k,AB}^{1}$ is the probability that k is not free on both link A and B. Wavelength-set I_{l} contains the first l members of set I and its cardinality is equal to l. After l steps the product in Equation 4.3 results in the conditional probability, that set I_{l} is available on link A, given that it is available on link B. Thus, after i steps we get the conditional probability for set I.

Let us consider the mean intensity of traffic on link o as λ_o and that of continuing traffic on two adjacent links p, q as $\lambda_{p,q}$. A continuing connection means, that the assigned route contains both the p and q links. Using a combinatoric approach we can derive the following probability values that hold for each wavelength w:

 P_j^i is the distribution of the number of connections of color w on link j:

$$P_{j}^{i}(k) = \sum_{m=M_{j}-k}^{C_{j}-k} q_{j}(m) \frac{\binom{M_{j}}{k} \binom{C_{j}-M_{j}}{m-(M_{j}-k)}}{\binom{C_{j}}{m}}$$
(4.4)

 P_c^j is the distribution of the number of continuing and noncontinuing connections of colour w on the adjacent links j and j+1:

$$P_{c}^{j}(l,k) = P_{l}^{j}(k+1) \left(\frac{\lambda_{j,j+1}}{\lambda_{j}}\right)^{l} \left(1 - \frac{\lambda_{j,j+1}}{\lambda_{j}}\right)^{k} \binom{k+l}{l}$$
(4.5)

 P_n^j is the conditional distribution of the number of continuing connections of color w on the adjacent links j-1 and j, given the number of non-continuing connections:

$$P_n^j(k \setminus l) = \frac{P_l^j(k+1) \left(\frac{\lambda_{j-1,j}}{\lambda_j}\right)^l \left(1 - \frac{\lambda_{j-1,j}}{\lambda_j}\right)^k \binom{k+l}{l}}{\sum_{n=0}^{M_j-l} P_l^j(n+l) \left(\frac{\lambda_{j-1,j}}{\lambda_j}\right)^l \left(1 - \frac{\lambda_{j-1,j}}{\lambda_j}\right)^n \binom{n+l}{l}}$$
(4.6)

Note that these values are independent from w due to the random assignment of wavelengths. To determine the values $\gamma_{k,AB}^0$ and $\gamma_{k,AB}^1$ we can use these distributions:

$$\gamma_{k,AB}^{0} = \sum_{i=0}^{M_{A}-1} \sum_{l=0}^{\min(M_{B,i})} P_{n}^{(B)}(M_{B}-l \setminus l) P_{c}^{(A)}(l,i-l)$$
(4.7)

$$\gamma_{k,AB}^{1} = \sum_{l=0}^{\min(M_{B},M_{A})} P_{n}^{(B)}(M_{B} - l \setminus l) P_{c}^{(A)}(l,M_{A} - l)$$
(4.8)

Now we introduce the conditional probability that the set I of wavelengths on the j^{th} link of route R is available, given that it is available on the subsequent link j+1:

$$\beta_{I,j}^{'} = \frac{g_{I}^{j,j+1}}{\beta_{I,j+1}^{mul}}$$
(4.9)

Starting from the above values we can calculate the probability that the wavelength set

I is available on the whole route R of |R| hops:

$$g_{I}^{R} = \beta_{I,H}^{mul} \prod_{j=1}^{|R|-1} \beta_{I,j}^{'}$$
(4.10)

The blocking probability on the route R, i.e. the blocking of the traffic that uses this route, can be computed easily, using the inclusion-exclusion rule of sets:

$$B_{R} = 1 - \left(\sum_{k=1}^{C} (-1)^{k-1} {\binom{C}{k}} g_{I_{k}}^{R}\right)$$
(4.11)

To get the total blocking probability of the network, we only need to take the weighted sum of the B_R values. The weights are the normalized offered load values between each pair of nodes, i.e. the values in the interest-matrix.

Let us show how load correlation effects can be considered in WDMM. Blocking on route R affects the offered load on each of its links. Thus, we can derive the intensity of connection request arrival on link j, given m free optical channels on it:

$$\alpha_{j}(m) = \sum_{R: j \in R} \left(\lambda_{R}(j,m) \sum_{k=1}^{\min(m,c)} (-k)^{k-1} \binom{C}{k} g_{I_{k}}^{R,j}(m) \right)$$
(4.12)

Where $\lambda_R(j,m)$ is the intensity of the traffic offered to route R

when there are *m* free channels on link *j*. For the *Poisson* traffic model $\lambda_R(j,m)$ does not depend on *j* and *m*. For the Binomial and Pascal traffic types a more complex calculation is required.

The conditional probability $g_{I_k}^{R,j}(m)$ means that the wavelength-set I is available on route R, given that there are m free channels on link j. Using the same idea as in Equation 4.2 this probability can be calculated as:

$$g_{I_{k}}^{R,j}(m) = \frac{g_{I}^{R}}{\beta_{I,j}^{mud}} \frac{\sum_{j=1}^{\min(i, \lfloor \frac{C_{j}-m}{M_{j}} \rfloor)} (-1)^{k} \binom{i}{k} \binom{C_{j}-M_{j}k}{C_{j}-M_{j}k-m}}{\binom{C_{j}}{C_{j}-m}}$$
(4.13)

4.2.2 Numerical results

The PEA DWDM network consists of 24 nodes and 35 optical links (consider only core node connected with IP core router). The numbers on the links are the length derived from the distance in kilometers and the capacity in wavelengths. Its design was based on previous chapter.



Figure 4.4 Blocking probability in the PEA DWDM network with 40 (left) and 20 (right) wavelengths per fiber

The number of wavelengths C was set to 40 in the first case and to 20 in the second case. The results are presented on Figure 4.4 left and right plot respectively. We can observe the robust accuracy of the WDMM model in both cases.

4.3 Performance of the data layer

This section analysis the performance in the data layer, with a specific interest on the IP routing solution. The aim of this work to find efficient but correct ways to assess network capabilities. On the other hand, the study of the existing algorithms can help us to develop new ones providing higher performance.

Many works were presented in the last decade on IP networks performance analysis and about the viable solutions. The emerging of the IntServ [59] and DiffServ [60] architectures for the future Internet, together with the possibility of building backbone Autonomous Systems based on Multiprotocol Label Switching (MPLS) [61] and the need for provisioning QoS in the Internet spawned a burst of work concerning new, QoS-based, dynamic routing algorithms suitable for implementation in IP networks. Among others, the studies [62-64] addressed the problem of stale link state information, analyzing different policies for triggering information exchange among nodes. The authors of these works considered network models where connection requests are generated with arrival processes and holding times that suit well to the IP traffic. However, they assumed constant bandwidth requirements and evaluated the connection blocking probability. Their results clearly show that different policies for information exchange lead to different performance of routing algorithms.

In the following sections we summarizes the results of PEA IP/MPLS Core layer (consider the data layer scenario) by presenting models introduced for the observation of elastic traffic and QoS.

The PEA IP/MPLS core network as we discussed in previous chapter, uses the IS-IS protocol as IGP. In order to provide the MPLS label mapping and exchange capability, the LDP is used along with the IS-IS. The services that can be provided by the PEA IP/MPLS core network are such as L2VPN (i.e. pseudowire), L3VPN (i.e VRF), MPLS-TE and etc.

For the best performance, we design the IP network (data layer) with QoS is the technique of prioritizing traffic flows and providing preferential forwarding for higher priority packets. The fundamental reason for implementing QoS in the network is to provide better service for certain traffic flows. A traffic flow can be defined as a combination of source and destination addresses, source and destination socket numbers and the session identifier. A traffic flow can more broadly be described as a packet moving from an incoming interface that is destined for transmission to an outgoing interface. The traffic flow must be identified, classified and prioritized on all routers and passes along the data forwarding path throughout the network to achieve end-to-end QoS delivery.

4.3.1 Quality of Service (QoS) Design

The traffic flow shown below is that of a customer. The figure shows a generic traffic flow from CE to CE and the QoS mechanisms employed in the network.



Traffic Flow Direction

Figure 4.5 QoS Traffic Flow

Edge devices are responsible for examining IP packets arriving from network users for various characteristics such as application type and destinations of the traffic. The packets can then be classified, using for example, IP precedence or MPLS Exp, according to agreed policy. For example, all Telnet traffic to a certain destination could be given a "gold" classification, which would mean it would be given priority over all other traffic of lesser priorities. The edge devices can also provide ingress bandwidth management on an interface and provide appropriate queuing on egress to the core network. In this way the edge device ensures that no one service can flood the network to the detriment of others. Core devices expedite forwarding while enforcing QoS levels assigned at the edge. The core does this by associating the MPLS Experimental fields in the label headers with various egress queues on transmission, which provide the appropriate quality of service. The core therefore, is freed up from understanding service requirements as all the classification has been done once, at the edge.

- 4.3.1.1 QoS implementation
 - 1) Packet Classification

We use the packet classification techniques to identify the traffic flow and provide the capability to partition network traffic into multiple priority levels or classes of service. After traffic flow is identified, it can be marked as a traffic class. Identification of a traffic flow can be performed by using several methods within a single router: access control lists (ACLs), protocol match, IP precedence, IP differentiated service code point (DSCP) and so on.

2) Congestion Management

We use congestion management features to control congestion by determining the order in which a traffic flow (or packets) is sent out an interface based on priorities assigned to packets.

3) Modified Deficit Round Robin (MDRR)

MDRR is a class-based composite scheduling mechanism that allows for queuing of up to eight traffic classes. It operates in the same manner as classbased weighted fair queuing (CBWFQ) and allows definition of traffic classes based on customer match criteria (such as access lists); however, MDRR does not use the weighted fair queuing algorithm. When MDRR is configured in the queuing strategy, nonempty queues are served one after the other. Each time a queue is served, a fixed amount of data is dequeued. The algorithm then services the next queue. When a queue is served, MDRR keeps track of the number of bytes of data that were dequeued in excess of the configured value. In the next pass, when the queue is served again, less data is dequeued to compensate for the excess data that was served previously. As a result, the average amount of data dequeued per queue is close to the configured value. In addition, MDRR allows for a strict priority queue for delay sensitive traffic.

4) Low-Latency Queuing with Strict Priority Queuing

The LLQ feature brings strict priority queuing (PQ) to the MDRR scheduling mechanism. PQ in strict priority mode ensures that one type of traffic is sent, possibly at the expense of all others. For PQ, a low-priority queue can be detrimentally affected, and, in the worst case, never allowed to send its packets if a limited amount of bandwidth is available or the transmission rate of critical traffic is high. Strict PQ allows delay sensitive data, such as voice, to be dequeued and sent before packets in other queues are dequeued. Through use of the priority command, we can assign a strict PQ to any of the valid match criteria used to specify traffic. These methods of specifying traffic for a class include matching on access lists, protocols, IP precedence and IP differentiated service code point (DSCP) values. Moreover, within an access list we can specify that traffic matches are allowed based on the DSCP value that is set using the first six bits of the IP type of service (ToS) byte in the IP header.

!
policy-map policy-name
class class-name
police rate {rate [units] | percent percentage}} [burst burst-size [burst-units]]
[peak-burst peak burst [burst-units]] [peak-rate value [units] / percent percentage]
exceed-action action
priority
interface type interface-path-id
service-policy {input | output} policy-map
show policy-map interface type instance [input | output]
!

Figure 4.6 LLQ with PQ Configuration example

5) Traffic Shaping

Traffic shaping make we to control the traffic flow exiting an interface to match its transmission to the speed of the remote target interface and ensure that the traffic conforms to policies contracted for it. Traffic adhering to a particular profile can be shaped to meet downstream requirements, thereby eliminating bottlenecks in topologies with data rate mismatches. To match the rate of transmission of data from the source to the target interface, you can limit the transfer of data to the specific configured rate. When the peak burst size equals 0, the interface sends no more than the burst size every interval, achieving an average rate no higher than the mean rate. However, when the peak burst size is greater than 0, the interface can send as many as the burst size plus peak burst bits in a burst, if in a previous time period the maximum amount was not sent. Whenever less than the burst size is sent during an interval, the remaining number of bits, up to the peak burst size, can be used to send more than the burst size in a later interval. policy-map policy-name
class class-name
shape average {percent value | rate [units]} [burst-size [burst-units]]
interface type interface-path-id
service-policy {input | output} policy-map
show policy-map interface type instance [input | output]
!

I

Figure 4.7 Traffic shaping configuration example

6) Traffic policing

We use traffic policing to control the maximum rate of traffic sent or received on an interface, and to partition a network into multiple priority levels or class of service (CoS). Traffic policing manages the maximum rate of traffic through a token bucket algorithm. The token bucket algorithm can use the user configured values to determine the maximum rate of traffic allowed on an interface at a given moment in time. The token bucket algorithm is affected by all traffic entering or leaving (depending on where the traffic policy with traffic policing is configured) and is useful in managing network bandwidth in cases in which several large packets are sent in the same traffic stream. Traffic policing is often configured on interfaces at the edge of a network to limit the rate of traffic entering or leaving the network. In the most common traffic policing configurations, traffic that conforms is sent and traffic that exceeds is sent with a decreased priority or is dropped. Users can change these configuration options to suit their network needs.

Markdown policing is the setting of a QoS field in a packet when traffic exceeds or violates the policed data rates.

!
policy-map policy-name
class class-name
police rate {rate [units] | percent percentage}} [burst burst-size [burst-units]] [peakburst peak-burst [burst-units]] [peak-rate value [units] / percent percentage]
conform-action action
exceed-action action
interface type interface-path-id
service-policy {input | output} policy-map
show policy-map interface type instance [input | output]
!

Figure 4.8 Traffic policing configuration example

7) Configured Guaranteed and Remaining Bandwidths

We can specify the minimum guaranteed bandwidth to be allocated for a specific class of traffic. MDRR is implemented as the scheduling algorithm. The bandwidth remaining command specifies a weight for the class to the MDRR. The MDRR algorithm derives the weight for each class from the bandwidth remaining value allocated to the class. If we do not configure the bandwidth remaining command for any class, the leftover bandwidth is allocated equally to all classes for which bandwidth remaining is not explicitly specified.



Figure 4.9 Configured Guaranteed and Remaining Bandwidths Configuration example

4.3.1.2 DiffServ Tunnel Modes

DiffServ Tunnelling Modes introduces a new Per-Hop-Behaviour (PHB), which allows differentiated QoS in a provider's network. The tunneling mode is defined at the edge of the network, normally in the LSRs router. Consideration should be given to make changes in the P routers; and also what occurs when the topmost label is removed from a packet due to Penultimate-Hop-Popping (PHP). It may be necessary to copy the MPLS EXP value from the top label that is being popped to the newly exposed label; this does not always apply to all tunneling modes. In some cases (for example, a plain non-VPN MPLS network), the PHP action on the final P router can expose a plain IP packet when a packet with only one label is received. When this IP packet is received by the egress LSR (PE), it is not possible to classify the packet based on the MPLS EXP bits because there is no label now. In these situations, the operator must configure the egress PE router to advertise an explicit-null label using "mpls ldp explicit null" at global. When the PHP action is performed on the P router, a label with a value of zero is sent, and with this special label you can mark the EXP bits as normally labelled packets, allowing the correct classification on the egress PE router.

4.3.1.3 QoS Transparency

There are different ways to deploy QoS transparency in service provider networks today. The most accepted way to do this is the usage of the MPLS DiffServ Tunnel modes. RFC3270 describes three different Models, namely Pipe Mode, Short Pipe Mode and Uniform Mode. Pipe and Short-Pipe modes are typically used when a packet transits multiple DiffServ domains with different QoS policies. With the Pipe and Short-Pipe modes, an MPLS we can provide QoS treatment to packets without modifying the DiffServ information (coded in IP precedence/DSCP bits or MPLS EXP bits) on the received packet. These modes are two standard ways of providing end-toend QoS transparency. In Uniform mode, a packet is assumed to transit a single DiffServ domain. As such, an MPLS service provider may modify the DiffServ information on the received packet in order to provide appropriate QoS treatment.

1) Pipe Mode provides a distinct PHB through an MPLS service provider network for use only within that network. Figure 4.10 show the Pipe Mode.



Figure 4.10 Pipe Mode

2) Short Pipe Mode is identical to Pipe mode on ingress PE and P routers. However, there is a slight difference on the egress PE router. Short pipe mode will queue based on the customers' IP precedence or MPLS EXP bits (inner label) on the egress interface of the PE router. Basically, the egress queuing is done based on the customer's QoS bits, not the service providers.



Figure 4.11 Short Pipe Mode

3) Uniform mode is identical to Pipe and Short Pipe mode on ingress PE and P routers. However, on egress PE router, Uniform mode will copy down the MPLS EXP bits from the topmost shim header to the customer's MPLS EXP bits or IP Precedence field. Therefore, in this case a SP can alter the customer's packets, which is why it is usually only used with one DiffServ domain.



Figure 4.12 Uniform Mode

4.4 QoS design for PEA

The QoS design for PEA IP Core network divides the traffic into 6 classes based on the traffic important. The QoS classes are shown in table 3.7. The assigned QoS policy is separated into two major components, internal IP core network traffic and the traffic from PEA departments. The description of each traffic class is as followed.

Class 5 and Class 6: These classes use priority queuing and has the maximum bandwidth limitation. These traffic classes guarantee the delay for the high important traffic (e.g. network protocol traffic) and the traffic that has low tolerance to loss and delay (i.e. IMS department's high priority voice traffic).

Class 2 to Class 4: These QoS classes guaranteed the minimum usable bandwidth. If the traffic demand exceeds the guaranteed bandwidth and the traffic pipe is not fully utilized yet, these classes of traffic can use the available bandwidth.

Class 0: This traffic class uses the Best Effort policy. It belongs to the traffic that does not belong to the above classes (e.g. web browsing traffic, non-critical traffic, and etc.).

In case of link or node down, the fast reroute mechanism will occur to guarantee the downtime to stay within the limit. When this happen, the QoS policies assigned to the primary traffic paths still remain intact. However, if the traffic demands exceed the link capacity, the QoS policies will choose to drop the traffic based on traffic priority.

Service	Packat Assignments	QoS Assignments for
Class	i acket Assignments	PEA Traffic
Class 6	k control traffic. This traffic is critical to	N/A
	maintaining the infrastructure. No user	
	traffic is ever assigned to this class.	
Class 5	Real time voice and very high priority	SCADA traffic has IP
	traffic. This class bears voice traffic and	precedence value equal
	SCADA.	to "5"
Class 4	IT-sanctioned video conferencing. This class	IMS traffic that has IP
	bears any IT-sanctioned video traffic and it	precedence value equal
	carries only traffic from one video	to "4"
	conferencing node to another but at this time	
	excludes the desktop. It is a real time class	
	and it already claims large portions of	
	bandwidth. Sometimes, it gets more	
	bandwidth than things that are more critical.	
Class 3	Voice and video and other signaling and	IMS department traffic
	control traffic. This class of traffic supports	that has IP precedence
	phone calls by sending signals to IP phones	value equal to "3"
	to ring. It has high priority against data	
	applications because this signaling traffic	
	will be retransmitted if lost, but it doesn't	
	need the same expedited guarantees that	
	voice traffic requires.	
Class 2	Business traffic.	IT department business
		traffic (i.e. SAP, E1 and
		GIS).
Class 0	Default traffic. All traffic enters the network	IT and IMS department
	as Class 0. In the interests of operational	traffic that do not
	simplicity, this traffic as a matter of course	belonged to the above
	is not remarked.	QoS classes.

Table 4.1 Service Class and Packet Assignments for PEA

For each traffic class, the classification of the traffic uses the MPLS EXP Bit to mark the traffic. In each class the allocated bandwidth and the guarantee delay are based on the workshop. These policies are shown in table 4.2

Table 4.2 QoS for Core MPLS (Rely on MPLS EXP Bit)

Service	MPLS EXP	Policy	
Class	Bit		
		The Highest Priority queue (Priority 1), Delay guarantee	
Class 6	6	at maximum 500 Mbps (5% Of 10 G)	
		Second priority (Priority 2), Delay guarantee at maximum	
Class 5	5	1,500 Mbps (15% Of 10 G)	
Class 4	4	Bandwidth guarantee at 1,000 Mbps (10% of 10 G)	
Class 3	3	Bandwidth guarantee at 500 Mbps (5% of 10 G)	
Class 2	2	Bandwidth guarantee at 5,000 Mbps (50% of 10 G)	
Class 0	0	Best effort class. No guarantee.	

 Table 4.3 Customer equipment facing classification and service policy (Ingress)

Service	Classification	Policy
Class		
Class 6	For Management &	Policing ingress traffic at 50 Mbps per interface
Class 0	Control traffic.	Impose MPLS EXP 6
	(eg. DCN Ingress	
Class 5		Hierarchy QoS with top level policing at I00
Class 4	Special request with	(Bandwidth contract). Inner level with:
Class 3	classification method	Class 5 policing at I5 and impose MPLS EXP 5
	(eg. Interface, DSCP,	Class 4 policing at I4 and impose MPLS EXP 4
Class 2	ACL)	Class 3 policing at I3 and impose MPLS EXP 3
		Class 2 policing at I2 and impose MPLS EXP 2
Class 0	Other traffic from CE	Best effort (Other traffic) can consume up to
		the rest of bandwidth.

Table 4.4	Customer equipment facing classification method and service j			
	(Egress)			

Service	Classification	Policy
Class		
		DiffServ Tunnel Mode : Pipe
Class 6	MPLS EXP 6	The Highest Priority queue (Priority 1), Delay
		guarantee at maximum 5% of interface speed. For
		management domain only.
Class 5	MPLS EXP 5	DiffServ Tunnel Mode:Pipe
Class 4	MPLS EXP 4	Hierarchy QoS with top level shaping at E00
Class 3	MPLS EXP 3	Inner level with: Priority queue (Delay guarantee)
Class 2	MPLS EXP 2	for EXP 5 up to E5 Bandwidth guarantee for
		EXP 4 up to E4 Bandwidth guarantee for EXP 3
Class 0	MPLS EXP 0	up to E3 Bandwidth guarantee for EXP 2 up to E2
		Best effort

For the major PEA departments (i.e. SCADA, IMS and IT), the QoS and bandwidth allocation policies are shown in table 4.5.

 Table 4.5 QoS and Bandwidth Allocation

Department	SCADA (L3)	IMS (L3)	IT (L3)
Ingress EXP 5 (I5)	100 Mbps(1,000	50 Mbps (200	
	Mbps at HQ)	Mbps at HQ)	-
Ingress EXP 4 (I4)		100 Mbps (400	
	-	Mbps at HQ)	-
Ingress EXP 3 (I3)		50 Mbps (200	_
	_	Mbps at HQ)	-
Ingress EXP 2 (I2)			500 Mbps (5,000
		-	Mbps at HQ)

All Ingress (E00)	100 Mbps	300 Mbps	1,000 Mbps
Bandwidth	(1,000 Mbps	(1,000 Mbps	(10,000 Mbps
contract)	at HQ)	at HQ)	at HQ)
Egress EXP 5 (E5)	100 Mbps	50 Mbps	
	(1,000 Mbps at HQ)	(200 Mbps at HQ)	-
Egress $EXP A (EA)$	_	100 Mbps	
	-	(400 Mbps at HQ)	_
Egress EXP 3 (E3)	-	50 Mbps	_
Egicss EAT 5 (E5)		(200 Mbps at HQ)	_
			500 Mbps
Egress EXP 2 (E2)	-	-	(5,000 Mbps
			at HQ)

 Table 4.5 QoS and Bandwidth Allocation (Continued)

4.5 Conclusion

In this Chapter, we study the performance evaluation of the IP over DWDM by separated in DWDM layer (optical layer) and IP layer (data layer). In the DWDM layer the blocking probability verifies the performance of network by non-blocking of wavelength. Approaching the study of performance evaluation of DWDM networks, we apply and devise WDMM as Wavelength Dependent Multifiber Model. For the IP layer, we use the QoS to verify and implement the performance for the data layer.

CHAPTER 5

STUDY AND RESULTS FOR MULTILAYER NETWORK

Although previous chapter we has considered multilayer networks as IP over DWDM with separated in two layer are DWDM layer (optical layer) and IP layer (data layer). The explicit modeling and study of IP/MPLS over OTN over DWDM as a three-layer model has not been examined. We have made several contributions in this chapter. We present an integrated capacity optimization model for planning of a three-layer network where modularity is explicitly considered. Further, sublayer signals of OTN are also included. We present an optimization model for network planning of IP/MPLS over OTN over DWDM multilayer networks while the DWDM capacity is fixed. We present a comprehensive study to quantify the interrelationship between layers through change unit cost of elements and capacity modularity, with network demand.

5.1 Introduction

Two-layer networks, such as IP over DWDM, that are made of a traffic layer over a DWDM transport layer, have received much attention in the literature reviews. In this architecture, the core routers are connected directly to the DWDM systems that provide point-to-point fiber links.

5.2 An Integrated Capacity Optimization Model

In this section, we present a link-path multi-commodity network model to describe the multilayer network capacity optimization problem. The cardinal concept behind the model is that each upper layer imposes demands on the neighboring lower layer, while explicitly considering all technological restrictions. Consider Figure 5.1; the demand volume is realized by the means of flows assigned to paths of layer IP/MPLS. The summation of flows passing through each link in the IP/MPLS layer determines the capacity of the layer. Next, the capacity of each link of the IP/MPLS layer becomes a demand realized by the means of flows assigned to paths in the OTN

layer. In doing so, we take into consideration capacity modularity, especially subsignal modularity within OTN, while the cost components are associated with modular capacity and node interfaces. And if we sum up the flows through each link of the OTN layer, the resulting loads determine the capacity of the layer. The last step is analogous for the DWDM layer. We first begin by describing the notations used in our formulation. Figure 5.2 shows the design approach of our integrated model. Then we discuss each set of constraints. For brevity, the list of notations is shown in section 5.2.1



Figure 5.1 IP/MPLS over OTN over DWDM Network



Figure 5.2 Integrated Model Design Approach

5.2.1 List of Notations (P1)

5.2.1.1 Indices:

d = 1, 2, ..., D demands between source-destination pairs of the IP/MPLS layer.

p = 1, 2, ..., Pd candidate paths for demand d.

e = 1, 2, ..., E links of the IP/MPLS layer.

q = 1, 2, ..., Qe candidate paths of OTN layer for realizing capacity

of link e.

g = 1, 2, ..., G links of the OTN layer.

z = 1, 2, ..., Zg candidate paths of DWDM layer for realizing of link g.

capacity of link g.

f = 1, 2, ..., F links of the DWDM layer. k = 0, 1, 2, 3, 4. modular interfaces of OTN link g.

5.2.1.2 Constants:

hd: Volume of demand d.

 δedp : =1 if link e belongs to path p realizing demand d; 0,

otherwise.

 $\gamma geq: =1$ if link g belongs to path q realizing capacity of link e; 0,

otherwise.

 $\Im fgz$: =1 if link f belongs to path z realizing capacity of link g; 0,

otherwise.

M: Module size for IP/MPLS layer.

Uk: Module size for OTN layer link capacities k = 0, 1, 2, 3, 4.

N: Module size for DWDM layer link capacities.

 ηe : Cost of one capacity unit of module M of IP/MPLS layer

link e.

 βgk : Cost of one capacity unit of type *Uk* of OTN layer link *g*. ξf : Cost of one capacity unit of module *N* of DWDM layer link *f*.

5.2.1.3 Variables:

xdp: IP/MPLS flow variable realizing demand d allocated to path p (non-negative, continuous or binary).

meq: OTN flow variable allocated to path q realizing capacity of link e (non-negative integral).

sgkz: DWDM flow variable allocated to path z realizing capacity of link g of interface k (nonnegative integral).

ye: Number of modules M to be installed on link e in the IP/MPLS layer (non-negative integral).

wgk: Number of modules Uk to be installed on link g in the OTN layer (non-negative integral).

bf: Number of modules N to be installed on link f in the DWDM layer (non-negative integral).

5.2.2 Constraints

An IP demand *d* between two routers is tunneled by consider one of the paths x_{dp} from the set of paths P_d . This can be expressed as follows:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{5.1}$$

Next, we consider the IP/MPLS layer capacity feasibility constraints (5.2). These assure that for each IP/MPLS layer link e, its capacity is allocated in modules of size M and is not exceeded by the flow using this link as shown below:

$$\sum_{d=1}^{D} h_d \sum_{d=1}^{P_d} \delta_{edp} x_{dp} \le M_{ye} \qquad e = 1, 2, ..., E$$
(5.2)

Here, M is the allowable granularity of each MPLS tunnel. The constraints (5.3) below specify how the capacity of each IP/MPLS layer link e is realized by means of flow m_{eq} and is allocated to its candidate paths from the routing list in the OTN layer.

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E$$
(5.3)

We next consider the OTN layer capacity feasibility constraints, shown below (5.4). These constraints assure that all flows routed on each OTN layer link g do not exceed their capacity that is allocated in modules of sizes U_k , which represent the five modular interfaces of OTN.

$$M\sum_{e=1}^{E}\sum_{q=1}^{Q_{e}}\gamma_{geq}m_{eq} \leq \sum_{k=0}^{4}U_{k}w_{gk} \qquad g=1,2,...,G$$
(5.4)

It should be noted that the above incorporate all OTN sub-signals through a single set of constraints, without requiring a separate set for each signal. We can accomplish this due to the way we assign unit cost, which is defined in the next section.

The following constraints (5.5) specify how the capacity of each OTN layer link g is realized by means of flow k_{gkz} , allocated to its candidate paths from the routing list in the DWDM layer.

$$\sum_{z=1}^{Z_g} U_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4, \quad g = 1, 2, ..., G$$
(5.5)

These next constraints (5.6) are the DWDM layer capacity feasibility constraints and assure that for each physical link f, its capacity allocated in modules of size N is not exceeded by the flow using this link. Note that N is the module size of the DWDM layer link capacity that is equal to the number of wavelengths per fiber, and b_f would be the number of fibers to be installed on link f.

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \mathcal{G}_{fgz} s_{gkz} \le N b_f \qquad f = 1, 2, ..., F$$
(5.6)

Finally, variables are integer or modular as summarized in section 5.2.1

Note that in the above constraints, we assume that each OXC has full wavelength conversion capability [31]; this means that the wavelength continuity constraint is relaxed in the model as in [3]. In our case, this relaxation is a reasonable assumption since we are considering the three-layer design problem in the network planning phase; secondly, based on the final solution from our model, we can indeed identify where to *not* put wavelength convertors, if necessary. Furthermore, wavelength continuity is more appropriate for allocation problems, as opposed to design problems.

5.2.3 Objective and Cost Model

The goal in our design model is to minimize the total network planning cost. The objective is given by:

$$F = \sum_{e=1}^{E} n_e y_e + \sum_{g=1}^{4} \sum_{k=0}^{4} \beta_{gk} w_{gk} + \sum_{f=1}^{F} \xi_f b_f$$
(5.7)

This objective function captures the total cost of network resources over all three layers generically, where n_e , β_{gk} and ξ_f are the weights across the three metrics associated with the three layers. The three layer cost structure is shown in Figure 5.3. An advantage of the cost structure model is that this allows to consider a number of different cost combinations that is helpful in understanding inter layer interactions. We now elaborate how the unit cost components associated with each layer may be constructed. For the IP/MPLS layer, n_e is the unit cost of link e; this is defined as the sum of the interface cost for the upper layer n_e^U and the lower layer n_e^L ends of the connection between the IP/MPLS layer node and the OTN layer node, i.e. $n_e = 2n_e^U + 2n_e^L$, where 2 is to count for both ends.

At the OTN layer, β_{gk} is the unit cost of link g and is equal to the cost of the interface of U_k signal on link β_g^U , plus the cost of multiplexing OTN signals β_g^k i.e. $\beta_{gk} = 2\beta_e^U + 2\beta_g^k$

For DWDM layer, ξ_f is the cost of link f and is equal to the interface cost for line cards connected to the transport end of a physical node to another physical node $\xi_f^{\ I}$, the optical transponder cost $\xi_f^{\ t}$, the OXC ports $\xi_f^{\ o}$, plus a physical link distance cost Δ_f , i.e., $\xi_f = 2(\xi_f^{\ I} + \xi_f^{\ t} + \xi_f^{\ o}) + \Delta_f$



Figure 5.3 Cost Structure of the Three-Layer Network

The capacity optimization problem (P1) for the IP/MPLS over OTN over DWDM multilayer is to minimize the cost F given by (5.7) subject to the set of constraints (5.1) – (5.6).

5.3 Optimizing Node Capacity

Models (P1), presented in Sections 5.2, do not consider the actual representation of the routing and switching nodes. In this section, we examine another design problem in IP/MPLS over OTN/DWDM multilayer networks. Here, we consider the problem of optimizing node capacity since label switched routers (LSRs) with high capacity and complex structures. Model (P2) presented in this section aims to optimize the capacity of LSRs and OXCs, rather than the links capacity at each network layer. We present an explicit networking optimization Model (P2) with IP/MPLS over OTN over DWDM that aims to minimize the total capacity at the LSRs and the OXCs. We also present a brief assessment by considering a sample network topology.

5.3.1 Problem Formulation

We now present the optimization model (P2). The notations used in this model are summarized in Tables 5.2 and 5.3. The objective in our design model (P2) is to minimize the total of LSRs and OXCs node capacity, which can be written as:

5.3.2 List of Notations (P2 Given Entities)

5.3.2.1 Indices:

d = 1, 2, ..., D demands between source-destination pairs of the IP/MPLS layer.

p = 1, 2, ..., Pd candidate paths for demand d. e = 1, 2, ..., E links of the IP/MPLS layer. v = 1, 2, ..., V LSRs. r = 1, 2, ..., R OXCs. q = 1, 2, ..., Qe candidate paths of OTN layer for realizing capacity

of link e.

g = 1, 2, ..., G links of the OTN layer. z = 1, 2, ..., Zg candidate paths of DWDM layer for realizing

capacity of link g.

f = 1, 2, ..., F links of the DWDM layer.

k = 0, 1, 2, 3, 4. modular interfaces of OTN link g.

5.3.2.2 Constants:

hd: Volume of demand *d*.

 δedp : =1 if link e belongs to path p realizing demand d; 0,

otherwise.

ygeq: =1 if link g belongs to path q realizing capacity of link e; 0,

otherwise.

 $\Im fgz$: =1 if link f belongs to path z realizing capacity of link g; 0,

otherwise.

 $\theta ve: = 1$ if link *e* is incident with LSR *v*; 0, otherwise.

 ϕrg : =1 if link g is incident with OXC r; 0, otherwise.

M: Module size for IP/MPLS layer links.

A: Module of capacity of the LSRs.

C: Module of capacity of the OXCs.

Uk: Module size for OTN layer link capacities k = 1, 2, 3.

N: Module size for DWDM layer link capacities.

bf: Number of modules N to be installed on link f in the DWDM layer (non-negative integral).

 σv : Weight factor of a LSR v.

 ρr : Weight factor of an OXC r.

5.3.3 List of Notations (P2 Variables)

5.3.3.1 Variables:

xdp: IP/MPLS tunnel variable realizing demand d allocated to path p (non-negative, binary).

meq: OTN flow variable allocated to path q realizing capacity of link e (non-negative integral).

sgkz: DWDM flow variable allocated to path z realizing capacity of link g of interface k(non-negative integral).

ye: Number of modules M to be installed on link e in the IP/MPLS layer (non-negative integral).

 Y_{v}^{l} : Capacity of LSR v.

wgk: Number of modules Uk to be installed on link g in the OTN layer (non-negative integral).

 Y_v^o : Capacity of OXC *r*.

Minimize
$$f \sum_{\nu=1}^{V} \sigma_{\nu} Y_{\nu}^{l} + \sum_{r=1}^{R} \rho_{r} Y_{r}^{o}$$
 (5.8)

Note that we introduce weight factors, σ_v and ρ_r , for each type of nodes. If these values are each set to one, then (5.8) represents pure node capacity. On the other hand, we can use the weight factors to consider, for example, site-dependent power consumption proportions of each type of node, or any other site-dependent costs. The constraints in model (P2) are as follows:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{5.9}$$

The IP/MPLS layer capacity feasibility constraints are given in (5.9) that assure that for each IP/MPLS layer link e, its capacity is allocated in modules of size M and is not exceeded by the flow using this link.

$$\sum_{e=1}^{E} \theta_{ve} M_{ye} \le A Y_{v}^{l} \qquad v = 1, 2, ..., V$$
(5.10)

Next, constraints (5.10) define the capacity Y_{ν} of each LSR ν in the IP/MPLS layer, expressed as the maximum of the link capacity connected to the router.

$$M\sum_{q=1}^{E} m_{qe} = y_{e} \qquad e = 1, 2, ..., E$$
(5.11)

The constraints (5.11) specify how the capacity of each IP/MPLS layer link e is realized by means of flow m_{eq} and is allocated to its candidate paths from the routing list in the OTN layer; thus, this relates the top layer to the middle layer.

$$M\sum_{e=1}^{E}\sum_{q=1}^{Q_{e}}\gamma_{geq}m_{eq} \leq \sum_{k=0}^{4}U_{k}w_{gk} \qquad g=1,2,...,G$$
(5.12)

The OTN layer capacity feasibility constraints are shown in (9.6) in relation to the three modular interfaces of OTN.

$$\sum_{k=0}^{4} \phi_{rg} U_k w_{gk} \le C Y_r^o \qquad g = 1, 2, ..., G \quad r = 1, 2, ..., R$$
(5.13)

We then show constraints (5.13) that define capacity Y_r of each OXC r in the OTN layer, expressed as the maximum of the link capacity connected to the OXC.

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4 \qquad g = 1, 2, ..., G$$
(5.14)

Next, constraints (5.14) specify how the capacity of each OTN layer link g is realized by means of flow k_{gkz} , allocated to its candidate paths from the routing list in the DWDM layer.

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \vartheta_{fgz} s_{gkz} \le Nb_f \qquad f = 1, 2, \dots F$$
(5.15)

Finally, constraints (5.15) are for DWDM layer capacity feasibility constraints and assure that for each physical link f, the capacity allocated in modules of size N is not exceeded by the flow using this link.

Note that Model (P1), presented in Section 5.2, does not consider the actual representation of the routing and switching nodes. The focus of that model is the link capacity of each layer in the network. Model (P2) on the other hand explicitly attempts to optimize the required capacity at each routing node v and switching node r. That is, Model (P2) aims to optimize the capacity of LSRs and OXCs, rather than the links capacity at each network layer. In addition, there is no explicit consideration of the routing cost in Model (P2). However, the routing cost is implicitly embedded in the model by introducing the cost of the capacity module at the routing and switching nodes. This is because routing and capacity modules are closely related. By optimizing the cost of capacity modules required, the design model forces to use shorter paths as possible to avoid increasing the number of the capacity modules when longer paths are used. More detailed discussion is presented in Section 5.4
5.4 STUDY AND RESULTS

Problem (P2) has D+2E+V+G(R+4)+F is constraints and the integer variables $P \times D + E(Q+1) + V + R + 3G(Z+1)$, where P denoted the average number of paths for each demand d. Even for small networks, this constitutes a large number of variables and constraints. A small network problem (P2) can be solved using CPLEX optimization package, through its integer linear programming solver. Thus, we study the case of a 7-node multilayer network in which each LSR is connected to an OXC in the OTN layer, and each LSR is an ingress/egress LSR. Note that from the model point of view, the 7-node per layer network has 21 nodes in total in the threelayer network. For this network we have 21 demands and the average demand $\simeq 7.8$ Gbps, giving a total demand volume of 165 Gbps. Furthermore, we assume the following network parameters: M=5 Gbps, A=5 Gbps, C=10 Gbps. We assign 8 wavelengths/fiber where each wavelength is 40 Gbps. For the weight factors, we experimented with three weight ratios of σ_v to ρ_r : 1:2, 1:1 and 1:1/2 to understand how the solution changes as the cost for OXC is changed while the LSR cost is kept fixed. A representative result of the final three-layer topology for the 7-node problem is shown in Figure 5.4.



Figure 5.4 IP/MPLS over OTN over DWDM Network



Figure 5.5 Network Cost with Increase in Load

Figure 5.5 shows the case when we increase the base load by 10% each run until a 50% load increase. The network shows a 36% increase of its cost to carry the 50% load increase. Each time the load is increased by 10%, the network needs to pay an average \simeq 7% of its current cost to sustain the load increase.



Figure 5.6 Node Capacity with Increase in Load

Figure 5.6 shows the required total capacity of the LSRs and the OXCs of the three weight ratios. We observe that on average $\approx 7\%$ of LSRs capacity increase is required for each 10% of load increase. At a 50% load increase, a 35% of the base LSRs capacity is needed to satisfy the demand. For the OXCs, on average $\approx 8\%$ increase in the capacity is noted for each 10% load increase. The total required capacity in case of a 50% load increase is 38% of the base capacity. We observe that different weight ratios do not generally impact the overall required node capacity in

each layer. Nevertheless, it is important to understand how the required capacity of each individual LSR or OXC may differ according to the weight ratios. To understand this aspect, we pick a particular load case to study, the case when the base load is increased by 20%, to highlight the differences. This case is shown in Figure 5.7 for the required LSR capacity that shows that different weight ratios lead to different capacities in each of the nodes in the 7-node network. The corresponding Figure 5.8 shows the required capacity at each OXC that shows differences in OXC capacity for two nodes r^2 and r^4 . In addition, Figure 5.7 and Figure 5.8 show that the weight ratio of 1:1/2 has the most effect on the results.



Figure 5.7 LSRs Capacity for Different Weight Factors (load: 20% inc)



Figure 5.8 OXCs Capacity for Different Weight Factors (load: 20% inc)

5.5 A Study on a PEA Network

Although we cannot solve problem (P2) to optimality using CPLEX for a network larger than the 7-node per layer network, we can obtain close-to-optimal solutions for large networks. Thus, for this study we consider the 14-node per layer PEA as shown in Figure 5.9.



Figure 5.9 14-node per Layer PEA (Area NE2)

 Table 5.1 Topology Information and Demands

Network	No. of Nodes per Layer	No. of Physical Links (F)	Total load	No. of D	Avg. Load/d
PEA	14	21	755	91	5

 Table 5.2 Parameter Values

Weight Ratio	M Gbps	A Gbps	C Gbps
1/2:1, 1:1, 1:1/2	2.5, 5, 10	2.5, 5, 10	10

Table 5.1 shows the network topology and demand volume used in this study. In addition, table 5.2 shows the considered values of each parameter of Model (P2). This table indicates that there are a total of 27 scenarios considered by varying the weight ratio, the size of M and the size of A, while fixing the size of C. This allows us to investigate the affects of changing these parameters on the network.



Figure 5.10 Total LSRs Capacity for Different sizes of M, A in PEA



Figure 5.11 Total OXCs Capacity for Different sizes of M, A in PEA

Figure 5.10 shows the total LSRs capacity for different cases of M and A. Similarly, Figure 5.11 shows the total OXCs capacity for different cases of M and A. Note that the pair value of each case in these figures refers to the values of M and A, respectively. For example, the case of (2.5, 5) indicates that M=2.5 and A=5, where M is the size of the capacity module of the IP/MPLS link e and A is the size of the capacity module of the LSR v. We can make a few observations considering Figure 5.10. These are as follows:

(1) The weight ratios do not significantly impact the total required capacity of the LSRs when the size of A is low, i.e A=2.5. This is the same observation we pointed out in our study on the 7-node per layer network in Section 5.4.

(2) As the size of A increases, the total LSRs capacity also increases.

(3) As the size of A increases, we clearly note the impact of the weight ratios on the required LSRs capacity. The case of 1:1/2 yields the lowest total needed LSRs capacity since in this case LSRs have more weight than the OXCs which means it is more expensive to acquire LSRs capacity at this ratio.

(4) The case of 1/2:1 yields the largest total needed LSRs capacity since in this case LSRs have less weight than the OXCs which means it is cheaper to acquire LSRs capacity at this ratio.

(5) The capacity gap between the ratios increases as we increase the size of A. For instance, the gap between the cases of (2.5, 10) is larger than the gap between the cases of (2.5, 5).

(6) Generally, as the size of the M increases, the total required LSRs capacity also increases. For example, we note that the total LSRs capacity is increasing as we go from case (2.5, 2.5) to case (5, 2.5) to case (10, 2.5).

Figure 5.11 shows the total required OXCs capacity for all of the cases considered in this study. We note similar and opposite observations to those made of the LSRs capacity of Figure 5.11. These are as the following:

(1) The weight ratios do not significantly impact the total required capacity of the OXCs when the size of A is low, i.e A=2.5. This is the same observation made in observation (1).

(2) Unlike observation (2), as the size of *A* increases, the total OXCs capacity de- creases. This is especially the case when the weight value of the OXC is equal or higher than the LSR weight.

(3) As the size of A increases, we clearly note the impact of the weight ratios on the required OXCs capacity. However, unlike observation (3), the case of 1:1/2 yields the largest total needed OXCs capacity since in this case OXCs have less weight than the LSRs which means it is cheaper to acquire OXCs capacity at this ratio. The figure also show that the case of 1/2:1 yields the lowest total needed

OXCs capacity since in this case LSRs have less weight than the OXCs which means it is cheaper to acquire LSRs capacity at this ratio which also result in higher acquired LSRs capacity as noted in observation (4).

(4) The capacity gap between the ratios increases as we increase the size of *A*. This is similar to observation (5).

(5) Generally, as the size of the M increases, the total required OXCs capacity also increases except for the case when M=10 and A=10 for weight ratios 1:1 and 1/2:1 in which scenarios the OXC weight is either equal or higher than the LSR. This means increasing M to 10 when A is already large increases the required OXC capacity only when its weight is less than the LSR weight.

By comparing these observations with those made in Section 5.4 for the 7-node network, we can clearly note that the weight ratios do not affect the total required LSRs and OXCs when the size of A is small, i.e. A is below the average demand in the network. We begin to observe the impact of the weight ratios when the size of A rises. Increasing A while M is fixed generally leads to more LSRs capacity and less OXCs capacity. In addition, increasing M while A is fixed generally leads to more LSRs and OXCs capacity required.

5.5.1 Individual LSRs and OXCs Capacity

In this section we focus on the required capacity of each individual LSR and OXC. We select one case to consider since other cases will show either the same or expected general behaviors. Thus, we select the case when M=10 and A=10 to study. Figure 5.12 shows the each individual LSR capacity and Figure 5.13 shows the each individual OXC capacity.

We previously observed from Figure 5.10 and Figure 5.11 that the weight ratio of 1:1/2 yields the lowest total LSRs capacity while the weight ratio of 1/2:1 yields the lowest total OXCs capacity. Now, the individual node capacity figures show the details of the case when M=10 and A=10. Figure 5.12 shows that the required individual capacity of each LSR v is usually the lowest for weight ratio of 1:1/2. This is because in this weight ratio it is more expensive to have LSR capacity than OXC capacity. In addition, we can observe that the weight ratio of 1/2:1 generally leads to more individual LSRs capacity as this weight ratio indicates less weight to the LSR node.



Figure 5.12 Individual LSRs Capacity when M=10, A=10 and C=10 in PEA



Figure 5.13 Individual OXCs Capacity when *M*=10, *A*=10 and *C*=10 in PEA

We can observe the opposite behaviors as we consider the individual OXC node capacity in Figure 5.13. In this case, the required individual capacity of each OXC r is usually the lowest for weight ratio of 1/2:1 as this weight ratio indicates that OXC capacity is more expensive than LSR capacity. Also, the weight ratio of 1:1/2 generally leads to more individual OXCs capacity as this weight ratio indicates less weight to the OXC node.

We also note that a high capacity at an LSR often indicates a high capacity at the corresponding OXC and vice versa. For example, LSR v6 has less capacity than its neighbors v4 and v8, at the same time OXC r6 has less capacity than its physically connected neighbors r4 and r8. However, this is not always the case. To illustrate, consider LSR v2 which has close capacity to LSR v4. Their corresponding OXCs do not maintain the same capacity proportion. OXC r4 has noticeably less capacity than OXC r2. This is because a path chosen for satisfying a demand at the OTN layer does not necessarily follow the same path taken at the

IP/MPLS layer. An LSR may appear as an intermediate router in the IP/MPLS layer path while its corresponding OXC may not appear as an intermediate OXC in the OTN layer path for satisfying that demand.

5.6 Conclusion

In Section 5.2 we present an optimization model for optimizing node capacity in a multilayer network that consists of IP/MPLS, OTN and DWDM layers for defining the characteristics and parameters of node capacity in the network model. In Section 5.3 we present a study on two different networks and results to show that the capacity is impacted by the network load increasing. The study and results of PEA network show the differences of the node capacity requirement at different nodes in different layers in Section 5.4. We also observed the significant impact of A when this value equal or is above the average demand traffic in the network.

CHAPTER 6 STUDY AND RESULTS FOR NETWORK CAPEX

The goal of our study in this Chapter is to understand of network impacted by the varying parameters associated the comparative unit cost assigned at different layers, and by the modularity factor (M). We first present a discussion on our choice of the parameters. The comparisons of cost on each layer (according the equipment cost) show the effect of CAPEX of network in fist implementation.

6.1 Parameter values

In the formulation of problem (P1), we have defined η_e to be the cost of one unit of module *M* of the IP/MPLS layer link *e*. In our study, this refer to as the *IP unit cost*, or simply as IP-cost. Similarly, β_{gk} is the cost of one capacity unit of module type U_k of the OTN layer link *g*. We call this U_k unit cost for k = 0, 1, 2, 3, 4, or simply as U_k -cost. At the DWDM layer, ξ_f is the cost of one capacity unit of module *N* of the DWDM layer link *f*. This will be referred to as the *DWDM layer* unit cost *W*, or simply as W-cost.

According to [39], one of the cost ratios of future network elements is 8, 0.5 and 1 representing costs of a DWDM transponder, IP/optical interface card and a photonic OXC port, respectively. Based on our cost model in Section 5.2, the IP/MPLS layer cost becomes $2 \times (0.5+1) = 3$ and the DWDM layer cost considering only the transponders and OXC port is $2 \times (8+1) = 18$. Then, we add other costs to the DWDM layer to include the interface cost for line-cards connected to the transport end of a physical node to another physical node and a physical distance cost; we assume a fixed cost of 66. This means that when the IP/MPLS layer cost is 3, the DWDM cost is 84. We transform this value when the IP-cost is 5, the W-cost is 140.

We fixed the W-cost at 140 throughout our study and adjusted the other units' costs to understand the impact due to cost ratio change at different layers. Especially, for the IP-cost, we vary the cost starting from IP-cost= 5 and doubling the cost to IP-cost= 10, 20 and 40 to study the impact of different IP-cost scenarios while the W-cost is fixed.

We refer to the case of IP-cost = 5 as a low IP unit cost, IP-cost = 10 and 20 as a medium IP unit cost, and IP-cost = 40 as a high IP unit cost. The values of the IP unit cost represent approximately 3.5, 7, 14 and 28% of the W-cost, respectively. The size of M also varies, according to the given set of demands. We assign the size of M in Gbps to represent three possible cases: below average, average, and above average demands in the network. We use the demand model of [49] to create a set of demands between the LSRs in a network.

Table 6.1 shows a cost mapping between the IP-cost and M. Each entry in the table indicates the cost per Gbps. For instance, when the IP-cost=5 and M=5, the cost of one Gbps =1. Our cost parameter values seem elaborate; however, this is necessary when we consider a three-layer network. It is tempting to list cost units simply as cost per Gbps; however, this misses out on information such as parameter M that has a significant impact on neighboring layers and the overall network cost.

IP-cost	<i>M</i> =2.5	<i>M</i> =5	<i>M</i> =10
5	2	1	0.5
10	4	2	1
20	8	4	2
40	16	8	4

Table 6.1 Cost per Gbps

For the OTN layer parameter values, we have three possible cost scenarios of U_k ($0 \le k \le 3$):

- (1) UK-cr1: 2 $U_k = U_{k+1}$
- (2) UK-cr2: 3 $U_k > U_{k+1}$
- (3) UK-cr3: 3 $U_k = U_{k+1}$

To represent them, we consider the following $Uk \operatorname{cost} (k = 0, 1, ..., 4)$, 2/4/8/16/32, 2/5/13/20/50 and 2/6/18/54/162, for UK-cr1, UK-cr2, UK-cr3, respectively. Note that the actual values of Uk s are not as important as the relationships between them. We avoid unrealistic $Uk \operatorname{cost}$ relationships such as when Uk = Uk+1 or when 4Uk = Uk+1. The former indicates equal costs of two different

OTN units, and the latter follows one of the signal multiplexing rules we explained in Chapter 3. For example, when 4U1 = U2 we have equal costs for two choices and it is negligible whether four U1s or one U2 is selected to satisfy a demand. This is the result while the size of four U1s is equal to the size of one U2, i.e., 4×2.5 Gbps = 10 Gbps. We summarize each layer's cost values in Table 6.2

Tab	le 6.2	Summary	of	Cost	Values	for	Each	Layer	•
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Cost Notation	Unit Cost Values
IP-cost (η_e)	5, 10, 20, 40
U_k -cost (β_{gk})	2/4/8/16/32, 2/5/13/20/50,
	2/6/18/54/162
W-cost (ξf)	140

The experiments we conducted in this study with various parameter values allowed us to investigate the impact of each layer cost on other layers and ultimately the overall network cost. Through this, we hope to perceive some issues. For example, how does increasing the IP-cost influence the types and numbers of U_k signals at the OTN layer? The number of wavelengths at the DWDM layer? What role does the size of M play on each layer and on the overall cost? How does the cost of each U_k scenario affect the final types and numbers of U_k s needed to satisfy a given set of demands? Eventually, given a set of demands and the cost values of each layer, we know what to expect in terms of minimal network resources required at each layer to satisfy these demands.

For all demand generation in this dissertation we use the demand model presented in [49]. According to [49], for each LSR pair (x, y), the demand between x and y is given by:

$$\alpha O_{x}D_{y}C_{(x,y)}e^{-\delta(x,y)/2\lambda}$$

where:

 $O_x D_y$ random numbers $\in [1,0]$ for each node x. $C_{(x,y)}$ a random number $\in [1,0]$ for each pair (x, y). α is a scale parameter.

 $\delta(x, y)$ is the Euclidean distance between x and y.

 Δ is the largest Euclidean distance between any pair of nodes.

In addition, the Euclidean distance between point a and point b is given by:

$$\sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}$$

6.2 Study on PEA network

We have conducted to extend the experiments with different parameter values, therefore, we selected two different larger topologies: a 19-node of PEA Northeast, and a 36-node PEA Central (Figure 9) for the physical topology. Note that 19 and 36 are the numbers of nodes *per layer* in the PEA Northeast (PEA-NE) and PEA Central (PEA-C), respectively. This means that the total nodes in these networks are 57 and 108. All physical links in these networks are assumed to be bidirectional multi-wavelength fibers. We assume that each LSR is connected to an OXC in the physical layer, and each LSR is an ingress/egress LSR. These topologies are selected as representative topologies to understand how the impact of different parameters values on different topologies.

We use different cost values of each network layer as described in Section 6.1. Those values consist of parameters of both topologies. We use the demand model of Section 6.2 to generate demand volume between LSRs. Information about network topologies and traffic scenarios are shown in Table 6.3. The average demand volume in these networks is 5 Gbps. Therefore, we consider three values of M: 2.5, 5, and 10 Gbps to represent three cases: below average, equal average, and above average demand in these networks.

The primary goal of our algorithm is to minimize the overall network cost; hence, we have tried the algorithm to find an appropriate value of Td, the number of

multilayered paths for each demand *d*. For PEA-NE, we observed that Td = 16 provides the best case performance for the baseline case in our experiment when M = 2.5 Gbps, IP-cost= 5 and *Uk* cost=UK-cr1 as shown in Figure 6.1 (a). We observed that the cost rose after Td = 16. This is because at Td = 16, our approach finds the best balance between utilizing the virtual layer efficiently and avoiding the costly fiber links. Note that we would like to avoid establishing a new lightpath for every demand over expensive fiber links, but at the same time we do not want to route the demands over many logical links. This is achieved when Td = 16 in PEA_NE. Increasing the value of Td after 16 means more expensive paths are used without efficiently utilizing the virtual topology leading to higher network costs. The cost difference between the best case of Td = 16 and the worst case when Td = 26 is 3.4%. For the PEA_C network, shown in Figure 6.1(b), we observed the best case when Td = 6 in the rest of our study with the PEA_C network. Note that the cost difference between the best case of Td = 6 and the worst case when Td = 2 is 3.3%.



(a) Total Cost of Different Values of *Td* in PEA_NE



(b) Total Cost of Different Values of TdTd in PEA_C

Figure 6.1 Total Cost of Various T_d When M = 2.5 and IP-cost=5

Table 6.3	Topology	Information	and	Demands
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Notwork	No. of Nodes	No. of Physical Total load		No.	Avg.
Network	per Layer	Links (F)	Total Ioau	of D	Load/d
PEA_NE	19	35	855	171	5
PEA_C	36	54	3,150	630	5

6.2.1 Cost of Different Layers

Figure 6.2 shows the cost of different layers and the total cost when the IPcost = 5 for different cases of Uk -costs and sizes of M in PEA_NE. We note that the total cost of IP is the lowest compared to OTN and fiber cost except when M = 2.5 and Uk-cr1. The IP cost decreases as we increase the size of M. This is because as we fix the unit cost of IP and increase the module size, we are getting more IP/MPLS capacity for the same price. We also note that the OTN cost increases for each scenario as we increase the Uk -cost. These observations are also true for the PEA_C network as shown in Figure 6.3.

Next we consider the case when the IP-cost is high (40) in Figure 6.4. The overall IP cost decreases again as we increase the size of M and fix the unit price. The OTN overall cost increases as the Uk-cost is increased. The difference in this figure from Figure 6.2 and 6.3 is that the IP overall cost is higher than the OTN overall cost in all cases except when M = 10 Gbps for the case of Uk = UK-cr3. The same results can be observed in the PEA_C network.









6.2.2 IP layer cost

Figure 6.5 shows the total IP cost for different values of M. The cost increases as the unit cost increases. Obviously, the case of M = 10 Gbps yields the lowest IP total cost since we have more capacity for the same price. However, having more capacity for the same price may not always lead to lowest network cost as we will see later in next Section.



Figure 6.4 Costs of Different Components for Different *M* When IP-cost=40 in PEA_NE.



(a) Total IP Cost in PEA_NE (b) Total IP Cost in PEA_C

Figure 6.5 Total IP Cost of Different *M*.

6.2.3 OTN Layer Cost

Figure 6.6 and Figure 6.7 show the OTN costs for PEA_NE and PEA_C network for various values of M, IP and U_k costs. In PEA_NE, the case of M = 2.5 Gbps yields the best OTN cost performance, and varying the IP-cost has a negligible effect in this case. The case when M = 5 follows in Uk-cr1 (except at IP-cost=5) and UK-cr2 in which M = 10 is better. In UK-cr3, the case of M = 10 is better than M = 5 except at IP-cost =40. As a general observation in PEA_NE, the size of M, such that M is below the average demand in the network is the most obvious to achieve the lowest OTN layer cost.



Figure 6.6 Total OTN Cost of Different *M* and *U_k* in PEA_NE.



Figure 6.7 Total OTN Cost of Different *M* and *Uk* in PEA_C

For the PEA_C, the case of M = 2.5 achieves the best OTN cost performance when the IP-cost is low (3.5% of the W-cost) or high (28% of the W-cost) as shown in Figure 6.7. While the IP-cost is of medium range (7% and 14% of the W-cost), it is more proper to get an M that is equal to the average demand that results in a small gain.

For both topologies, the case of IP/MPLS module size of M = 10 (above average demand) should be avoided if the focus is to reduce the OTN layer cost. Although this case is the best to achieve the minimum IP/MPLS layer and the minimum total network costs, it is the worst for the OTN layer cost. This is because when the size of M is large, some of the bandwidth is larger than the real one is required at the IP/MPLS layers. However, the OTN layer must satisfy all demands from the upper layer resulting in a higher OTN layer cost.

6.2.4 Total Network Cost

Now we focus on the total network costs for different scenarios as depicted in Figure 6.8. The case of M = 10 is always the best case to achieve the minimum network cost regardless of the Uk -cost and the size of M. However, it may not be always the best case to have more capacity at the IP/MPLS layer for the same price. Consider Figure 6.8 (a) that shows the case when IP-cost= 5. In this case it may appear surprising at the first glance to observe that the case when M = 2.5 yields a lower cost than the one for M = 5 Gbps in UK-cr3. This is not like the cases of IP-cost= 20 and IP-cost= 40 when M = 5 gives a lower network cost than M = 2.5 Gbps as shown in figures 6.8b and 6.8c. One may wonder why the case of M = 2.5 Gbps is cheaper than the case when M = 5 Gbps with IP-cost = 5 is fixed. In other words, why would the total cost be higher if the IP/MPLS layer module size is increased but the unit cost is kept the same. Interestingly, in a multilayer network, demands from the IP/MPLS layer will have to be satisfied in the lower layers. Getting more than needed because of the modularity and integral flow requirements and the cheap unit cost at the IP/MPLS layer means that those unneeded resources still must be accommodated in the lower layers leading to an overall cost increase. Note that this depends on several factors such as the demand volumes, the average demand, the network topology, the size of M, and the Uk -cost. However, when the IP-cost is high, the unnecessary resources are minimal; the network will be conservative in acquiring expensive resources. We note exactly the same trends in the PEA_C topology as depicted in Figure 6.8 (a).



Figure 6.8 Total Network Cost of Different *M* in PEA_NE



Figure 6.9 Total Network Cost of Different *M* in PEA_C

6.3 Conclusion

If we only consider the total cost of the IP/MPLS layer, we find that when M is above the average demand in the network is the best case that minimizes the cost of this layer. This is also the best case that minimizes the overall network cost followed by the case when M is equal to the average demand in most cases. However, when the cost ratio of IP to W is 3.5%, this becomes the worst case for the overall network cost. This is due to the observation that when the IP-cost is low, the network attempts to satisfy more demands in the IP/MPLS layer and therefore, acquires more capacity modules that may result in some extra bandwidth being unused. This becomes unnecessary demand on the lower layers that must be satisfied. This consequently increases the network cost. On the other hand, the case when M is below the average demand is the best case that minimizes the OTN layer cost in both PEA_NE and PEA_C except in PEA_C network when the cost ratio of IP to W is 14% in which case the case of M = 5 is better. Note that these are rough observations for the OTN layer since there is a small effect due to the different U_k -cost scenarios. For reducing the DWDM layer cost, the case when M is below the average demand, is the best option for both PEA_NE and PEAC networks. The case of M is equal the average demand is the worst case for reducing the cost of the DWDM layer in most cases.

From this discussion we can observe that some parameter values may be the best for reducing the cost of an individual layer but these are not for minimizing the overall network cost, and vice versa. We present Tables 6.4, 6.5 and 6.6, to summarize the above discussion. In each table, we place the best values of M for each case that minimizes the corresponding cost. Here B, E and A, refer to below, equal, and above average demands, respectively. We note that when the IP to W cost ratio is 3.5%, an Mbelow the average demand is the best solution for reducing the OTN layer, the DWDM layer, and the overall network cost. On the other hand, when the IP to W cost ratio is 28%, above average demand M is best solution for reducing the overall network, below or equal average M is best case for reducing the OTN layer cost, and equal average M is the best case for reducing the OTN layer cost.

Table 6.4 Best Cases of M to Minimize Network Cost

	Cost Ratio of IP to W					
	3.5%	7%	14%	28%		
PEA_NE	А	А	А	А		
PEA_C	А	А	А	А		

Table 6.5 Best Cases of M to Minimize OTN Layer Cost

	Cost Ratio of IP to W						
	3.5%	7%	14%	28%			
PEA_NE	А	В	В	В			
PEA_C	В	B/E	E	В			

Table 6.6 Best Cases of M to Minimize DWDM Layer Cost

	Cost Ratio of IP to W					
	3.5%	7%	14%	28%		
PEA_NE	В	В	В	В		
PEA_C	В	В	B/E	В		

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this thesis, we have considered five related topics in design and performance evaluation in IP over DWDM network. These are:

(1) Design the DWDM network based on the physical parameters of PEA optical systems (optical fiber cable parameters and DWDM equipment). The advanced modulation format of 100 GE transponder card by coherent DQPSK offers approximately 4 dB improvement in OSNR sensitivity compared to noncoherent DQPSK. We could also extend long reach distance the 100 GE wavelength channel without regeneration by using FEC/EFEC/HG-FEC function in the designing phase. The benefit of coherent CP-DQPSK provides high CD robustness, PMD robustness and low OSNR needed. As the result we can avoid the DCUs, no need the precise the fiber characterization and can reach more distance without E-O-E regeneration. Finally, we can observe in the results for the network protection in DWDM layer when using Y-cable protection gives more efficiency than using Fiber-Switched with the contrast value of link availability.

(2) The design of IP/MPLS network depends the IP traffic and bandwidth requirement in each department of PEA. The designing and planning focuses mainly in IP layer in core layer of the network. The IP/MPLS core router maps across DWDM layer by connecting the IP/MPLS with ROADM node in DWDM network. The 100 GE signals are carried by 100G Trunk transponder card. We use MPLS-TE for traffic planning in IP layer. We define, classify and set policy of the QoS and also bandwidth guarantee for the best benefit and performance of the network.

(3) The performance of the designed PEA IP over DWDM network is evaluated by considering the performance separated into DWDM layer (optical layer) and IP layer (data layer). The performance of the optical layer is obtained by the blocking probability. This shows that there is no blocking at full load with 40 channels of the the network. The QoS verifies and indicates the performance for the data layer. The QoS includes guaranteed bandwidth of each department in the PEA network and no failure link for significant services of the organization.

(4) We present the multilayer network as IP over OTN over DWDM network for applying the benefit used in DWDM layer (optical layer) and IP layer (data layer). We consider the problems in IP/MPLS over OTN over DWDM multilayer networks including the capacity conditions, the IP/MPLS and OTN layers interrelation and the optimization of node capacity. The principal contributions in this work are the OTN sublayer technological constraints. We have also defined comprehensive cost models that cover the sets of cost components in each layer in the network. We can significantly reduce the number of the constraints of each OTN signal quantum for the structure cost at the OTN layer. We have presented a networking optimization model that aims to reducing the routing and switching node capacity.

Furthermore, we have developed a network protection design that bases on the separation of the capacity components of each layer to provide the protection to the normal traffic and hence avoid double or triple protection in the three-layer networks.

(5) This study includes the CAPEX that presents the network cost based on the costs of models. This includes the extensive studies through various costs and network parameters. We have investigated the impacts of varying those values on each layer and the overall network performance. These studies have given us insights on (1) how those values of each layer are influencing the overall network cost and (2) what resources needed at each layer for a given set of network demands. The cost of the Gbps of the IP/MPLS layer is relatively cheap. We have also observed the important impact of the IP/MPLS capacity module on the entire network. Generally, when this parameter is above the average demand, it results the best overall network performance. However, this case is the worst case if the goal considers either the OTN or DWDM layer costs separately. We have also noted the impact of the OTN signals. We have observed that the OTN signal cost does not influence the DWDM layer. The DWDM layer deals with the upper layer capacity that it must satisfy, but not the cost of that capacity. We have seen that there are three factors that effect on the OTN

layer signals including the size of the IP/MPLS layer capacity module, the cost relationship of the OTN signals and the demand volumes.

7.2 Suggestions and Future Works

We should point out that our models do not include path constraints or number and location of node constraints. Instead, we have assumed in the models that the node numbers and locations and the k-shortest paths between node pairs. In addition, even though our models consider a broad set of technological constraints, there are other nonessential constraints that could be addressed, for example, the restriction on the maximum number of tunnels and lightpaths. Another constrain is the limitation lies in the size of the IP/MPLS capacity module and the nature of the IP demands. First, we have assumed in the formulations that M is a fixed constant. The models could be extended to consider multiple IP/MPLS interfaces. Second, we have only considered a few sets of static IP demands. The work could be extended to consider multi-hour and multi-period traffic demands.

We also wish to clarify that our models do not consider the wavelength continuity constraints or the wavelength converter placement problem in the DWDM layer. We define the ability of ROAMD node in DWDM layer for managing and switching the wavelength without the constraints. We focus in this research on the capacity design without the allocation problems. Indeed, since our models solve the design problems in the network planning phase, the output could be used as an input to the allocation problems. However, the available capacity of the DWDM layer can solve the allocation problems and determine where to place the wavelength converters or how to assign the wavelengths per lightpath.

The suggestions for working well and future work for a particular layer maybe in conflict with the ultimate goal;

(1) Concerning economic even when resources are inexpensive.

(2) The demand volume is an important factor in resource usage (e.g. OTN signals).

(3) IP layer plays a decisive role in multilayer networks.

(4) Cost and Capacity are different perspectives.

We plan to continue to investigate multilayer networks and emerging technologies. This study would benefit future communication networks by creating more efficient and resilient network designs, deployments and operations. We particularly plan to consider : (1) load balancing in the IP layer and the optical layer with minimizing the cost of the overall network, (2) the effects of the dynamic demand of the IP/MPLS layer and reconfigurability of the optical layer on the network performance, (3) the modularity of each layer and a heuristic algorithm based on the notion of the multilayer shortest path to solve the problem for large size networks and (4) the label switched routers (LSRs) expected to be bottleneck in future systems. Since LSRs with high capacity and complex structures consume significant power, an important problem is to optimize the node capacity.

We also plan to explore new areas related to future multilayer communication networks, such as multilayer cloud computing and green computing. For instance, through a preliminary investigation, we found that most works on cloud computing have been focusing on the first layer of the cloud on which the service is provided. However, since cloud architecture typically involves multiple cloud components communicating with one another over web servers, we are interested in modeling and studying this paradigm as multilayer network architecture, i.e. Cloud-over-IP. For green networks, we plan to design and model the multilayer networks to capture multi-hour and multi-period traffic aiming to reduce overall power consumptions and leading to less *CO2* emission.

However, due to a very large and unrelenting growth in IP traffic in both the amount and the bandwidth demands, the large organization such as PEA faces many challenges. While the organization and its ICT services demand increasingly stringent service level agreements (SLAs), the underlying network infrastructure must maintain higher levels of reliability. Thus the OPEX cost should be carefully considering for installing and implementing phase in the future network.

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APPENDICES

APPENDIX A

10 GE Service Trail and 100 GE Trunk

ID.	10G Service Loca	tion and Direction		Wavelength	Signal Rate	Equipment
1	ChiangMai.A	Lamphun.B	Working	0-34 (1,556.55)	10GE LAN PHY	15454-OTU2-XP
1	ChiangMai.D	Lamphun.C	Protection	O-34 (1,556.55)	10GE LAN PHY	15454-OTU2-XP
2	ChiangMai.C	Lampang.D	Working	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
2	ChiangMai.B	Lampang.B	Protection	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
3	ChiangMai.B	Phrae.A	Working (Regen)	0-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
3	Phrae.B	Phitsanulok.E	Working (Regen)	O-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
3	ChiangMai.C	Phitsanulok.D	Protection	O-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
4	Lamphun.C	Lampang.D	Working	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
4	Lamphun.A	Lampang.A	Protection	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
5	Lamphun.A	Phitsanulok.D	Working	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
5	Lamphun.C	Phitsanulok.E	Protection	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
6	Lamphun.A	NakhonSawan.B	Working	0-29 (1,552.52)	10GE LAN PHY	15454-OTU2-XP
6	Lamphun.C	UttaRadit.A	Protection (Regen)	O-29 (1,552.52)	10GE LAN PHY	15454-OTU2-XP
6	UttaRadit.D	NakhonSawan.A	(Regen)	O-29 (1,552.52)	10GE LAN PHY	15454-OTU2-XP
7	Lampang.C	Phitsanulok.E	Working	O-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
7	Lampang.A	Phitsanulok.D	Protection	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
8	Phitsanulok.B	NakhonSawan.A	Working	0-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
8	Phitsanulok.A	NakhonSawan.D	Protection	0-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
9	Phitsanulok.A	NakhonSawan.B	Working	0-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
9	Phitsanulok.C	NakhonSawan.F	Protection	0-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
10	Phitsanulok.B	LopBuri.A	Working	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
10	Phitsanulok.C	LopBuri.B	Protection	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
11	NakhonSawan.C	LopBuri.A	Working	0-36 (1,558.17)	10GE LAN PHY	15454-01U2-XP
11	NakhonSawan.D	LopBuri.D	Protection	0-36 (1,558.17)	10GE LAN PHY	15454-01U2-XP
12	NakhonSawan.D	LopBuri.C	Working	0-34 (1,556.55)	10GE LAN PHY	15454-01U2-XP
12	NakhonSawan.F	LopBuri.B	Protection	0-34(1,556.55)	10GE LAN PHY	15454-01U2-XP
13	NakhonSawan.D	SuphanBuri.B	Working	0.32(1,554.94)	10GE LAN PHY	15454-01U2-XP
13	NaknonSawan.C	SupnanBuri.E	Working	0.32(1,554.94)	10GE LAN PHY	15454-0102-AP
14	Phitsanulok E	Lonikao.B	Protection	0.37(1,558.98)	10GELAN PHY	15454 OTU2 XP
14	Nakhon Sawan F	Lomkao D	Working	0-37(1,538.98)	10GELAN PHY	15454-0TU2-XP
15	NakhonSawan A	Lomkao B	Protection	0-36(1,558,17)	10GELAN PHY	15454-0TU2-XP
16	LonBuri B	Lomkao D	Working	0-30(1,550.17)	10GE LAN PHY	15454-0TU2-XP
16	LopBuri F	Lomkao A	Protection	0.39(1,560.61)	10GE LAN PHY	15454-OTU2-XP
17	LopBuri B	Lomkao D	Working	0.39(1,500.01) 0.28(1.551.72)	10GE LAN PHY	15454-OTU2-XP
17	Lopbund	Lonikuo.D	(Regen)	0.20(1,001.12)		10101 0102 14
17	Lomkao.A	KhonKaen.D	Working	O-28 (1.551.72)	10GE LAN PHY	15454-OTU2-XP
15			(Regen)		10051 111 5111	
17	LopBuri.F	KhonKaen.E	Protection	0-28 (1,551.72)	10GE LAN PHY	15454-OTU2-XP
18	сорвиті.F	INAKHORKATCHASIMA.D	working	0-29 (1,552.52)	10GE LAN PHY	15454-0102-XP
18	LopBuri.B	Lomkao.D	(Regen)	O-29 (1,552.52)	10GE LAN PHY	15454-OTU2-XP
18	Lomkao.A	NakhonRatchasima.F	(Regen)	O-29 (1,552.52)	10GE LAN PHY	15454-OTU2-XP
19	LopBuri.D	SuphanBuri.E	Working	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
19	LopBuri.C	SuphanBuri.B	Protection	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
20	LopBuri.E	Ayutthaya.C	Working	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
20	LopBuri.D	Ayutthaya.B	Protection	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
21	LopBuri.E	HQ.D	Working	O-02 (1,531.12)	10GE LAN PHY	100G-LC-C + 10X10G-LC
21	LopBuri.D	SuphanBuri.E	Protection (Regen)	O-02 (1,531.12)	10GE LAN PHY	15454-M-100G- LC-C= / 100G- LC-C + 10X10G- LC
21	SuphanBuri.C	HQ.A	Protection (Regen)	O-02 (1,531.12)	10GE LAN PHY	15454-M-100G- LC-C= / 100G- LC-C + 10X10G- LC

Table A: 10 GE Service Trail and 100 GE Trunk

ID.	10G Ser	10G Service Location and Direction		Wavelength	Signal Rate	Equipment
22	LopBuri.F	SMC.E	Working	0-03 (1.531.90)	10GE LAN PHY	100G-LC-C +
22	LopBuri.C	SuphanBuri.B	Protection (Regen)	O-03 (1,531.90)	10GE LAN PHY	10X10G-LC 15454-M-100G- LC-C= / 100G- LC-C + 10X10G- LC
22	SuphanBuri.C	SMC.C	Protection (Regen)	O-03 (1,531.90)	10GE LAN PHY	100G-LC-C + 10X10G-LC / 15454-M-100G- LC-C=
23	Ayutthaya.B	SuphanBuri.D	Working	O-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
23	Ayutthaya.C	SuphanBuri.E	Protection	O-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
24	Ayutthaya.D	NakhonRatchasima.E	Working	O-36 (1,558.17)	10GE LAN PHY	15454-OTU2-XP
24	Ayutthaya.G	NakhonRatchasima. B	Protection	O-36 (1,558.17)	10GE LAN PHY	15454-OTU2-XP
25	Ayutthaya.E	HQ.D	Working	0-06 (1,534.25)	10GE LAN PHY	100G-LC-C + 10X10G-LC
25	Ayutthaya.B	SuphanBuri.D	Protection (Regen)	O-06 (1,534.25)	10GE LAN PHY	15454-M-100G- LC-C= / 100G- LC-C + 10X10G- LC
25	SuphanBuri.C	HQ.A	Protection (Regen)	O-06 (1,534.25)	10GE LAN PHY	15454-M-100G- LC-C= / 100G- LC-C + 10X10G- LC
26	Ayutthaya.F	SMC.E	Working	O-04 (1,532.68)	10GE LAN PHY	100G-LC-C + 10X10G-LC
26	Ayutthaya.B	SuphanBuri.D	Protection (Regen) Protection	0-04 (1,532.68)	10GE LAN PHY	15454-M-100G- LC-C= / 100G- LC-C + 10X10G- LC 100G-LC-C + 10X10G-LC /
20	Suphanburi.e	SMC.C	(Regen)	0-04 (1,552.00)		15454-M-100G- LC-C=
27	UdonThani.A	Lomkao.E	Working	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
27	UdonThani.C	Lomkao.A	Protection	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
28	UdonThani.C	KhonKaen.A	Working	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
28	UdonThani.B	KhonKaen.B	Protection	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
29	UdonThani.B	UbonRajchathani.A	Working	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
29	UdonTham.C	UbonRajchathani.D	Protection	0-31(1,554.13)	10GE LAN PHY	15454-OTU2-XP
30	KnonKaen.D	Lomkao.A	Working Destantion	0-34(1,556.55)	10GE LAN PHY	15454-01U2-AP
30	KnonKaen.A	Lomkao.E	Protection	0-34 (1,556.55)	10GE LAN PHY	15454-0102-XP
31	KhonKaen.E	Ratchasima.C	Working	O-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
31	KhonKaen.C	Ratchasima.G	Protection	O-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
32	KhonKaen.C	Rajchathani.D	Working	O-34 (1,556.55)	10GE LAN PHY	15454-OTU2-XP
32	KhonKaen.B	Rajchathani.A	Protection	O-34 (1,556.55)	10GE LAN PHY	15454-OTU2-XP
33	Ubon Rajchathani.B	Nakhon Ratchasima.A	Working	O-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
33	Ubon Rajchathani.D	Nakhon Ratchasima.G	Protection	O-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
34	Nakhon Ratchasima.B	HQ.B	Working	O-04 (1,532.68)	10GE LAN PHY	100G-LC-C + 10X10G-LC
34	Nakhon Ratchasima.E	HQ.D	Protection	O-04 (1,532.68)	10GE LAN PHY	100G-LC-C + 10X10G-LC
35	NakhonRatcha sima.D	SMC.E	Working	O-01 (1,530.33)	10GE LAN PHY	100G-LC-C + 10X10G-LC
35	Nakhon Ratchasima.B	ChaChoengSao.D	Protection (Regen)	O-01 (1,530.33)	10GE LAN PHY	100G-LC-C + 10X10G-LC / 15454-M-100G- LC

Table A: 10 GE Service Trail and 100 GE Trunk (Continued)
ID.	10G Serv	vice Location and Dir	ection	Wavelength	Signal Rate	Equipment
	ChaChoeng		Protection			100G-LC-C +
35	Sao.A	SMC.A	(Regen)	O-01 (1,530.33)	10GE LAN PHY	10X10G-LC /
36	ChonBuri B	SMC A	Working	0-34 (1 556 55)	10GE I AN PHY	15454-M-100G- 15454-OTU2-XP
36	ChonBuri D	SMC.A SMC F	Protection	0-34(1,556,55)	10GE LAN PHY	15454-0TU2-XP
37	ChonBuri E	HOB	Working	O-38(1,559,79)	10GE LAN PHY	15454-OTU2-XP
37	ChonBuri.D	HQ.D	Protection	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
38	ChonBuri.D	Nakhon Ratchasima.B	Working	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
38	ChonBuri.E	Nakhon Ratchasima.D	Protection	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
39	ChonBuri.E	Ayutthaya.G	Working	O-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
39	ChonBuri.D	Ayutthaya.D	Protection	0-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
40	Nakhon Pathom.D	HQ.A	Working	O-01 (1,530.33)	10GE LAN PHY	100G-LC-C + 10X10G-LC
40	Nakhon Pathom.A	HQ.D	Protection	0-01 (1,530.33)	10GE LAN PHY	100G-LC-C + 10X10G-LC
41	Nakhon Pathom.E	SMC.C	Working	0-01 (1,530.33)	10GE LAN PHY	100G-LC-C + 10X10G-LC
41	Nakhon Pathom.B	SMC.B	Protection	0-01 (1,530.33)	10GE LAN PHY	100G-LC-C + 10X10G-LC
42	Nakhon Pathom.A	SuphanBuri.C	Working	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
42	Nakhon Pathom.B	SuphanBuri.A	Protection	O-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
43	Nakhon Pathom.C	PhetchaBuri.D	Working	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
43	Nakhon Pathom.B	PhetchaBuri.B	Protection	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
44	PhetchaBuri.B	SuphanBuri.A	Working	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
44	PhetchaBuri.D	SuphanBuri.C	Protection	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
45	PhetchaBuri.E	SMC.B	Working	0-02 (1,531.12)	10GE LAN PHY	100G-LC-C + 10X10G-LC
45	PhetchaBuri.D	SMC.C	Protection	0-02 (1,531.12)	10GE LAN PHY	100G-LC-C + 10X10G-LC
46	PhetchaBuri.D	HQ.A	Working	O-03 (1,531.90)	10GE LAN PHY	100G-LC-C + 10X10G-LC
46	PhetchaBuri.B	SuphanBuri.A	Protection (Regen)	O-03 (1,531.90)	10GE LAN PHY	100G-LC-C + 10X10G-LC / 15454-M-100G- LC-
46	SuphanBuri.D	HQ.D	Protection (Regen)	O-03 (1,531.90)	10GE LAN PHY	15454-M-100G- LC-C= / 100G- LC-C + 10X10G- LC
47	PhetchaBuri.A	Prachuap.B	Working	0-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
47	PhetchaBuri.C	Prachuap.E	Protection	O-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
48	PhetchaBuri.C	Chumphon.A	Working Protection	0.31(1,554.13)	10GE LAN PHY	15454-0TU2-XP
48	Prachuan C	Pranburi B	Working	O-31(1,534.13) O-18(1,543,73)	10GE LAN PHY	15454-01U2-XP
49	Pranhuri A	SMC B	(Regen) Working	0-18(154373)	10GE WANPHY	15454-OTU2-XP
			(Regen)	0 10 (1,5+5.75)		13434 0102-24
49	Prachuap.B	SMC.D	Protection	0-18 (1,543.73)	10GE WANPHY	15454-OTU2-XP
50	Prachuap.D	Chumphon.A	Working Protection	0-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
51	Prachuap.A	Chumphon A	Working	0-36(1,339.79) 0-36(1.558.17)	10GELAN PHY	15454-0102-AP
51	Prachuap A	Chumphon B	Protection	0-36(1,558,17)	10GE LAN PHY	15454-OTU2-XP
52	Prachuap.A	Punpin.D	Working	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
52	Prachuan.D	Punpin.E	Protection	0-33 (1,555.75)	10GE LAN PHY	15454-OTU2-XP
53	Chumphon.B	Punpin.A	Working	O-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
53	Chumphon.A	Punpin.D	Protection	0-32 (1,554.94)	10GE LAN PHY	15454-OTU2-XP
54	Chumphon.C	Nakhon SriThama.A	Working	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP

Table A: 10 GE Service Trail and 100 GE Trunk (Continued)

ID.	10G Ser	vice Location and	Direction	Wavelength	Signal Rate	Equipment
54	Chumphon.B	NakhonSri Thama.E	Protection	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
55	Punpin.C	NakhonSri Thama.E	Working	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
55	Punpin.B	NakhonSri Thama.A	Protection	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
56	Punpin.D	Songkhla2.B	Working	0-34 (1,556.55)	10GE LAN PHY	15454-OTU2-XP
56	Punpin.B	Songkhla2.D	Protection	O-34 (1,556.55)	10GE LAN PHY	15454-OTU2-XP
57	Nakhon SriThama.B	Songkhla2.D	Working	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
57	Nakhon SriThama.D	Songkhla2.B	Protection	0-31 (1,554.13)	10GE LAN PHY	15454-OTU2-XP
58	Nakhon SriThama.B	Yala.A	Working	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
58	Nakhon SriThama.D	Yala.D	Protection	0-39 (1,560.61)	10GE LAN PHY	15454-OTU2-XP
59	Songkhla2.C	Yala.D	Working	O-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
59	Songkhla2.D	Yala.A	Protection	O-38 (1,559.79)	10GE LAN PHY	15454-OTU2-XP
60	Songkhla2.A	Yala.B	Working	O-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
60	Songkhla2.B	Nakhon SriThama.D	Protection (Regen)	0-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
60	Nakhon SriThama.B	Yala.A	Protection (Regen)	0-37 (1,558.98)	10GE LAN PHY	15454-OTU2-XP
61	Songkhla2.D	Yala.A	Working	O-36 (1,558.17)	10GE LAN PHY	15454-OTU2-XP
61	Songkhla2.A	Yala.B	Protection	O-36 (1,558.17)	10GE LAN PHY	15454-OTU2-XP

Table A: 10 GE Service Trail and 100 GE Trunk (Continued)

APPENDIX B

1 G Service Trail

Table B: 1 G Service Trail

ID	1C Com	ica I contian and Direc	tion	Woyalangth	Signal Data	Fauinment
<u>ID.</u>	IG Serv	Lengthen D	N/- ul-i-u-	wavelength	Signal Kate	Equipment
1			working	0-55 (1,555.75)		15454-AR-AP=
1	ChiangMai.A	Lamphun.B	Protection	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
2	ChiangMai.C	Phayao.C	Working	0-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
2	ChiangMai.B	Phayao.A	Protection	0-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
3	ChiangMai.C	Lampang.D	Working	0-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
3	ChiangMai.B	Lampang.B	Protection	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
4	ChiangMai.C	Turn.B	Working	O-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=
4	ChiangMai.D	Turn.C	Protection	0-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=
5	Phitsanulok.A	KamphaengPhet.D	Working	O-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
5	Phitsanulok B	KamphaengPhet C	Protection	0-39 (1.560.61)	Gigabit Ethernet	15454-AR-XP=
6	Phitsanulok D	Sawankaloak C	Working	0-39(1,560,61)	Gigabit Ethernet	15454-AR-XP=
6	Phitsanulok E	Sawankaloak A	Protection	0.39(1,560.61)	Gigabit Ethernet	15454-AR-XP-
7	Phiteanulok E	Dhrae B	Working	0.34(1.556.55)	Gigabit Ethernet	15454 AP YP-
7	Thitsanulok.E	Thrae D	Destastion	0-34(1,556,55)	Cigabit Ethermet	15454 AD VD-
/	Philtsanulok.D	Phirae.D	Westeine	0.34(1,330.33)	Gigabit Ethernet	15454 - AR - AP = 15454 - AR - AP
8	Phitsanulok.E	UttaRadit.D	Working	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-AP=
8	Phitsanulok.D	UttaRadit.C	Protection	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
9	LopBuri.A	NakhonSawan.C	Working	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
9	LopBuri.B	NakhonSawan.F	Protection	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
10	LopBuri.C	ChaiNat.D	Working	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
10	LopBuri.A	ChaiNat.C	Protection	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
11	LopBuri.B	Bungsampan.A	Working	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
11	LopBuri.A	Bungsampan.B	Protection	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
12	LopBuri.B	Lomkao.D	Working	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
12	LopBuri.A	Lomkao.B	Protection	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
13	UdonThani.A	NongBuaLamPhu.B	Working	0-39 (1.560.61)	Gigabit Ethernet	15454-AR-XP=
13	UdonThani C	NongBuaLamPhu C	Protection	0-39(156061)	Gigabit Ethernet	15454-AR-XP=
14	UdonThani A	Darnsai B	Working	0.36(1.558.17)	Gigabit Ethernet	15454 - AR - XP -
14	UdonThani C	Darnsai C	Protection	0-36(1,558,17)	Gigabit Ethernet	15454-AR-AR = 15454-AR - XP = 15454AR - XP = 1545
14	UdonThani A	Chumpoo A	Working	0.30(1,338.17)	Gigabit Ethernet	15454 AD VD-
15	UdonThani.A	Chumpae.A	Destastion	0.37(1,338.98)	Gigabit Ethernet	15454 AD VD
15		Спитрае.в	Protection	0-37(1,338.98)	Gigabit Ethernet	15454-AR-AP=
16	Udon I hani.C	KhonKaen.A	Working	0-32 (1,554.94)	Gigabit Ethernet	15454-AR-XP=
16	UdonThani.A	KhonKaen.D	Protection	0-32 (1,554.94)	Gigabit Ethernet	15454-AR-XP=
17	Ubon Rajchathani.A	MukDahan.B	Working	O-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
17	Ubon Rajchathani.C	MukDahan.C	Protection	O-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
18	Nakhon Ratchasima.A	Surin.B	Working	O-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
18	Nakhon Ratchasima.G	Surin.C	Protection	O-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
19	Ubon Rajchathani.C	MahaSarakham.C	Working	O-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=
19	Ubon Rajchathani.B	MahaSarakham.B	Protection	O-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=
20	Ayutthaya.D	SaraBuri.B	Working	0-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
20	Ayutthaya.C	SaraBuri.A	Protection	0-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
21	Ayutthaya.G	Nontri.C	Working	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
21	Ayutthaya.D	Nontri.A	Protection	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
22	ChonBuri.A	Pattya.B	Working	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
22	ChonBuri.C	Pattya.D	Protection	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
23	ChonBuri.E	ChaChoengSao.A	Working	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
23	ChonBuri.A	ChaChoengSao.B	Protection	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
24	ChonBuri.D	Krang.C	Working	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
24	ChonBuri.C	Krang.B	Protection	0-39 (1.560.61)	Gigabit Ethernet	15454-AR-XP=
25	Nakhon Pathom A	SuphanBuri.C	Working	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
25	Nakhon Pathom.B	SuphanBuri.A	Protection	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
26	Nakhon Pathom.B	Banpo.C	Working	0-34 (1,556.55)	Gigabit Ethernet	15454-AR-XP=
26	Nakhon Pathom.C	Banpo.A	Protection	0-34 (1,556.55)	Gigabit Ethernet	15454-AR-XP=
27	PhetchaBuri.B	SamutSongkhram.C	Working	O-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=
27	PhetchaBuri.C	SamutSongkhram.B	Protection	O-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=

ID.	1G Service Location and Direction		Wavelength	Signal Rate	Equipment	
28	PhetchaBuri.C	Pranburi.D	Working	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
28	PhetchaBuri.A	Pranburi.C	Protection	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
29	PhetchaBuri.A	Prachuap.B	Working	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
29	PhetchaBuri.C	Prachuap.E	Protection	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
30	PhetchaBuri.C	Bangsapran.A	Working	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
30	PhetchaBuri.A	Bangsapran.E	Protection	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
31	PhetchaBuri.C	Chumphon.A	Working	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
31	PhetchaBuri.A	Chumphon.D	Protection	0-39 (1,560.61)	Gigabit Ethernet	15454-AR-XP=
32	PhetchaBuri.A	Tasae.B	Working	O-34 (1,556.55)	Gigabit Ethernet	15454-AR-XP=
32	PhetchaBuri.C	Chumphon.D	Protection (Regen)	O-34 (1,556.55)	Gigabit Ethernet	15454-OTU2- XP(Regen) / 15454-AR-XP=
32	Chumphon.B	Tasae.C	Protection (Regen)	O-34 (1,556.55)	Gigabit Ethernet	15454-OTU2- XP(Regen) / 15454-AR-XP=
33	PhetchaBuri.A	Langsuan.C	Protection	0-29 (1,552.52)	Gigabit Ethernet	15454-AR-XP=
34	PhetchaBuri.A	Ranong.B	Working	0-28 (1,551.72)	Gigabit Ethernet	15454-AR-XP=
34	PhetchaBuri.C	Ranong.D	Protection	O-28 (1,551.72)	Gigabit Ethernet	15454-AR-XP=
35	Nakhon SriThama.A	Punpin.B	Working	O-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
35	Nakhon SriThama.E	Punpin.C	Protection	0-38 (1,559.79)	Gigabit Ethernet	15454-AR-XP=
36	Nakhon SriThama.E	Huayord.C	Working	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
36	Nakhon SriThama.A	Huayord.B	Protection	O-37 (1,558.98)	Gigabit Ethernet	15454-AR-XP=
37	Nakhon SriThama.A	Aualuk.C	Working	O-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=
37	Nakhon SriThama.E	Aualuk.A	Protection	O-36 (1,558.17)	Gigabit Ethernet	15454-AR-XP=
38	Yala.D	Songkhla2.C	Working	0-34 (1,556.55)	Gigabit Ethernet	15454-AR-XP=
38	Yala.B	Songkhla2.A	Protection	0-34 (1,556.55)	Gigabit Ethernet	15454-AR-XP=
39	Yala.D	Songkhla1.C	Working	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
39	Yala.B	Songkhla1.A	Protection	0-33 (1,555.75)	Gigabit Ethernet	15454-AR-XP=
40	Yala.D	Rattapoom.A	Working	0-32 (1,554.94)	Gigabit Ethernet	15454-AR-XP=
40	Yala.A	Rattapoom.C	Protection	0-32 (1,554.94)	Gigabit Ethernet	15454-AR-XP=

 Table B: 1 G Service Trail (Continued)

APPENDIX C

Total Network Equipment Unit and Cost

Product ID	Description	Quantity	Unit Price	Total Price
	MSTP / NCS 2K Transport			
15454-M-TNCE-K9	Node Controller with	684	6500	4446000
	Ethernet PTP			
	15454 ETSI MSTP R9 6 0			
SF15454ME-R960K9	SW Pre-loaded on TNC/E	684	0	0
	TSC/F	001	Ŭ	0
	MSTD / NCS 2K Transport			
15454 M TSCE VO	Shalf Controllor with	74	2250	240500
15454-WI-15CE-K9	Silen Controller with	/4	5250	240300
	Ethernet PTP			
	15454 ETSI MSTP R9.6.0	- 4	0	0
SF15454ME-R9.6.0K9	SW, Pre-loaded on TNC/E,	74	0	0
	TSC/E			
	ONS15454 Any-Rate			
15454-AR-XP-LIC	Xponder - SW License	80	9000	720000
	Upgradeable			
15454 OTU2 VD	4 X OTN 10G MR	111	17000	1007000
15454-0102-XP	TRANSPONDER	111	17000	1887000
	15454 MSTP - Optical			
15454-OPT-EDFA-17	Amplifier - C-band - 17dB	57	20000	1140000
	Gain	0,	20000	1110000
	15454 MSTP - Optical			
15454 OPT EDEA 24	Amplifier C hand 24dB	230	20000	4600000
15454-OF 1-EDFA-24	Coin	230		
	ONE 15454 Option			
15454-OPT-PRE	OINS 15454 Optical	263	18500	4865500
	Pre-Amplifier Module			
	ONS 15216 40ch			
15216-EF-40-ODD	Mux/DeMux Exposed	175	20000	3500000
	Faceplate Patch Panel			
15454F-BLANK	15454 ETSI Blank Module	842	115	96830
	(Slot Filler)	042	115	70050
ONS SE 155 1510	SFP - OC3/STM1 CWDM,	173	2100	003300
013-32-133-1310	1510 nm, EXT	475	2100	993300
ONS VC 10C S1	XFP - OC192/STM64/	102	4900	490600
UNS-AC-10G-51	10GE - 1310 SR - SM LC	102	4800	489000
	SFP - 1000BASE-SX Gigabit			
ONS-SI-GE-SX	Ethernet, 850nm, MM,	640	500	320000
	I-TEMP			
	SCSI Alarm cable 24AWG 8			
15454-M-ALMCBL2	inputs	379	75	28425
	ONS15454 Apy Poto			
15454 LIC 10G DM	VD/MVD Data Muxponder	80	12500	1000000
15454-LIC-100-Divi	SW License	80	12300	1000000
	SW LICENSE			
ONG VG 10G G	XFP -10G Multikate Full C	202	20500	7021000
ONS-XC-10G-C	Band Tunable DWDM XFP,	382	20500	/831000
	50 Ghz,			
15454-MPO-8LC-2	Multi-fiber patchcord - MPO	112	630	70560
	to 8xLC - 2m	112	0.50	,0000
15216-LC-LC 10	Fiber patchcord - LC to	200	90	26100
13210-LC-LC-10	LC - 6m	290	90	20100
15454 1 0 1 0 2	Fiber patchcord - LC to	2075	90	259750
13434-LU-LU-2	LC - 2m	2813		258750
	Multi-fiber patchcord - MPO			
15454-MPO-8LC-6	to 8xLC - 6m	38	630	23940

 Table C: Total Network Equipment Unit and Cost

Product ID	Description	Quantity	Unit Price	Total Price
15454-WXC-LIC	80-WXC - 80 chs - C-Band - 10ch Licensed Restricted	151	35900	5420900
15454-OSC-CSM	THIS ITEM IS EOL: PLEASE CONTACT THE SUPPORT ALIAS	80	6500	520000
15454-M6-DC	6 slot MSTP chassis 30A DC power filter	758	125	94750
15454-M6-SA	6 service slot MSTP shelf, includes M-SHIPKIT,M6- FTF,	379	800	303200
15454-M6-ECU	6 service slot MSTP chassis external cable connections	379	150	56850
15454-M6-FTA2	6 service slot MSTP chassis 2nd gen fan tray	379	200	75800
15454-M6-LCD	6 service slot MSTP chassis LCD Display with backup Memory	379	80	30320
15454-PP-MESH-8	2RU 8-Degree Mesh Patch Panel	29	17135	496915
15216-DCU-SA	Mechanical shelf (housing 2 DCM)	381	560	213360
15454-R9.6.0SWK9	15454 ANSI ETSI MSTP Rel. 9.6.0 Pkgs., DVD, RTU License	379	1995	756105
15454-M6-DCCBL- RE	DC power cable for ETSI right exit	379	300	113700
15454-M-USBCBL	USB cable for passive devices	175	80	14000
15454-M6-DCCBL- LE	DC power cable for ETSI left exit	379	300	113700
15216-DCU-350	DCF of -350 ps/nm and 4dB loss	32	4900	156800
15216-DCU-750	DCF of -750 ps/nm and 6dB loss	63	7700	485100
15454-SMR2-LIC	SM ROADM 2-PRE-AMP- BST 100GHZ-CBAND-10ch	67	37500	2512500
15454-MPO-MPO-2	Multi-fiber patchcord - MPO to MPO - 2m	67	750	50250
15454-PP-4-SMR	1RU 4-Degree SM ROADM Mesh Patch Panel	19	8000	152000
15216-DCU-950	DCF of - 950 ps/nm	90	9200	828000
15216-DCU-1150	DCF of -1150 ps/nm and 8dB loss	83	10500	871500
15216-DCU-450	DCF of - 450 ps/nm	53	5600	296800
15216-DCU-550	DCF of - 550 ps/nm	42	6300	264600
15216-DCU-100	DCF of -100 ps/nm	108	3100	334800
ONS-SC-OSC-ULH	SFP - OC3/STM1/FE Optical Service Channel SFPs ULH -	21	2500	52500
15454-PP-MESH-4	2RU 4-Degree Mesh Patch Panel	6	9085	54510
15216-DCU-1550	DCF of -1550 ps/nm	24	15500	372000
15216-DCU-1350	DCF of -1350 ps/nms	48	14100	676800

 Table C: Total Network Equipment Unit and Cost (Continued)

Product ID	Description	Quantity	Unit Price	Total Price
15216-DCU-1950	DCF of -1950 ps/nm	17	18600	316200
15454-M-100GC-LIC	100G OTU-4 ITU-T CP- DQPSK Full C Band Tunable LC	40	128000	5120000
15454-M-10X10-LIC	10x10G Multi rate Client LC Licensed w/ 1 Licence at 10G	40	25000	1000000
15454-OPT-AMP-C	ONS 15454 Enhanced Optical Amplifier	147	32000	4704000
ONS-SC+-10G-SR	SFP+ SR - Commercial Temp	40	1495	59800
15454-MPO-8LC-8	Multi-fiber patchcord - MPO to 8xLC - 8m	1	630	630
15216-LC-LC-20	Fiber patchcord - LC to LC - 8m	11	90	990
15216-LC-LC-5	Fiber patchcord - LC to LC - 4m	20	90	1800
15454-YCBL-LC	15454 - 2RU Y-Cable Drawer (8 Modules positions)	14	1480	20720
15454-YCM-SM-LC	15454 - Y-Cable Module - SM - LC (1 channel)	20	1500	30000
15216-DCU-E-350	E-LEAF Dispersion Compensation Unit 350 ps/nm	16	14500	232000
15216-DCU-E-200	E-LEAF Dispersion Compensation Unit 200 ps/nm	9	9500	85500
15454-OPT-AMP-17C	17dB Gain, Amp	3	17000	51000
15216-ATT-LC-10	Bulk Attenuator - LC Connector - 10dB	18	200	3600
15454-M-100G-LC-C	100G OTU-4 ITU-T CP- DQPSK Full C Band Tuneable LC	12	242000	2904000
15216-ATT-LC-7	Bulk Attenuator - LC Connector - 7dB	13	200	2600
15216-ATT-LC-3	Bulk Attenuator - LC Connector - 3dB	1	200	200
15216-ATT-LC-15	Bulk Attenuator - LC Connector - 15dB	1	200	200
15216-ATT-LC-5	Bulk Attenuator - LC Connector - 5dB	1	200	200
15216-ATT-LC-18	Bulk Attenuator - LC Connector - 18dB	1	200	200

 Table C: Total Network Equipment Unit and Cost (Continued)

VITAE

NAME-SURNAME	Chaowarit Boonta		
PLACE / DATE OF BIRTH	Amnatcharoen Province, Thailand		
	October 13 th , 1982		
EDUCATION	2004, Bachelor Degree (Telecommunication		
	Engineering)		
	Institute of Engineering, Suranaree University of		
	Technology, Thailand.		
	2012, Master Degree (Electrical Engineering),		
	Department of Electrical Engineering,		
	Ubon Ratchathani University (UBU), Thailand.		
SCHOLARSHIPS	Fund for the Ph.D. in engineering program from		
	the Office of Provincial Electricity Authority		
	(PEA), Thailand.		
WORK	2009-Present, Telecommunication engineer of		
	Provincial Electricity Authority (PEA), Thailand.		