IP/MPLS OVER OTN OVER DWDM MULTILAYER NETWORKS:

OPTIMIZATION MODELS, ALGORITHMS, AND ANALYSES

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University of Missouri–Kansas City, 2011

ABSTRACT

Over the past decade, multilayer network design has received significant attention in the scientific literature. However, the explicit modeling of IP/MPLS over OTN over DWDM in which the OTN layer is specifically considered has not been addressed before. This multilayer network architecture has been identified as promising that bridges integration and interaction between the IP and optical layers. In this dissertation, we consider four related problems.

First, we present an integrated capacity network optimization model for the operational planning of such multilayer networks. The model considers the OTN layer as a distinct layer with its unique technological ODU sublayer constraints. Secondly, we present a design model to investigate the correlation effects of the IP and OTN layers when the physical DWDM layer capacity is a given constant. We also develop a heuristic algorithm to solve the models for large networks.

We provide comprehensive numeric studies that consider various cost parameter values of each layer in the network and analyze the impact of varying the values on network layers and overall network cost. We have observed the significant impact of the IP/MPLS capacity module on each layer and the entire network. Generally, when this parameter size is above the average demand in the network, it leads to the best overall network design.

Thirdly, we consider the problem of optimizing node capacity in this architecture as our design goal, since routers with more capacity and complex structure consume significant power. We present an explicit networking optimization model that aims to minimize the total capacity at the LSRs and the OXCs. 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.

Finally, we factor in the survivability of the multilayer network by considering a suitable protection mechanism for each network layer. We provide a phase-based heuristic approach, study and analysis. We have also examined the network performance from cost vs. protection capacity perspectives while varying the size of the IP/MPLS capacity module.

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined a dissertation titled "IP/MPLS over OTN over DWDM Multilayer Networks: Optimization Models, Algorithms, and Analyses," presented by Iyad A. Katib, candidate for the Doctor of Philosophy degree, and certify that in their opinion it is worthy of acceptance.

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LIST OF ACRONYMS

ATM	Asynchronous Transfer Mode
BCH	Bose – Chaudhuri – Hocquenghem
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
DWDM	Dense Wavelength-Division Multiplexing
EXC	Electrical Cross Connet
FEC	Forward Error Correction
GE	Gigabit Ethernet
ILP	Integer Linear Programming
ISP	Internet Service Provider
ITU-T	International Telecommunications Union - Telecommunication Standardization Sector
LSR	Label Switch Router
MLNCD	Multi Layer Network Capacity Design
MPLS	Multiprotocol Label Switching
OAM	Operation, Administration, and Maintenance
ODU	Optical Data Unit
OPEX	Operating Expenditure
OXC	Optical Cross-Connect
OTN	Optical Transport Network
QoS	Quality of Service
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Networking
TCM	Tandem Connection Monitoring
TE	Traffic Engineering
WDM	Wavelength-Division Multiplexing

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CHAPTER 1

INTRODUCTION

The rising number of Internet users and advanced applications that demand instant and massive network bandwidth such as video conferencing, high quality data visualization applications, online gaming, and High Definition TV, with high QoS requirements, have created new challenges to the current operational network architecture.

At the IP layer, the Multiprotocol Label Switching (MPLS) ability to provide class-specific traffic engineering (TE) features has made it a popular technology. MPLS-TE allows destination-based, constraint-based, and explicit routing to take place simultaneously, bringing viable solutions to network services with QoS guarantees. However, these advantages are of limited value if the underlying network layers do not embrace them by supplying the adequate resources and a contrivable environment.

At the transmission layer, Optical Transport Network (OTN) [21, 22] is 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 in mind. OTN designers combined the benefits of both SONET (synchronous optical network) and DWDM (dense wavelength-division multiplexing) in OTN. OTN offers efficient multiplexing and switching of high-speed signals (around 100 Gbps [7]) and cross connect dispatching of wavelengths and sub-wavelengths that lead to superior bandwidth utilization. OTN also defines a digital wrapper layer that is advantageous over SONET. 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. This is beneficial in reducing the number of transmitted errors that result in longer distances between optical repeaters and leads to lower costs. Because of these benefits, the introduction of OTN explicitly in a multilayer architecture in which OTN interfaces are employed in DWDM (dense wavelength-division multiplexing) systems has been identified as an important consideration [5] for operational architecture. The advantages of OTN over SONET can be exploited in the multilayer architecture leading to superior service-level performance monitoring, support for higher bit-rate client signals, and efficient bandwidth utilization.

In this dissertation, we consider a three-layer architecture explicitly with IP/MPLS over OTN over DWDM. In this architecture, the label switched routers (LSRs) in the IP/MPLS layer are physically connected to optical transport networks that are slated on top of optical cross-connects (OXCs), which are interconnected by DWDM fiber transmission medium at the physical level.

1.1 Problem Definition

The primary goals of our work are: (1) to develop network optimization models specifically for IP/MPLS over OTN over DWDM multilayer networks where the technological constraints of the OTN layer are explicitly considered, (2) to develop heuristic solutions to solve the problems for large networks, and (3) to provide comprehensive analysis of the results that are based on chancing various network parameters and cost values. Under these goals, we address four different problems in such multilayer networks. These are: the multilayer capacity design, the layer correlation effects, the optimization of routing and switching nodes capacity, and the survivability design.

1.2 Motivation

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 WDM systems that provide point-to-point fiber links. One problem is that when a demand has to travel on multiple hops, an expensive optical-electronic-optical 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 is used for forwarding services instead of processing local add/drop services on the nodes [5]. Another issue is that DWDM, being a purely analog form, a fiber failure in a network may only be recognized by 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 electro-optical cross-connects (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 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. Consequently, a demand that is used to be routed on multiple links can be accommodated in a fewer number of links over the OTN-over-DWDM layer. This significantly reduces the forwarding services that the core routers perform and shifts a bulk of the burden to OXCs. As a result, core routers will be less loaded with transit traffic and their capacity is efficiently utilized for local services. Moreover, it has been noted that the introduction of OTN leads to cost reduction in the overall network cost by reducing the amount of transit IP routers [43].

1.3 Contributions of the Dissertation

Although previous work has considered multilayer networks such as IP-over-SONET or IP-over-WDM, the explicit modeling and study of IP/MPLS over OTN over DWDM as a three-layer model has not been examined before. We have made several contributions in this dissertation:

- Chapter 4: 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. The consideration of the OTN layer sublayer technological constraints. Note that although each OTN signal quantum (see Chapter 3 for U_k) can form its own virtual network (sublayer), we can consider them together without considering each sublayer separately because of the way the costing is defined in the objective function in Section 4.2; this reduces the number of constraints considerably.

- Chapter 5: The model of Chapter 4 is an integer linear programming problem that is difficult to solve with an ILP solver such as CPLEX except for small networks. We propose a heuristic algorithm to solve this model for large networks that introduces the notation of multilayer paths with modularity.
- Chapter 6: Based on our heuristic, we present a comprehensive study that considers different sets of cost parameter values in each layer that changes the unit cost ratio between layers for large network topologies.

  This gives us insight on how the cost of each layer is influencing the overall network cost. Moreover, it tells us what resources are needed at each layer for a given set of network demands. This work is presented through a comprehensive study using our heuristic on large networks.

  To our knowledge, there is no such study available on three-layer networks where modularity plays a key role.
- Chapter 7: We present an optimization model for network planning of IP/MPLS over OTN over DWDM multilayer networks while the DWDM capacity is fixed.
- Chapter 8: 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 9: We develop an explicit networking optimization model with IP/MPLS over OTN 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.

- Chapter 11: We develop a networking capacity and protection design model and a phase-based heuristic approach for providing a 100% protection only for the normal traffic. Moreover, the design is based on the separation of capacity components at each layer to avoid double or triple protection of the upper layer capacity.
- Chapter 12: We present a study and analysis for the protection design based on various network parameters to understand their impacts on three-layer networks.

1.4 Outline of the Dissertation

The rest of this dissertation is organized as follows. In Chapter 2 we present a literature survey. We give a brief overview of the OTN signals bit rates and the multiplexing rules in Chapter 3. In Chapter 4, we specify the capacity design optimization problem formulation. In Chapter 5, we present our heuristic algorithm to solve the problem for large networks. In Chapter 6, we present a comprehensive study. In Chapter 7 we present the model on the IP and OTN layer correlation effects along with a study and analysis in Chapter 8. In Chapter 9 we address the problem of node optimization in different layers presenting a model and a study. In Chapter 11 we present a design model that provides multilayer network protection and present a study and analysis in Chapter 12. Finally, in Chapter 13, we draw our conclusion and outline our direction for future work.

CHAPTER 2

LITERATURE SURVEY

Multilayer networks have been an important research topic for a number of years. The focus primarily has been on the two-layer architecture such as IP-over-WDM. In this Chapter we present related topics to OTN and multilayer networks.

2.1 OTN

Recent work has considered the OTN as a new transmission layer technology. Carroll et al., in [9], 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 [19], 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 Tandem Connection Monitoring and automatic protection switching technique and requirement. Jean et al., in [14], 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 [23], addresse forward error correction codes for 100 Gb/s 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 choice for the component code in such systems. Puglia, in [39], describes the tendency of shifting from an all-optical to a digital transport network concept.

2.2 Multilayer Networks

2.2.1 Traffic Engineering

Androulidakis et al., in [2], 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 [41], review the challenges raised by the integrated routing and wavelength assignment problem in GMPLS-based IP over WDM networks. Vigoureux et al., in [44], 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 [10], present a comparison study on protection scenarios when protection is performed jointly with TE and grooming in a multi-layer network.

2.2.2 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 [38]. The goal of the traffic grooming problem is to minimize equipment required to multiplex lower rate signals into higher rate signals for routing over transmission links. Modiano and Lin, in [35], present an overview of the traffic grooming problem and presents a survey on some representative work.

In a seminal work, Doverspike [13] 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 [11] 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 [47], 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 multihop grooming approach. Ou et al., in [36] extend the work of [47] 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 WDM.

2.2.3 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 [12,34]. 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 [18], 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 [42]. Kubilinskas and Pióro present two design problems providing protection in either the WDM layer or the IP layer in [32]. Zhang and Durresi investigate the necessity, methods, and advantages to coordinate multilayer survivability in IP over WDM networks in [45]. The joint multilayer survivability in IP/WDM networks is investigated and studied in [33, 40]. Bigos et al., in [6], 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.

2.2.4 Other Related Work

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 [30]. Bréhon et al. develop a design of a virtual topology in a bus-LSP-capable network that aims to maximize the network utilization in [8]. 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 [4]. Gouveia et al., in [20], 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 [24], 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 [37]. 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 [43]. A heuristic algorithm for solving the cross-connects capacity management problem in OTN over DWDM is presented in [46]. 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 [15] and [16], 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.

2.3 A Remark

In Table 1 we summarize related work that mentions OTN in the context of multilayer networks. We note that all those work have embedded the OTN layer in the DWDM layer implicity. We observe that mostly when OTN is mentioned, a reconfigurable optical backbone is meant. That is, the core routers are connected through electro-optical cross-connects (OXCs) with no consideration for OTN as a distinct layer with its unique technological constraints. However, the functionalities each technology provides are distinguishable, and this prompted us to model each of them separately. To the best of our knowledge, no previous work has considered the OTN sublayer technological constraints specifically in a multilayer network except in our work in [26], [28], and [29]. Considering the OTN sublayer constraints gives a more precise view of this layered architecture that captures OTN explicitly.

Table 1: Summary of Selected Related Work

Paper	Topic	Approach	Objective	Study
[4]	Nodes Locations	ILP Model, Lagrangian Relaxation	Min. cost of capacity and number and location of MPLS nodes	Compares 3 node cost scenarios under 3 sets of demands
[6]	Protection Design	ILP model, close to optimal results	Min. cost of capacity	Compares protection methods under 3 cost ratio
[11]	Traffic Grooming	Algorithm	Design the IP/MPLS logical topology and the routing of the capacity on the physical topology	Compares algorithm with other algorithms under different demands and given elements costs
[37]	Homing Architecture	LP Model	Min. network equipment cost	Compares different homing architectures
[43]	Architecture Comparison	Simulation (VPISystems™)	Compares cost of IP/WDM vs. IP/OTN	Case study based on given network elements costs

CHAPTER 3

OTN TECHNOLOGY OVERVIEW

Many many large-granule broadband services exist today such as, the Gigabit Ethernet, or 10 Gigabit Ethernet (GE/10GE) service. Such large-granule broadband services need efficient transmission and management in order to appropriately attend to bandwidth operations needs. These services require a resilient, efficient, reliable, and cost-effective transport network.

The traditional SONET/SDH transmission network offers a limited transmission capacity; it is basically incapable of transporting large-granule broadband services. The traditional WDM network only enables large transmission capacity. However, as a point-to-point tool that expands capacity and distances, the WDM network offers poor networking and service protection, which cannot meet the requirements of large-granule broadband services for resilient, efficient, reliable, and cost-effective transmission.

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 WDM systems. It offers viable solutions for the deficiencies typically found in traditional WDM networks such as, the lack of the sub wavelength service capability, and poor networking and management

Table 2: OTN Signals, Data Rates and Multiplexing.

U_k Signal	Bit-Rate (Gbps)	Max. U_ks in a wavelength
U_0	1.25	80
U_1	2.5	40
U_2	10	10
U_3	40	2
U_4	100	1

capability. Moreover, it enhances the support for operation, adminstration, maintenance and provisioning functions of SONET/SDH in DWDM. Tandem Connection Monitoring (TCM) 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 hight 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 [1]. 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 [22]. The interfaces of OTN to be used within and between subnetworks of the optical networks are defined in [21]. 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 dissertation, we are interested in the Optical Data Unit (ODU) sublayer that provides (1) tandem connection monitoring, (2) end-to-end path supervision, (3) adaptation of client data that can be of diverse formats such as IP, ATM, Ethernet, SONET, 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 ODUk ($k = 0, 1, 2, 3, 4$), respectively (see Table 2 rates and how these fit into a wavelength assuming each wavelength is 100 Gbps).

OTN also defines the ODUk 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 ODUk signals is easy to visualize from the the bit-rates shown in Table 2.

The multiplexing rules are defined as follows: 2 ODU0 can be multiplexed into an ODU1, up to 4 ODU1 can be multiplexed into an ODU2, up to 4 ODU2 can be multiplexed into an ODU3, and 2 ODU3 can be multiplexed into an ODU4. Also, up to 80 ODU0s, 40 ODU1s, 10 ODU2s, or 2 ODU3s can be multiplexed into an ODU4. It is possible to mix some lower rate signals into a higher rate signal. For instance, ODU1s and ODU2s can be multiplexed into an ODU3, but to reduce the overall network complexity only one stage multiplexing is allowed. For example, it is possible to perform the multiplexing of (ODU1 $\rightarrow$ ODU2) or (ODU1 and ODU2 $\rightarrow$ ODU3), but not (ODU1 $\rightarrow$ ODU2 $\rightarrow$ ODU3). There are two additional specifications: ODU2e and ODUflex. For the purpose of capacity planning modeling, ODU2e can be treated as ODU2, is not considered separately. ODUflex is any rate over ODU0, 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, ODUflex is not considered separately. In the rest of the dissertation, U_k denotes ODUk 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: $U_3 = j \times U_2 + (4 - j) \times 4 \times U_1$, where $(0 \leq j \leq 4)$.

To Summarize, OTN features the following advantages:

- 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.
- Improved monitoring and management operations leading to superior transmission.

CHAPTER 4

AN INTEGRATED CAPACITY OPTIMIZATION MODEL

In this Chapter, 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 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 sub-signal 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 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 Table 3.

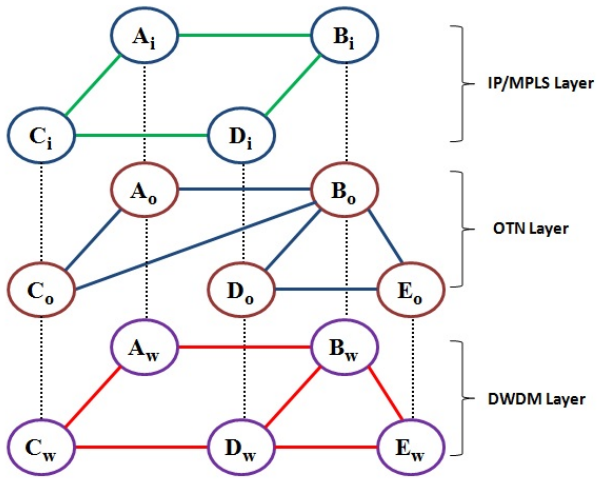


Figure 1: IP/MPLS over OTN over DWDM Network

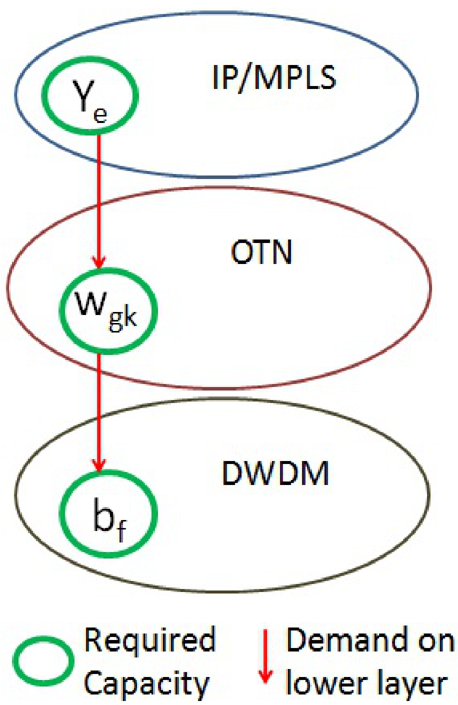


Figure 2: Integrated Model Design Approach

Table 3: List of Notations (P1)

Indices:

d = 1, 2, ..., D demands between source-destination pairs of the IP/MPLS layer.
p = 1, 2, ..., P_d candidate paths for demand d.
e = 1, 2, ..., E links of the IP/MPLS layer.
q = 1, 2, ..., Q_e candidate paths of OTN layer for realizing capacity of link e.
g = 1, 2, ..., G links of the OTN layer.
z = 1, 2, ..., Z_g 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.

Constants:

h_d: Volume of demand d.
δ_{edp}: =1 if link e belongs to path p realizing demand d; 0, otherwise.
γ_{geq}: =1 if link g belongs to path q realizing capacity of link e; 0, otherwise.
ϑ_{fgz}: =1 if link f belongs to path z realizing capacity of link g; 0, otherwise.
M: Module size for IP/MPLS layer.
U_k: Module size for OTN layer link capacities $k = 0, 1, 2, 3, 4$.
N: Module size for DWDM layer link capacities.
η_e: Cost of one capacity unit of module M of IP/MPLS layer link e.
β_{gk}: Cost of one capacity unit of type U_k of OTN layer link g.
ξ_f: Cost of one capacity unit of module N of DWDM layer link f.

Variables:

x_{dp}: IP/MPLS flow variable realizing demand d allocated to path p (non-negative, continuous or binary).
m_{eq}: OTN flow variable allocated to path q realizing capacity of link e (non-negative integral).
s_{gkz}: DWDM flow variable allocated to path z realizing capacity of link g of interface k (non-negative integral).
y_e: Number of modules M to be installed on link e in the IP/MPLS layer (non-negative integral).
w_{gk}: Number of modules U_k to be installed on link g in the OTN layer (non-negative integral).
b_f: Number of modules N to be installed on link f in the DWDM layer (non-negative integral).

4.1 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:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{4.1}$$

Next, we consider the IP/MPLS layer capacity feasibility constraints (4.2). 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:

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \leq M y_e \qquad e = 1, 2, ..., E \tag{4.2}$$

Here, M is the allowable granularity of each MPLS tunnel.

The constraints (4.3) 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.

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{4.3}$$

We next consider the OTN layer capacity feasibility constraints, shown below(4.4). 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.

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \qquad g = 1, 2, ..., G \tag{4.4}$$

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 (4.5) 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.

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4, \;\; g = 1, 2, ..., G \tag{4.5}$$

These next constraints (4.6) 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.

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f \qquad f = 1, 2, ..., F \tag{4.6}$$

Finally, variables are integer or modular as summarized in Table 3.

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 our 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.

4.2 Objective and Cost Model

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

$$\mathcal{F} = \sum_{e=1}^{E} \eta_e y_e + \sum_{g=1}^{G} \sum_{k=0}^{4} \beta_{gk} w_{gk} + \sum_{f=1}^{F} \xi_f b_f \tag{4.7}$$

This objective function captures the total cost of network resources over all three layers generically, where η_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 3. An advantage of our 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, η_e is the unit cost of link e; this is defined as the sum of the interface cost for the upper layer η_e^U and the lower layer η_e^L ends of the connection between the IP/MPLS layer node and the OTN layer node, i.e., $\eta_e = 2\eta_e^U + 2\eta_e^L$, 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 g, β_g^U, plus the cost of multiplexing OTN signals β_g^k, i.e., $\beta_{gk} = 2\beta_g^U + 2\beta_g^k$.

For the 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 ξ_f^I, the optical transponders cost ξ_f^t, the OXC ports ξ_f^o, plus a physical link distance cost Δ_f, i.e., $\xi_f = 2(\xi_f^I + \xi_f^t + \xi_f^o) + \Delta_f$.

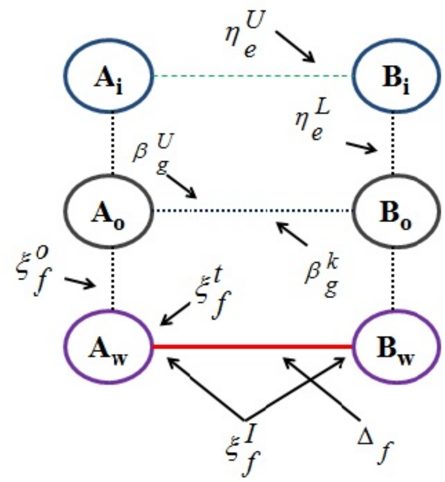


Figure 3: Cost Structure of The Three-Layer Network

The capacity optimization problem (**P1**) for the IP/MPLS-over-OTN-over-DWDM multilayer is to minimize the cost $\mathcal{F}$ given by (4.7) subject to the set of constraints (4.1)–(4.6).

4.3 Interface Cost Example

Figure 4 shows an example of a 2-node per layer network. Let the the IP/MPLS capacity module size M be 10 Gbps. In this example, y_1=3 which indicates that the required capacity at the IP/MPLS layer link e=1 is $M \times y_1$=30 Gbps. There are many ways the 30 Gbps could be carried over OTN signals. For this sample network, we have w_{12} =3 which indicates 3 U_2s on OTN link g=1; each is 10 Gbps. Then, these 3 U_2s are carried over a single wavelength at the DWDM layer; i.e. b_f=1. Thus, this network has used three y_1, three U_2s, and one wavelength. If we compute the cost of the network according to our objective function 4.7, then we will have:

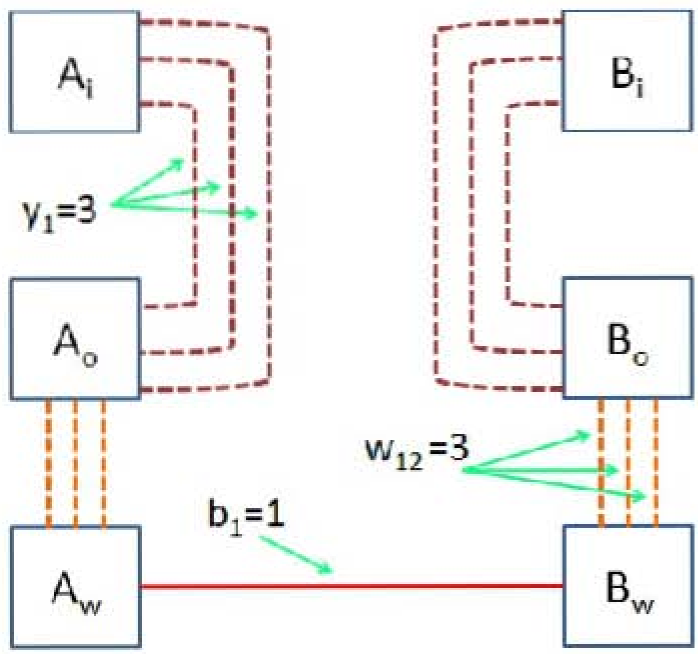


Figure 4: Interface Cost Example: 2-node per Layer Network

$\mathcal{F} = (\eta_1 \times 3) + (\beta_{12} \times 3) + (\xi_1 \times 1)$

Note that η_1, β_{12}, and ξ_1 are the units cost of each layer and are derived as described in Section 4.2.

4.4 Model P1

To make it more readable and illustratable, the entire Model (**P1**) is summarized below.

$$\text{Minimize} \qquad \sum_{e=1}^{E} \eta_e y_e + \sum_{g=1}^{G}\sum_{k=0}^{4} \beta_{gk} w_{gk} + \sum_{f=1}^{F} \xi_f b_f \tag{4.8}$$

Subject to:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{4.9}$$

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \leq M y_e \qquad e = 1, 2, ..., E \tag{4.10}$$

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{4.11}$$

$$M \sum_{e=1}^{E}\sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \qquad g = 1, 2, ..., G \tag{4.12}$$

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4, \ \ g = 1, 2, ..., G \tag{4.13}$$

$$\sum_{g=1}^{G}\sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f \qquad f = 1, 2, ..., F \tag{4.14}$$

Note that the variables of Model (**P1**) are defined in Table 3.

CHAPTER 5

A HEURISTIC APPROACH TO SOLVE (P1)

Model (**P1**) described in Chapter 4 has a large number of constraints and variables even for a small network problem. The total number of constraints for this problem is $D + 2E + 6G + F$. And the number of variables is $P \times D + E(Q+1) + 5G(Z+1) + F$, where P denoted the average number of paths for each demand d. Furthermore, the problem is NP-hard, since simpler forms of network design problems, such as the single-path flow allocation or modular link design, are shown to be NP-hard [38]. An integer linear programming solver such as CPLEX cannot solve this model for large networks. Thus, we have developed a heuristic algorithm to solve (**P1**) for large networks.

5.1 Algorithm Description

The Multilayer Network Capacity Design (MLNCD) heuristic is presented in Algorithm 1; the notations used in the algorithm are summarized in Table 4. Its novelty lies in the consideration of a multilayer path with the requirement of modular link capacities across the three layers, and allowing a path to be set up from source to destination across the three layers. That is, a candidate path T_d^i for routing demand d is a multilayer path if it is constructed over a combination of links e, g, and f. To briefly illustrate, consider Figure 5 that shows a partial view of a multilayer network. A multilayer path between node A_i and D_i in this multilayer network consists of links I_1, O_2, and W_3, representing

Table 4: Notations Used in The Heuristic Algorithm

Notation	Discription
d	a demand between a source-destination pair of the IP/MPLS layer
T_d	a set of candidate multilayer paths for demand d
R_d	a routing table for demand d contains T_d
T_d^i	a candidate path i in R_d for routing demand d
k	modular interfaces of OTN $k = 0, 1, 2, 3, 4$
U_k	Module size for OTN layer link capacities
U_k^c	a counter for U_k module of an OTN layer link
U_k^u	unit cost of one U_k
U_k^m	multiplexing factor = 2,4,4,2 for $k = 0, 1, 2, 3$
h_d	Volume of demand d
$l_v(T_d^i)$	link v on T_d^i

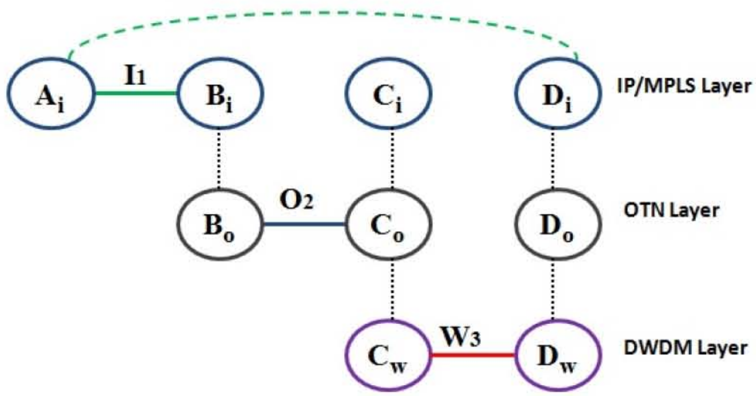


Figure 5: A Multilayer Path Between A_i and D_i

an IP/MPLS tunnel, a lightpath, and a fiber link, respectively. Note that I_1, O_2, and W_3 are the original links on which the path from A_i to D_i is provisioned.

5.1.1 Algorithm MLNCD

Algorithm 1 starts by constructing an initial multilayer network topology. It then assigns a starting fiber capacity in the DWDM layer based on the demand volume and tries to pack demand addressing multilayer requirements; at the end, the unused fiber capacity is released. From our preliminary analysis, we found that by sorting a given set of demands in descending order of the demand volume, the algorithm achieves better link utilization and requires a fewer number of resources (U_k signals and wavelengths) in most cases. Therefore, the algorithm sorts the demands at the beginning before attempting to satisfy them. Next, for each demand d the algorithm finds a set of T_d multilayer shortest paths. The paths are sorted in routing table R_d according to their cost values where the cost of a path is equal to the sum of all links' costs on the path. The demand and its R_d are passed to procedure `ReserveCapacity()`.

Algorithm 1: MLNCD Heuristic Algorithm

input : D, h_d, F, T_d
output: Final Network Cost and Configurations

```
Construct the multilayer network graph;
Assign a starting fiber capacity in the DWDM to satisfy demand h_d, d = 1, ..., D;
Sort h_d in descending order and renumber the demand index as d = 1, 2, .., D such that
h_1 > h_2 > ... > h_D;
repeat
    foreach d do
        if d is not satisfied then
            R_d ← find T_d-multilayer-shortest-paths;
            call Procedure ReserveCapacity(h_d, R_d);
    detach links that have no resources;
    update the multilayer topology;
until all D are satisfied;
foreach OTN link l do
    call Procedure CombineOTN(l);
```

If capacity is available, the algorithm reserves the required bandwidth on each link, updates the links' capacities, and routes the demand on the selected path. This process is repeated for each demand. Each time the algorithm satisfies a demand, it updates the topology since it is changed by satisfying that demand. This form of routing is somehow similar to dynamic state-dependent routing in which the routing tables are changed according to the state of the network.

Note that in the beginning only the physical fibers F are known to the algorithm, while the OTN links G and IP/MPLS links E are created by the algorithm. That is, while the algorithm is in the process of satisfying the demands, the virtual IP/MPLS and optical topologies are developed. A new demand can be satisfied in the existing logical topology if sufficient capacity is available, or using existing lightpaths if these have free capacity to honor the demand, or by establishing a new lightpath, or by using a combination of the three.

As the virtual topology is created and new virtual links are added to the network, the number of multilayer shortest paths T_d increases. We put a limit on T_d for each d. If all T_d are attempted for a given demand and no free path is available, the algorithm then skips this demand and goes to the next. If all demands are processed and still some are not satisfied, the algorithm detaches all links that have no capacity to satisfy any demand, e.g. a lightpath reaches its maximum capacity, and reruns for the unsatisfied demand. The process continues until all demands are satisfied.

5.1.2 Procedure `ReserveCapacity()`

This procedure attempts the shortest multilayer path and checks whether capacity is available on each link of the path. If so, the demand is satisfied. If capacity is not available, it considers the next path. The process repeats until a path that can accommodate the demand is found, or declares a demand unsatisfiable because of inadequate resources.

Note that initially there are no virtual links to satisfy the demands, i.e., paths contain only fiber links at the physical level. Therefore, the first few demands (between 3 and 5 in a 7-node network) will be routed in the DWDM layer. Then, while processing the selected physical path, a lightpath is created between the end OXC nodes, and an IP/MPLS capacity module is acquired. The capacity for the IP/MPLS tunnel is assigned in multiples of M where M is the module size for IP/MPLS layer. Each new lightpath is assigned a wavelength or more if it spans more than one fiber link, and the maximum capacity of the

Procedure ReserveCapacity(h_d,R_d)

input : h_d,R_d
output: Multilayer path availability

$i = 1$;
repeat
    if capacity is available on T_d^i **then**
        if one or more $l_v(T_d^i)$ are physical fiber(s) **then**
            create a lightpath connecting the two ends of the OXCs;
            create a tunnel connecting the two ends of the LSRs;
        reserve h_d on each $l_v(T_d^i)$;
        if one or more $l_v(T_d^i)$ are OTN (lightpaths) **then**
            foreach OTN $l_v(T_d^i)$ **do**
                if current $U_k,\ (k = 0, 1, 2, 3, 4)$ available capacity $\geq h_d$ **then**
                    reserve capacity;
                else
                    call Procedure U_k`Calc()`;
        update links capacities;
        update the multilayer topology;
        return d is satisfied;
    else
        i++;
until all T_d are considered;

lightpath is dependent on the wavelength bandwidth. This step of creating the lightpaths is repeated whenever a physical fiber link is encountered in a path. Consequently, this develops the virtual topologies.

5.1.3 Procedure `UkCalc()`

If the path contains one or more OTN links (lightpaths), the algorithm checks whether the previously acquired U_k signals on each link have free capacity to satisfy the demand. If not, it determines the type and number of signals required to satisfy the

Procedure UkCalc

input : OTN $l_v(T_d^i), h_d, U_k^u$
output: Types and Numbers of required U_ks

$f \leftarrow \infty$;
$x_f \leftarrow \infty$;
for $k \leftarrow 0$ **to** 3 **do**
  $x_k \leftarrow \lceil h_d/U_k \rceil \times U_k^u$;
  $x_{k+1} \leftarrow \lceil h_d/U_{k+1} \rceil \times U_{k+1}^u$;
  if $x_k \leq x_{k+1}$ **then**
    $min \leftarrow k$;
  else
    $min \leftarrow k+1$;
  if $x_f > x_{min}$ **then**
    $f \leftarrow min$;
    $x_f \leftarrow \lceil h_d/U_{min} \rceil$;
$U_f^c \leftarrow U_f^c + x_f$;

demand on each individual link. Some links may have signals that have not been fully utilized, and others may ask for new signals. Determining the type and the number of signal(s) needed is based on the OTN unit cost and the demand volume. For instance, it might be cheaper to acquire one U_2 than three U_1 to satisfy a demand of 7.5 Gbps. The OTN unit cost for satisfying a demand will be the deciding factor on the type and number of U_k signals to be installed in the OTN layer. Procedure U_k`Calc()` shows this step.

5.1.4 Procedure `CombineOTN()`

Finally, procedure `CombineOTN()` is called on each OTN link. It checks whether a better U_ks combination can be achieve. It compares the cost of the current numbers of U_ks on the link with the cost of a new combination based on the multiplexing rules

Procedure CombineOTN(l)

input : OTN link l
output: Final U_ks combination on each l

```
for k ← 0 to 4 do
    nU_k ← U_k^c;
for k ← 0 to 3 do
    cont ← true;
    tU_k ← nU_k;
    tU_{k+1} ← nU_{k+1};
    repeat
        if (tU_k mod U_k^m) == 0 then
            cont ← false;
            tU_{k+1} ← nU_{k+1} + (tU_k/U_k^m);
            tU_k ← nU_k − tU_k;
            if (nU_k × U_k^u + nU_{k+1} × U_{k+1}^u) > (tU_k × U_k^u + tU_{k+1} × U_{k+1}^u) then
                nU_k ← tU_k;
                nU_{k+1} ← tU_{k+1};
        else
            tU_k−−;
    until cont← false Or tU_k == 0;
for k ← 0 to 4 do
    U_k^c ← nU_k;
```

(Chapter 3). If it finds a cheaper combination, it updates the number of U_ks on that link accordingly.

5.2 Effect of T_d

As stated earlier, multilayer shortest paths T_d are sorted in R_d according to their cost values. The sum of all $l_v(T_d^i)$ costs on T_d^i determines the order of T_d^i in R_d. Links' costs and the number of multilayer shortest paths T_d in R_d control which layer to foster routing. For example, if the cost of DWDM links are higher than the cost of of IP/MPLS and OTN links, and the number of T_d is limited, our algorithm forces to utilize the IP/MPLS and OTN layers as much as possible before attempting to establish a new lightpath. This form of routing that favors routing in existing virtual topology is referred to as routing in the lightpath layer. Now we can allow the algorithm to establish more lightpaths than before over DWDM links by increasing the number of T_d at the start. If the DWDM links are cheaper than the IP/MPLS and OTN links, then our algorithm favors routing in the optical layer, i.e., to establish a new direct lightpath and avoid routing over existing multiple lightpaths. Consider Figure 6. Suppose we have a demand d between LSRs A_i and C_i. Assume that at this state of the algorithm, there are two lightpaths established, one from A_o to B_o, and the second between B_o and C_o. Suppose both lightpaths have enough capacity to satisfy d. There are two options to route d in this case. The first is to use the existing lightpaths O_1 and O_2. The second is to establish a new direct lightpath between A_o and C_o over two DWDM links W_1 and W_2 providing that each one has a free wavelength. Our algorithm chooses the path with the minimum cost.

If we assume that $T_d = 1$ and the first option is cheaper then only this path appears in R_d. If this path has no capacity to satisfy d then the algorithm skips this demand and goes to the next. After processing all D, the algorithm detaches links O_1 and O_2 and reruns for the set of unsatisfied demands. This time, the first path will disappear from R_d since links O_1 and O_2 are no longer in the network. Instead, the second path over DWDM links W_1 and W_2 will be the first path in R_d. If in the second run link W_1 or W_2 has no

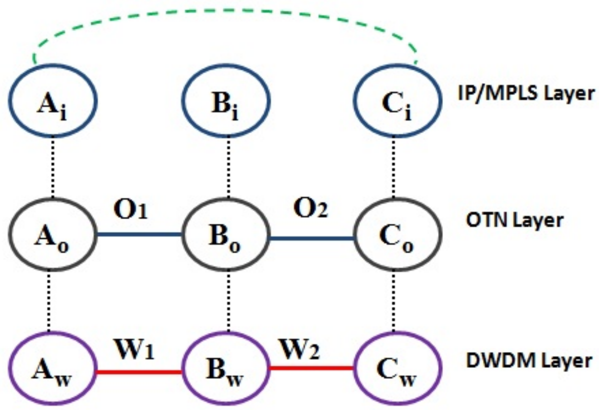


Figure 6: Two Multilayer Paths Between A_i and C_i

free wavelength, then the algorithm declares that d is unsatisfiable because of inadequate resources. As a rule of thumb, if the DWDM links are noticeably more expensive than the IP/MPLS and OTN links, a smaller value of T_d such that T_d is less than the total number of all paths for d is auspicious for reducing overall network cost. However, to find the best value of T_d that allows efficient use of the virtual and optical layers clearly depends on the network topology. We have experimented with different values of T_d, which will be reported later in Chapter 6.

5.3 Heuristic Running Time

Let N = nodes/layer, $N' = 3N$ (total nodes in a 3-layer network), K =number of shortest paths, L = total number of links in the network, L_p = average number of links/path, L' = total number of OTN links, J = number of ODUk signals, C = number of times the outer loop of the heuristic is executed. Then, the upper bound running time for the following are:

- `ReserveCapacity()`: $\mathcal{O}(KL_p)$.
- `UkCalc()`: $\mathcal{O}(J)$.
- `CombineOTN()`: $\mathcal{O}(L')$.
- `k-shortestPath()`: $K(3N+L)\log 3N = \mathcal{O}(N \log N)$.
- Demand pairs: $\mathcal{O}(N^2)$.
- C: $\mathcal{O}(N)$.

Note that the implementation of the k-shortest paths is based on the extension of Dijkstra's algorithm for computing the single-source shortest paths. With a binary heap implementation of Dijkstra's algorithm, the algorithm complexity is $\mathcal{O}((N+L)\log N)$. We note that the heuristic is dominated by the by k-shortest paths computations for given demand pairs. Thus, the heuristic running time for sparse networks is $N^2 \times (N \log N) = \mathcal{O}(N^3 \log N)$ in the best case scenario when the outer loop is executed once. In this case, when $C = 1$, all demands are satisfied in one run. However, in the worst case scenario, the heuristic running time is $N \times N^2 \times (N \log N) = \mathcal{O}(N^4 \log N)$.

CHAPTER 6

STUDY AND RESULTS FOR (P1)

The goal of our study in this Chapter is twofold: a) to compare our heuristic proposed in Chapter 5 against CPLEX solver to understand its performance for solving Model (**P1**) for a small network, b) to understand how a number of network parameters are impacted by varying associated values such as the comparative unit cost values assigned at different layers, and the modularity factor (M). We first present a discussion on our choice of parameter values.

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 is also referred 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 [6], 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 photopic OXC port, respectively. Based on our cost model in Section 4.2, 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 plus a physical distance cost; we assume this is a fixed cost of 66. This means when the IP/MPLS layer cost is 3, the DWDM cost 84. We transform this value so that 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. Specifically, for the IP-cost we vary the cost starting from IP-cost$= 5$ and double 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 [17] to create a set of demands between the LSRs in a network.

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

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

To represent them, we consider the following U_k cost ($k = 0, 1, ..., 4$), 2/4/8/16/32,

Table 5: Cost per Gbps

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

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 U_ks are not as important as the relationships between them. Note that we avoid unrealistic U_k cost relationships such as when U_k = U_{k+1} or when 4U_k = U_{k+1}. The former indicates equal cost of two different OTN units, and the latter follows one of the signal multiplexing rules we explained in Chapter 3. For example, when 4U_1 = U_2 we have equal costs for two choices and it is negligible whether four U_1s or one U_2 is selected to satisfy a demand. This is because the size of four U_1s is equal to the size of one U_2, i.e., 4×2.5 Gbps = 10 Gbps. We summarize each layer's cost values in Table 6.

Table 5 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 is=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.

The experiments we conducted in this study with various parameter values allowed

Table 6: Summary of Cost Values for Each Layer.

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 (ξ_f)	140

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_ks 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.

6.2 Demands Generation

For all demand generation in this dissertation we use the demand model presented in [17]. According to [17], for each LSR pair (x, y), the demand between x and y is given by:

$\alpha\, O_x\, D_y\, C_{(x,y)}\, e^{-\delta(x,y)/2\Delta}$

where:

O_x D_y random numbers $\in [0, 1]$ for each node x.

$C_{(x,y)}$ a random number $\in [0, 1]$ for each pair (x, y).

α is a scale parameter.

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

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

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

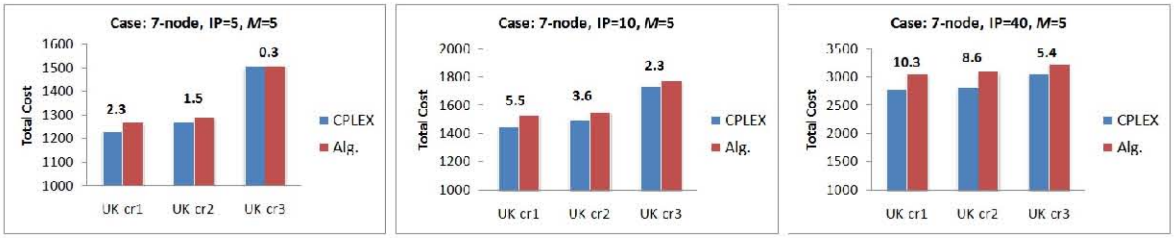
$\sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}$

A sample demand volume generated by this model is given in Appendix A.

6.3 Heuristic vs. Optimal Solutions

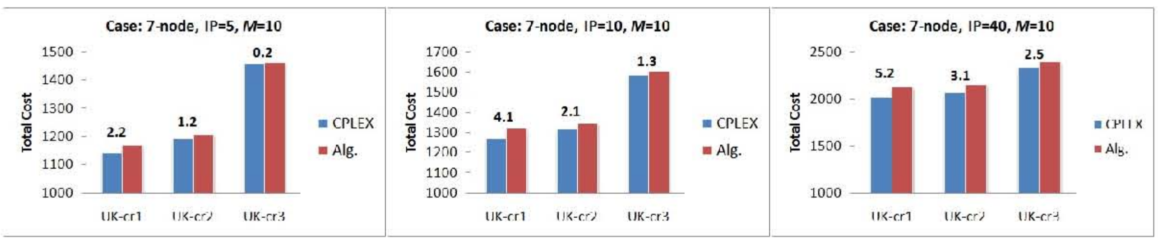
To evaluate our heuristic algorithm against an exact solution, we have also run problem (**P1**) using CPLEX 12.2 optimization package, through its integer linear programming solver. We compare our heuristic against the CPLEX solution for a fully-connected 7-node multilayer network, the largest problem that could be solved using CPLEX. In this example network, we assume that each LSR is connected to an OXC in the physical layer, and each LSR is an ingress/egress LSR. Thus, the overall three-layer network has $7 \times 3 = 21$ nodes. Traffic demand is assumed to be bi-directional between all the LSR nodes, i.e., there 21 demands generated as described in Section 6.2 where the average demand $\simeq$ 7.8 Gbps, giving a total demand volume of 165 Gbps. The sizes of M used are $M = 5$, and 10 Gbps to represent two cases: below average and above average demand in the network.

From Figure 7 and 8, we can see that our heuristic is within 0.3% of optimal for UK-cr3 with the IP-cost set to 5. The heuristic performed the worst when the IP-cost is



(a) IP-cost= 5 (b) IP-cost= 10 (c) IP-cost= 40

Figure 7: CPLEX vs. Heuristic When $M = 5$ Gbps.

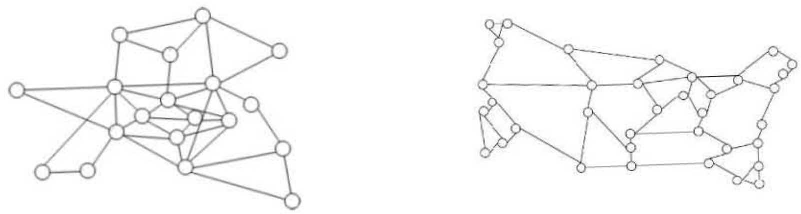


(a) IP-cost= 5 (b) IP-cost= 10 (c) IP-cost= 40

Figure 8: CPLEX vs. Heuristic When $M = 10$ Gbps.

high at 40 for UK-cr1. In other words, the efficiency of the heuristic increases as the ratio of IP-cost to W-cost decreases. We also note that the heuristic performs better for $M = 10$ than $M = 5$.

In general, we observe that our algorithm does well, as the cost ratio of IP to W decreases and the size of the capacity module is more than the average demand volume in the network. The cases where the heuristic does not work well is because the algorithm attempts to use the multilayer shortest path with the least cost to start with. The problem is when the IP-cost increases, the algorithm does not maintain a perfect balance between routing demands over longer but cheaper virtual links and routing the demands over shorter but more expensive physical links. At the time of selecting the path, it may be cheaper to route a demand over more virtual links than routing over fewer physical



(a) European Optical Network (EON)

(b) SPRINT Network

Figure 9: Network Topologies.

links because of the higher cost of the physical links. Eventually as this process continues, it may result in more IP/MPLS capacity units added due to the longer virtual links considered.

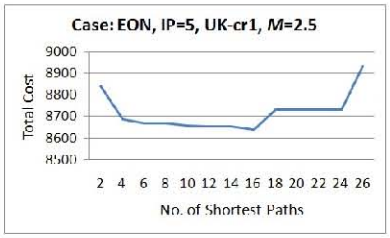
6.4 Study on Larger Networks

We have conducted extensive experiments with different parameter values for which we selected two different larger topologies: a 19-node European optical Network (EON), and a 36-node Sprint network (Figure 9) for the physical topology. Note that 19 and 36 are the numbers of nodes *per layer* in the EON and Sprint network, respectively. This means 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.

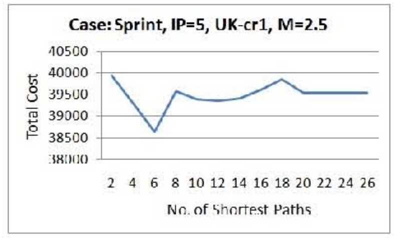
We use different cost values of each network layer as described in Section 6.1. Those values are consistent for both topologies. We use the demand model of Section 6.2

to generate demand volume between LSRs. Information about network topologies and traffic scenarios are shown in Table 7. 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 amply ran the algorithm to find an appropriate value of T_d, the number of multilayered paths for each demand d. For EON, we observed that $T_d = 16$ yields the best case performance for the baseline case in our experiment when $M = 2.5$ Gbps, IP-cost= 5, and U_k cost=UK-cr1 as shown in Figure 10a. We observed that the cost rose after $T_d = 16$. This is because at $T_d = 16$, 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 $T_d = 16$ in EON. Increasing the value of T_d 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 $T_d = 16$ and the worst case when $T_d = 26$ is 3.4$\%$. For the Sprint network, shown in Figure 10b, we observed a the best case when $T_d = 6$; we have set $T_d = 6$ in the rest of our study with the Sprint network. Note that the cost difference between the best case of $T_d = 6$ and the worst case when $T_d = 2$ is 3.3$\%$.



(a) Total Cost of Different Values of T_d in EON



(b) Total Cost of Different Values of T_d in Sprint Network

Figure 10: Total Cost of Various T_d When $M = 2.5$ and IP-cost=5.

Table 7: Topology Information and Demands

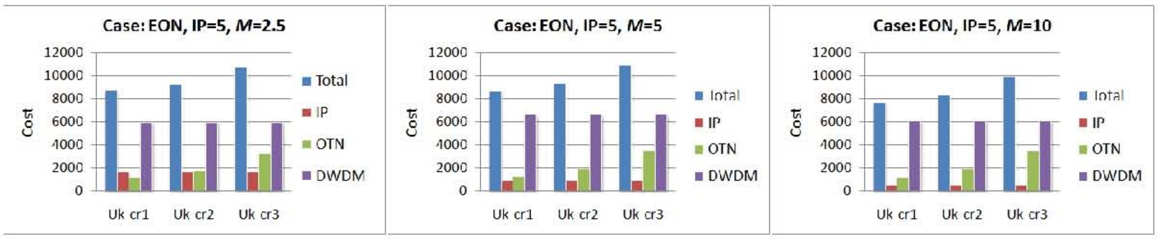
Network	No. of Nodes per Layer	No. of Physical Links (F)	Total load	No. of D	Avg. Load/d
EON	19	35	855	171	5
SPRINT	36	54	3,150	630	5

6.5 Illustrative Numeric Results

6.5.1 Cost of Different Layers

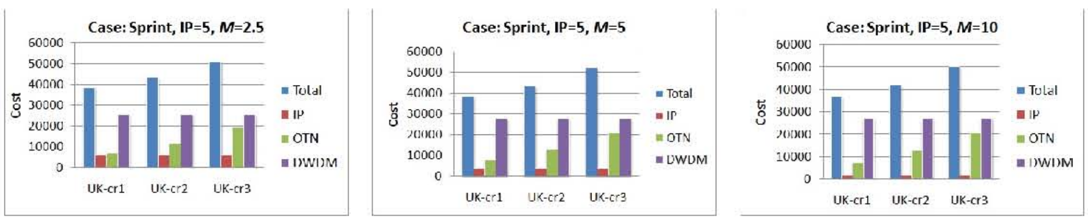
Figure 11 shows the cost of different layers and the total cost when the IP-cost is $= 5$ for different cases of U_k-costs and sizes of M in EON. We note that the total cost of IP is the lowest compared to OTN and fiber cost except when $M = 2.5$ and Uk-cr1. The IP cost decreases as we increase the size of M. This is because as we fixed 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 U_k-cost. These observations are also true for the Sprint network as shown in Figure 12.

Next we consider the case when the IP-cost is high (40) in Figure 13. The overall



(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 11: Costs of Different Components for Different M When IP-cost=5 in EON.



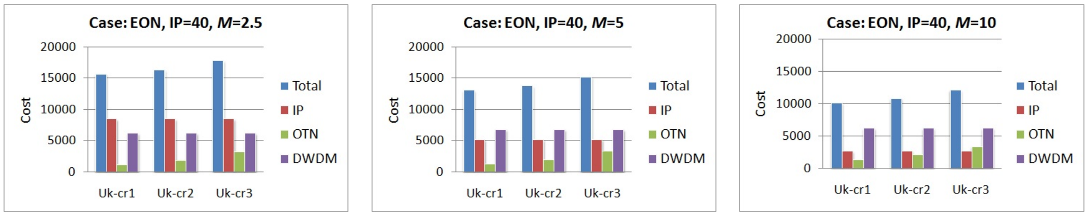
(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 12: Costs of Different Components for Different M When IP-cost=5 in Sprint Network.

IP cost decreases again as we increase the size of M and fix the unit price. The OTN overall cost increases as the U_k-cost is increased. The difference in this figure from Figure 11 and 12 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 U_k=UK-cr3. The same can be observed in the Sprint network.

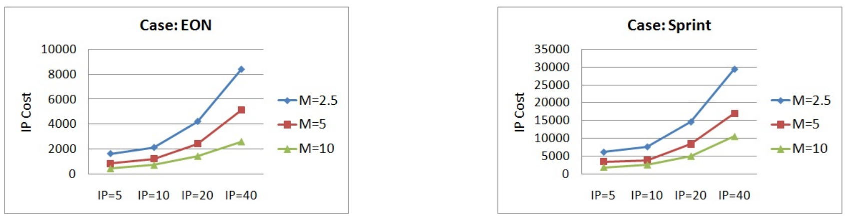
6.5.2 IP Layer Cost

Figure 14 shows the total IP cost for differen 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 are having 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



(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 13: Costs of Different Components for Different M When IP-cost=40 in EON.



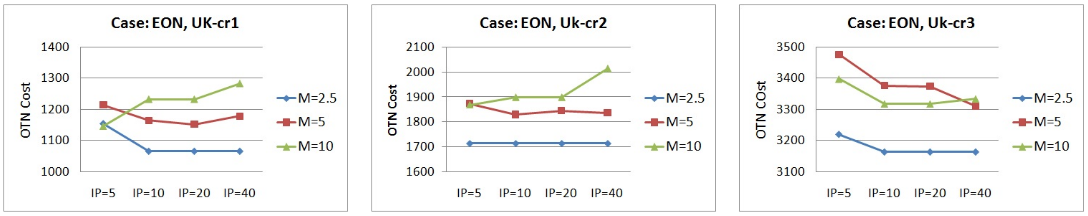
(a) Total IP Cost in EON (b) Total IP Cost in Sprint Network

Figure 14: Total IP Cost of Different M.

Section 6.5.4.

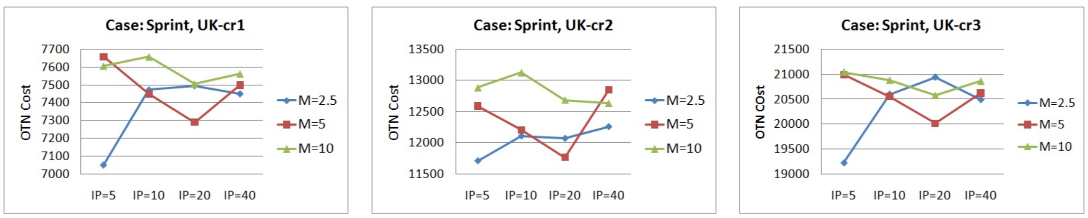
6.5.3 OTN Layer Cost

Figure 15 and Figure 16 show the OTN costs for EON and the Sprint network for various values of M, IP, and U_k costs. In EON, 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 EON, the size of M, such that M is below the average demand in the network is the most convenient to achieve the lowest OTN layer cost.



(a) UK-cr1 (b) UK-cr2 (c) UK-cr3

Figure 15: Total OTN Cost of Different M and U_k in EON.



(a) UK-cr1 (b) UK-cr2 (c) UK-cr3

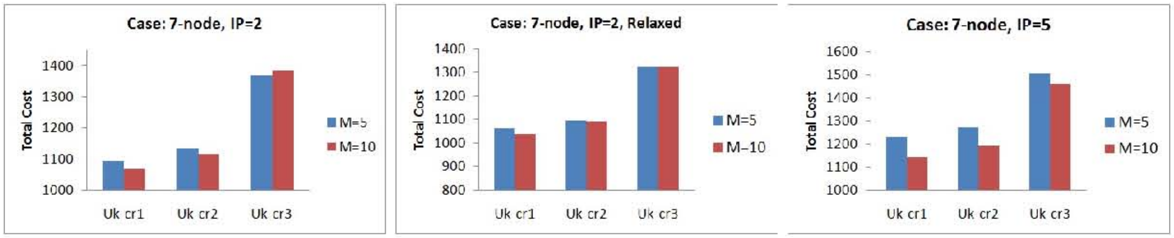
Figure 16: Total OTN Cost of Different M and U_k in Sprint Network.

For the Sprint Network, 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 16. When the IP-cost is of medium range (7% and 14% of the W-cost), it is more suitable to have 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 more than what really 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.

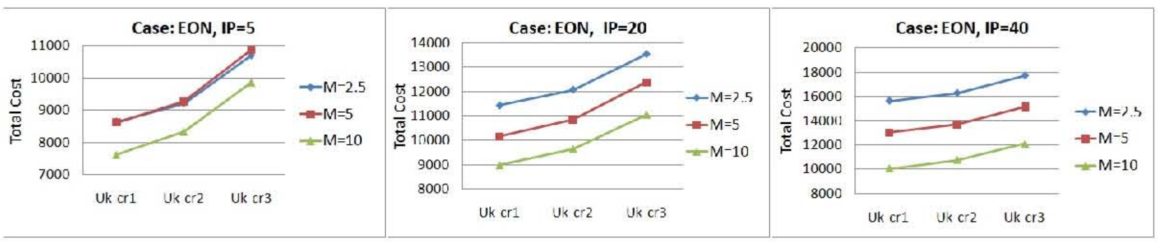
6.5.4 Total Network Cost

Now we focus on the total network costs for different scenarios as depicted in Figure 18. The case of $M = 10$ is always the best case to achieve the minimum network cost regardless of the U_k-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 18a 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 $M = 5$ Gbps in UK-cr3. This is unlike the cases of IP-cost$= 20$ and IP-cost$= 40$ when $M = 5$ has a lower network cost than $M = 2.5$ Gbps as shown in figures 18b and 18c. One may wonder why the case of $M = 2.5$ Gbps is cheaper than the case when $M = 5$ Gbps when 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 U_k-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 Sprint topology as depicted in Figure 18a. Note that this is



(a) IP/MPLS Integral Constraints (b) IP/MPLS Relaxed Constraints (c) Increasing the IP-cost (Integral Constraints)

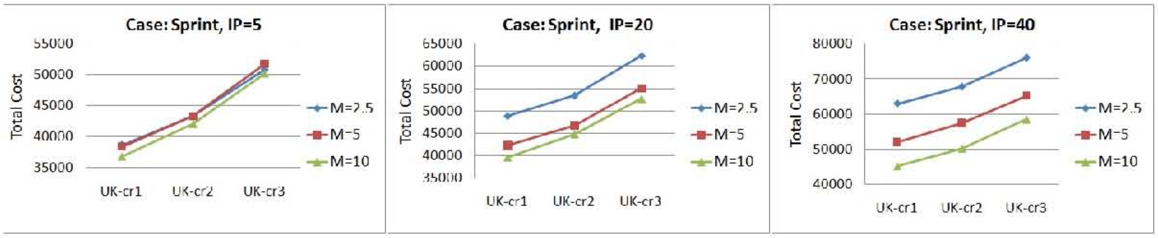
Figure 17: CPLEX Solution: Total Network Cost in 7-node Network.



(a) IP-cost=5 (b) IP-cost=20 (c) IP-cost=40

Figure 18: Total Network Cost of Different M in EON.

not a repercussion of how the heuristic was designed; we confirmed a similar behavior by re-running the 7-node network using CPLEX as depicted in Figure 17a. Here, it is shown in the UK-cr3 case in which the total cost when $M = 5$ is lower than when $M = 10$ even though the IP-cost is fixed. On the other hand, when the IP/MPLS layer integral constraints are relaxed, the case of $M = 10$ has an equal cost to the case of $M = 5$ at UK-cr3 (Figure 17b). Figure 17c confirms that we no longer observe this occurrence due to the higher IP-cost=5 even with the integral constraints.



(a) IP-cost=5 (b) IP-cost=20 (c) IP-cost=40

Figure 19: Total Network Cost of Different M in Sprint Network.

6.5.5 No. of Required U_k

We observe that the numbers of U_ks in EON and Sprint follow the same patterns. Because of the space limitation we will present Figure 20 that shows the required numbers of U_ks in Sprint. We note that the required number of each U_k is largely affected by the U_k-cost scenarios rather than by the size of M or the IP-cost. We observe a pattern for each U_k based on the UK-cr. For U_0, a relatively low number of U_0 is required (between 41 and 65) in the case of UK-cr1. This number significantly rises to a number between (2047 and 2320) in UK-cr2. Then it slightly increases in UK-cr3 to a number between (2321 and 2669). This shows that U_0 is mostly used in UK-cr2 and UK-cr3 due to the increasing gap between the cost of U_ks. U_1 is only seen in the case of UK-cr1. For U_2, the required number is relatively high in Uk-cr1 (between 271 and 297) which decreases in UK-cr2 (between 164 and 288) and then not used in UK-cr3. U_3 starts with a relatively low number (between 14 and 23) in UK-cr1 and then increases to a number between (244 and 278) in UK-cr2, and further increases in UK-cr3 to a number between (270 and 295). Finally, U_4 is only used in the case of UK-cr1. It is not used in UK-cr3 because the cost of 2 U_3 plus 16 U_0 = 140 is less than the cost of a U_4=162. And it is not used in UK-cr2

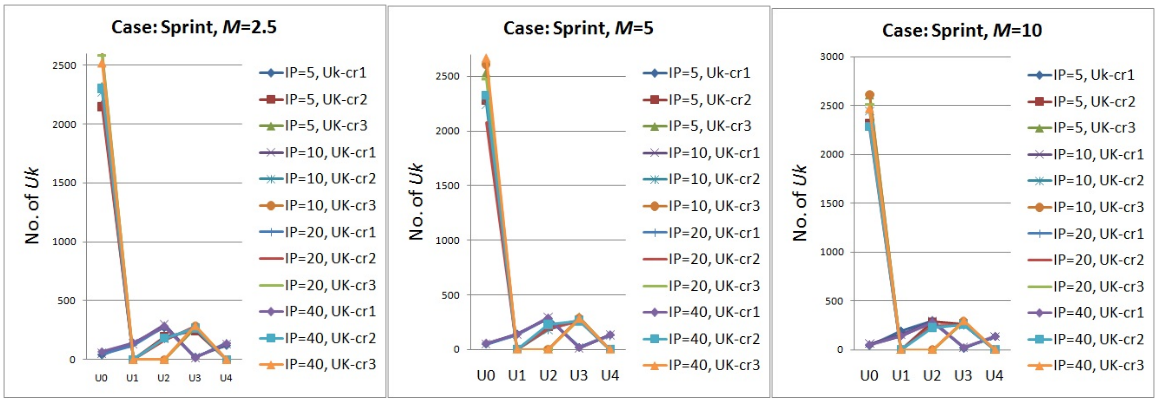
Table 8: Summary of The Numbers of U_k for EON

	UK-cr1: 2 $U_k = U_{k+1}$						UK-cr2: 3 $U_k > U_{k+1}$						UK-cr3: 3 $U_k = U_{k+1}$					
	$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$	
	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP
U_0	L	↓	L	↓	L	↑	H	↑	H	↑	H	↑	H	↑	H	↑	H	↓
U_1	M	↓	M	↓	M	↑	-	-	-	-	-	-	-	-	-	-	-	-
U_2	H	↓	M	M	H	↑	L	↓	L	↓	M	L	-	-	-	-	-	-
U_3	L	↓	L	↓	L	↓	H	↓	H	↓	M	H	H	↓	H	↓	H	↓
U_4	L	↓	M	M	L	M	L	L	L	L	L	↓	-	-	-	-	-	-

because the demand volume on each OTN link does not reach 100 Gbps in which a U_4 would be cheaper than 2 U_3. We will see in section 6.5.7 that U_4 is used in Uk-cr2 when the average demand is increased and hence requires using U_4s. CPLEX solutions for the UK-cr3 case showed the same trends for the small size network. That is, only U_0 and U_3 are used in UK-cr3.

Table 8 shows a summary of the numbers of U_ks used in EON. We note that, if we exclude U_0, the maximum number of a U_k used in EON is 54 U_2s. Thus, we make three categories to describe the number of a U_k used in EON: Low (L) between 0-18, Medium (M) between 19-36, and High (H) > 36. An up arrow (↑) in the table indicates the number of U_k falls in the same previous category but increasing. A down arrow (↓) indicates the number of U_k falls in the same previous category but decreasing. LIP refers to a low unit cost of IP while HIP refers to a high unit cost of IP.

The maximum number of a U_k used in the Sprint network is 297 U_2s, excluding U_0. Again, we make three categories to describe the number of a U_k used in the Sprint topology: Low (L) between 0-99, Medium (M) between 100-199, and High (H) > 199. Table 9 shows a summary of numbers of U_ks used in the Sprint network.



(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

Figure 20: No. of U_k in Sprint Network for Different Sizes of M

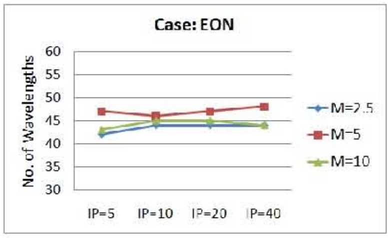
Table 9: Summary of The Numbers of U_k for Sprint Network

	UK-cr1: 2 $U_k = U_{k+1}$						UK-cr2: 3 $U_k > U_{k+1}$						UK-cr3: 3 $U_k = U_{k+1}$					
	$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$	
	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP	LIP	HIP
U_0	L	↑	L	↑	L	↑	H	↑	H	↑	H	↓	H	↑	H	↑	H	↓
U_1	M	M	M	↓	M	↓	-	-	-	-	-	-	-	-	-	-	-	-
U_2	H	↑	H	H	H	↓	M	↓	H	↑	H	↓	-	-	-	-	-	-
U_3	L	↓	L	↓	L	↑	H	↑	H	↓	H	↓	H	↑	H	↓	H	↑
U_4	M	↑	M	↓	M	↓	-	-	-	-	-	-	-	-	-	-	-	-

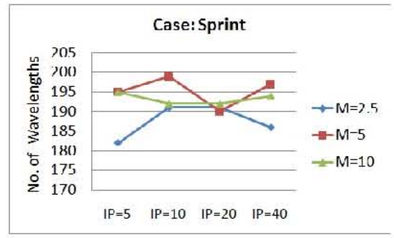
6.5.6 No. of Wavelengths

Figure 21 shows the number of wavelengths used in both networks. The number of wavelengths does not change when the U_k-cost changes. This is because the DWDM layer does not consider the cost of the U_ks but their bandwidth. However, the number of wavelengths is affected by the size of M and its cost since this alters the types and numbers of required U_ks.

We observe that the case of $M = 2.5$ Gbps is almost always the best to achieve the lowest number of wavelengths in both networks regardless of the IP-cost and the size



(a) No. of Wavelength in EON



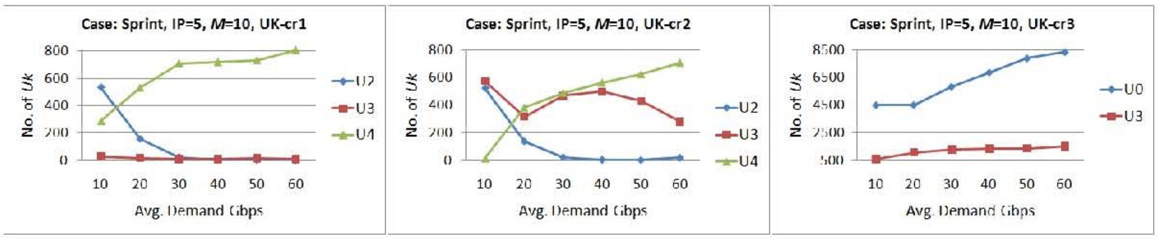
(b) No. of Wavelength in Sprint Network

Figure 21: Total No. of Wavelength.

of M. This suggests that using $M = 2.5$ (below the average demand in the network) is beneficial to reduce the total number of used wavelengths in both networks. The case when $M = 10$ comes second in both networks except when IP-cost=20 in which case $M = 5$ is slightly better. This generally suggests that the size of $M = 5$ (equal average demand) should be avoided if the focus is to reduce the total number of wavelengths required as this mostly results in the worst performance in both networks.

6.5.7 Load Effect on U_k

Figure 22 shows the numbers of U_k when we increase the average demand in the Sprint network starting from 10 Gbps to 60 Gbps, while $M = 10$ and IP-cost=5. This significant increase in the demand volume justifies the usage of U_4 particularly in UK-cr1 and UK-cr2. We observe in UK-cr1 and UK-cr2 that U_0 and U_1 are not used because it is cheaper to use other U_ks for such high demands. Also, U_2 decreases as the average demand increases. However, in UK-cr3 we note that only U_0 and U_3 are used. This is because the cost of 2 U_3s is less than the cost of a U_4. And since 2 U_3s take only 80 Gbps of the wavelength, the rest is filled with U_0s.



(a) UK-cr1 (b) UK-cr2 (c) UK-cr3

Figure 22: No. of U_k in Sprint Network When Average Demand Increases.

6.5.8 Summary

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 EON and Sprint except in Sprint 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 EON and Sprint networks. The case of M is equal the

Table 10: Best Cases of M to Minimize Network Cost

	Cost Ratio of IP to W			
	3.5%	7%	14%	28%
EON	A	A	A	A
Sprint	A	A	A	A

Table 11: Best Cases of M to Minimize OTN Layer Cost

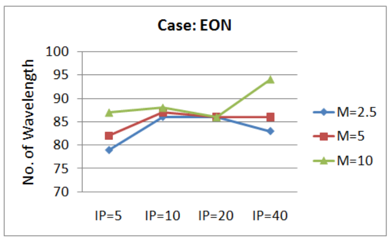
	Cost Ratio of IP to W			
	3.5%	7%	14%	28%
EON	A	B	B	B
Sprint	B	B/E	E	B

average demand is the worst case for reducing the cost of the DWDM layer in most cases. For the required types and numbers of U_ks, Tables 8 and 9 summarize the results.

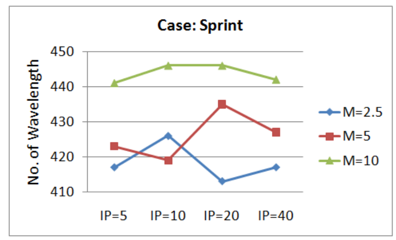
From this discussion we can observe that some parameter values may be the best for reducing the cost of an individual layer but these are not for minimizing the overall network cost, and vice versa. We present Tables 10, 11, and 12, to summarize the above discussion. In each table, we place the best 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 M below the average demand is the best 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 for reducing the overall network, below or equal average M is best for reducing the OTN layer cost, and equal average M is the best for reducing the DWDM layer cost.

Table 12: Best Cases of M to Minimize DWDM Layer Cost

	Cost Ratio of IP to W			
	3.5%	7%	14%	28%
EON	B	B	B	B
Sprint	B	B	B/E	B



(a) No. of Wavelength in EON



(b) No. of Wavelength in Sprint Network

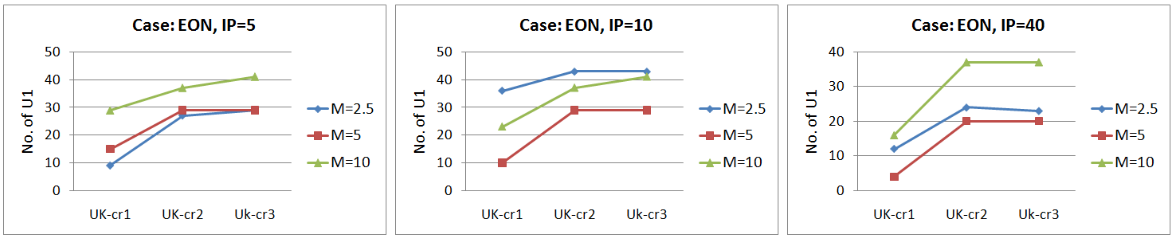
Figure 23: Total No. of Wavelength, 3 U_ks Study.

6.6 Study Based on U_1, U_2, and U_3

We observed from the results that the usage of U_0 and U_4 are not always justified. In this section, we present a study that is based on three OTN signals: U_1, U_2 and U_3, where each wavelength bit rate is 40 Gbps.

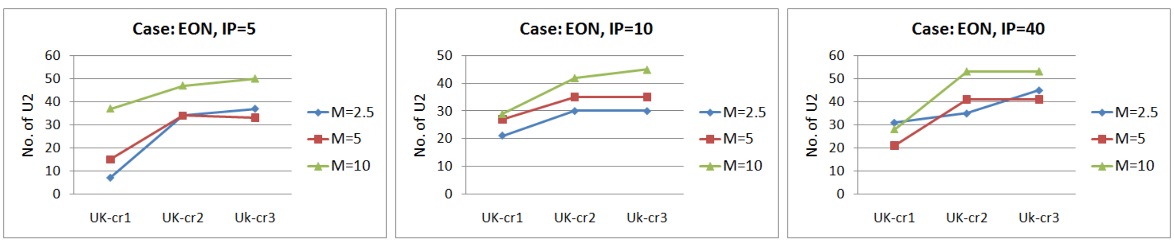
6.6.1 No. of Wavelengths

Figure 23 shows the number of wavelengths used in EON and Sprint network. Similar to our observation in Section 6.5.6, we observe that the case of $M = 2.5$ Gbps is almost always the best to achieve the lowest number of wavelengths in both networks regardless of the IP-cost and the size of M. However, we note the larger numbers of wavelength is this case due to the assumption that each wavelength is 40 Gbps unlike what it was in the previous study when each wavelength was assumed to 100 Gbps.



(a) IP=5 (b) IP=10 (c) IP=40

Figure 24: No. of U_1 in EON for Different IP-cost, 3 U_ks Study



(a) IP=5 (b) IP=10 (c) IP=40

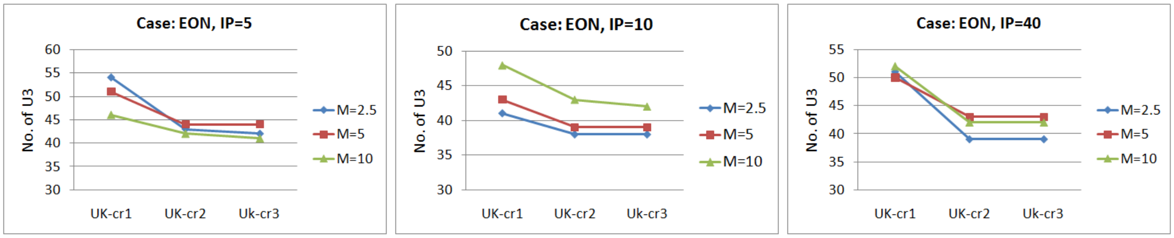
Figure 25: No. of U_2 in EON for Different IP-cost, 3 U_ks Study

6.6.2 No. of Required U_ks

We observe that the numbers of U_1s and U_2s are increasing as we go from UK-cr1 to UK-cr2 to UK-cr3 as shown in Figure 24, 25, 27, and 28. At the same time, the numbers of U_3 are decreasing as shown in Figure 26 and Figure 29. This is because as we increase the gap cost between the U_ks, U_3 becomes more expensive and hence is not used as much as when the gap cost at its minimum, i.e. when UK-cr1.

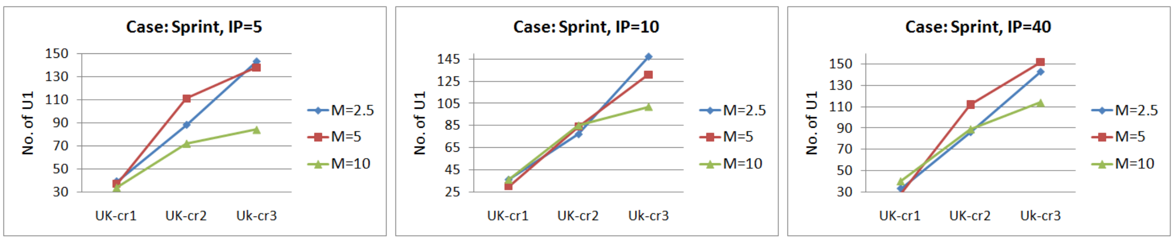
6.7 Conclusion

In this Chapter we introduced an explicit architecture for IP/MPLS-over-OTN-over-DWDM network it as a three layer network. While previous work has not explicitly



(a) IP=5 (b) IP=10 (c) IP=40

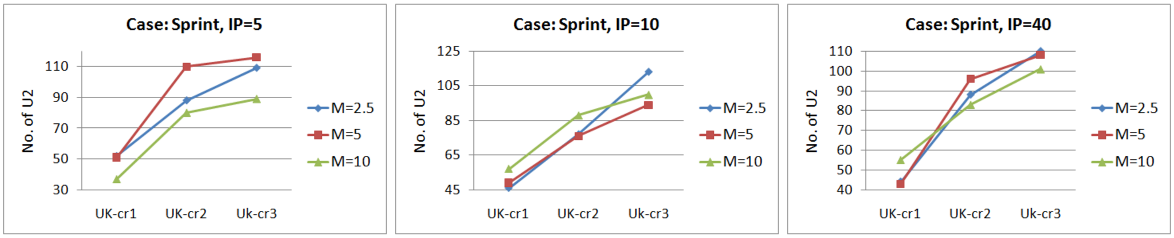
Figure 26: No. of U_3 in EON for Different IP-cost, 3 U_ks Study



(a) IP=5 (b) IP=10 (c) IP=40

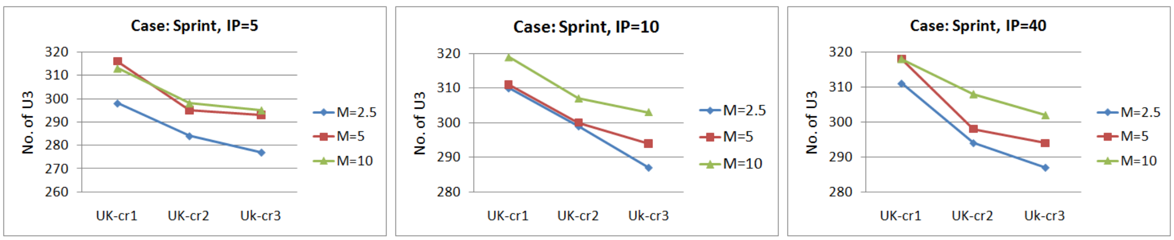
Figure 27: No. of U_1 in Sprint for Different IP-cost, 3 U_ks Study

considered the OTN layer or its restrictions, we have considered the OTN layer as a distinct layer with its own sublayer technological constraints. We developed an integrated capacity optimization model that is useful for the network planning problem. Since this problem is NP-hard, we then proposed a heuristic algorithm to solve it for large networks. Comparing our algorithm solution to CPLEX solution, we find that our algorithm performs well when the cost ratio of IP to W is less than 28%. We then presented an analysis on the network cost impact due to a number of factors. The results show that for reducing the overall multilayer network cost, the size of M needs to be above the average. The OTN layer cost and the number of U_ks required are affected by the size of M, the IP unit cost, and the U_k unit cost. Finally, the number of wavelengths is affected by the size of M, the cost of IP, and the types and numbers of U_k. We have observed through this study



(a) IP=5 (b) IP=10 (c) IP=40

Figure 28: No. of U_2 in Sprint for Different IP-cost, 3 U_ks Study



(a) IP=5 (b) IP=10 (c) IP=40

Figure 29: No. of U_3 in Sprint for Different IP-cost, 3 U_ks Study

how each layer resources and various costs can impact the neighboring lower layers.

CHAPTER 7

IP/MPLS AND OTN LAYER CORRELATION EFFECTS

In Chapter 4 we described a design Model (**P1**) where the capacity of each layer is a variable subject to optimization. In this Chapter, we present another design model for network planning of IP/MPLS over OTN over DWDM multilayer networks in which the DWDM capacity is a given constant. This allows us to focus on the interrelation between the IP/MPLS and OTN layers.

7.1 A Two-Layer Interrelation Design Model

In this section, we present a network optimization Model (**P2**) where it is assumed that the capacity at the WDM layer is given. This model incorporates modularity of capacity at the IP/MPLS and OTN layers.

The list of notations is shown in Tables 13 and 14.

7.1.1 Constraints

The first constraint represents IP demand d carried on a single tunnel out of a set of possible tunnel paths P_d.

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{7.1}$$

Table 13: List of Notations (P2 Given Entities)

Indices:

d = 1, 2, ..., D demands between source-destination pairs of the IP/MPLS layer.
p = 1, 2, ..., P_d candidate paths for demand d.
e = 1, 2, ..., E links of the IP/MPLS layer.
q = 1, 2, ..., Q_e candidate paths of OTN layer for realizing capacity of link e.
g = 1, 2, ..., G links of the OTN layer.
z = 1, 2, ..., Z_g 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.

Constants:

h_d: Volume of demand $d \in D$.
δ_{edp}: =1 if link e belongs to path p realizing demand d; 0, otherwise.
γ_{geq}: =1 if link g belongs to path q realizing capacity of link e; 0, otherwise.
ϑ_{fgz}: =1 if link f belongs to path z realizing capacity of link g; 0, otherwise.
M: Module size for IP/MPLS layer.
U_k: Module size for OTN layer capacities for $k = 0, 1, 2, 3, 4$.
η_e: Cost of one capacity unit of module M of the IP/MPLS layer link e.
β_{gk}: Cost of one capacity unit of module type U_k of the OTN layer link g.
α_{gkz}: Routing cost of the DWDM layer.
N: Module size for DWDM layer link capacities.
b_f: Number of modules N to be installed on link f in the DWDM layer (non-negative integral).

Table 14: List of Notations (P2 Variables)

Variables:

x_{dp}: IP/MPLS flow variable realizing demand d allocated to path p (non-negative, continuous or binary).
m_{eq}: OTN flow variable allocated to path q realizing capacity of link e (non-negative integral).
s_{gkz}: DWDM flow variable allocated to path z realizing capacity of link g of interface k (non-negative integral).
y_e: Number of modules M to be installed on link e in the IP/MPLS layer (non-negative integral).
w_{gk}: Number of modules U_k to be installed on link g in the OTN layer (non-negative integral).

For each IP/MPLS layer link e, the IP/MPLS tunnels x_{dp} that use it by carrying the demand, the capacity allocated in modules of size M is satisfied by

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \leq M y_e \qquad e = 1, 2, ..., E \tag{7.2}$$

Now, for y_e's that are activated in the above constraints, the appropriate candidate paths sets in the OTN layer must provide this connectivity, which is represented by

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{7.3}$$

We next consider the OTN layer link g's capacity feasibility constraints by allowing the possibility of modular capacities in terms of U_k such that the OTN layer paths path with demand is satisfied.

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \qquad g = 1, 2, ..., G \tag{7.4}$$

The capacity of each OTN layer link g for each U_k is the demand that is to be satisfied by candidate paths from the routing list in the DWDM layer:

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4, \;\; g = 1, 2, ..., G \tag{7.5}$$

Finally, we consider the DWDM layer capacity feasibility constraints that assure that the capacity of each physical link f is not exceeded by the flow using this DWDM link.

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f \qquad f = 1, 2, ..., F \tag{7.6}$$

Note that N is the module size of the DWDM layer link capacity that is equal to the wavelength capacity, and b_f is the number of wavelengths to be installed on link f. Both are given constants.

7.1.2 Objective and Cost Model

The objective is to minimize the three layers cost that can be written as:

$$\sum_{e=1}^{E} \eta_e y_e + \sum_{g=1}^{G} \sum_{k=0}^{4} \beta_{gk} w_{gk} + \sum_{g=1}^{G} \sum_{k=0}^{4} \sum_{z=1}^{Z_g} \alpha_{gkz} s_{gkz} \tag{7.7}$$

This captures the total cost of network elements over the IP/MPLS, OTN and DWDM layers and the routing cost at the DWDM layer. This formulation addresses a different problem than our previous Model (**P1**) in Chapter 4 where the DWDM capacity is also unknown.

Note that each layer has a different cost structure. We now elaborate how the unit cost components associated with each layer may be constructed. For the IP/MPLS layer, η_e is the unit cost of link e; this is defined as the sum of the interface cost for the upper layer η_e^U and the lower layer η_e^L ends of the connection between the IP/MPLS layer node and the OTN layer node, i.e., $\eta_e = 2\eta_e^U + 2\eta_e^L$, 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 g β_g^U plus the cost of multiplexing OTN signals β_g^k, i.e., $\beta_{gk} = 2\beta_g^U + \beta_g^k$. Note that we assume in problem (**P2**) that the DWDM capacity is given. For the DWDM layer, α_{gkz} is the routing cost associated with the flow variable s_{gkz}. The three layers cost structure is shown in Figure 30.

Thus, the overall optimization (**P2**) is to minimize (7.7) subject to the set of constraints (7.1)–(7.6). The final solution gives us the optimal number of capacity modules (IP/MPLS layer), and signals (OTN layer), needed to satisfy the demands.

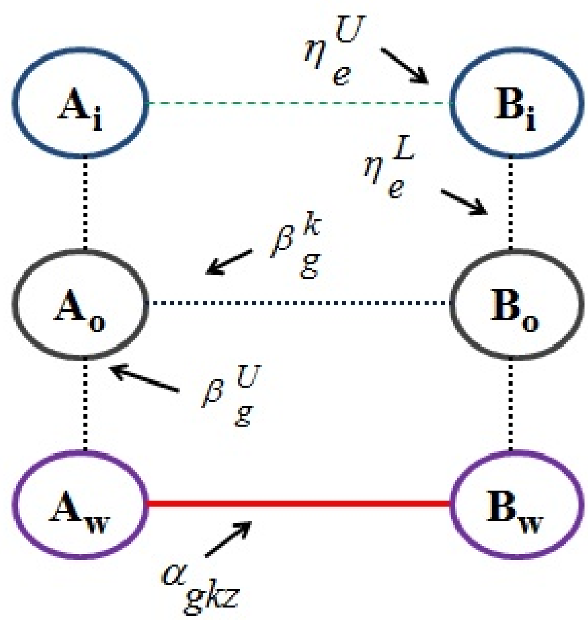


Figure 30: Cost Structure of The Multilayer Network

7.2 Model P2

To make it more readable and illustratable, the entire Model (**P2**) is summarized below.

$$\text{Minimize} \qquad \sum_{e=1}^{E} \eta_e y_e + \sum_{g=1}^{G} \sum_{k=0}^{4} \beta_{gk} w_{gk} + \sum_{g=1}^{G} \sum_{k=0}^{4} \sum_{z=1}^{Z_g} \alpha_{gkz} s_{gkz} \tag{7.8}$$

Subject to:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{7.9}$$

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \leq M y_e \qquad e = 1, 2, ..., E \tag{7.10}$$

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{7.11}$$

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \qquad g = 1, 2, ..., G \tag{7.12}$$

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4, \;\; g = 1, 2, ..., G \tag{7.13}$$

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f \qquad f = 1, 2, ..., F \tag{7.14}$$

Note that the variables of Model (**P2**) are defined in Table 14.

CHAPTER 8

STUDY AND RESULTS FOR (P2)

The main scope of this study is to understand IP/MPLS and OTN layer correlation effects under a number of parameters such as the comparative unit cost values assigned at the IP/MPLS and OTN layers, the modularity factor (M). Thus, we extended our heuristic (Chapter 5) to solve Model (**P2**) for larger networks, again with the main focus being understanding of the correlation between layers. A discussion on the modified version of the heuristic follows.

8.1 Heuristic Extension

Our heuristic, presented in Chapter 5, is developed to solve the operational planning design of the multilayer networks in which all three layers' links capacity are subject to optimization as described in Model (**P1**). In the beginning of Algorithm 1, we assigned an initial fiber capacity to the DWDM layer and then released the unused capacity at the end of the algorithm. We have also associated a DWDM capacity cost for each fiber link used; this was (ϑ_{fgz}) in Model (**P1**) and the W-cost in our heuristic. However, in Model (**P2**) we no longer associate any capacity cost to the DWDM layer. Instead, we assume the capacity of this layer is given and can be used free of charge. Nonetheless, we assign a small routing cost to the DWDM layer to limit the number of hops in this layer's paths.

From the above discussion on how Model (**P2**) differs from Model (**P1**), we can see that our heuristic needs a minor modification to solve the new problem. In our modified version of the heuristic, the capacity and the routing cost of the DWDM layer are given constants. The W-cost, in the modified version, corresponds to the routing cost (α_{gkz}) of the DWDM layer. Moreover, the fiber capacity (b_f) is constant and a given input to the heuristic. Therefore, in the modified version of Algorithm 1, we assign the input value of (b_f) to the DWDM layer's links instead of assigning a starting capacity and releasing it at the end as it was done in the original version of Algorithm 1. A consequence of these changes is that the order of the multilayer shortest paths in the routing tables will be largely determined by the IP-cost and U_k-cost. This is because the values assigned to the W-cost are significantly smaller than the values of the IP-cost and U_k-cost as we describe in Section 8.2. This also indicates that our modified version of the heuristic favors routing in the DWDM layer over the virtual layers due to the lower cost of using this layer. We have addressed the routing aspect in Section 5.2.

Other procedures used in the heuristic such as `ReserveCapacity()`, `UkCalc()`, and `CombineOTN()` are not changed.

8.2 Parameter Values

In the formulation of Model (**P2**), η_e is defined as the cost of one unit of module M of the IP/MPLS layer link e. In our study, this is also referred to as the *IP unit cost*, or simply as IP-cost. Likewise, β_{gk} is the cost of one capacity unit of module type U_k of the OTN layer link g. We refer to this cost as U_k *unit cost for* $k \in K$, or simply as U_k-cost. According to [6], 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 photopic OXC port, respectively. Based on our cost model in Section 7.1, the IP/MPLS layer cost becomes $2 \times (0.5 + 1) = 3$, and the OTN signal cost is $2 \times (1) + 1 = 3$ that is assigned to U_1. For the OTN layer cost parameter values, we consider the following scenarios:

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

These three OTN cost scenarios avoid unrealistic U_k-cost relationships such as when U_k = U_{k+1} or when $4U_k$ = U_{k+1}. The former indicates equal costs of two different OTN units, and the latter follows the signal multiplexing rule. For this work, we use the OTN signal rates of 2.5, 10, and 40 Gbps. Thus, we choose three representative values to reflect above three scenarios: 3/6/12, 3/7/18 and 3/9/27, to reflect $U_1/U_2/U_3$ costs. For the DWDM layer cost α_{gkz} we choose to assign 10% of the basic U_1 signal. That is, we fixed α_{gkz} to be equal to 0.3. This is a small routing cost at the DWDM layer and is not associated with the capacity used at this layer. Another cost ratio of network elements reported in [6], is 1, 8, and 0.5 representing costs of a DWDM transponder (10 Gbps), IP/optical interface card (10 Gbps), and a photopic OXC port, respectively. Thus, the IP/MPLS layer cost becomes $2 \times (8 + 0.5) = 17$, and the OTN signal cost is $2 \times (0.5) + 1 = 2$. This becomes the U_1 cost. Thus, in addition to the cost scenarios, we also define three different U_k-cost scenarios: 2/4/8, 2/5/12, and 2/6/18. We also fixed the DWDM routing cost to be equal to 10% of the basic U_1 signal. To understand the impact of IP-cost, we also define another network elements cost ratio in which the IP/optical interface is reduced by 50%,

Table 15: Summary of Cost Values for Each Layer.

	Unit Cost Values		
Cost Notation	Case1	Case2	Case3
IP-cost (η_e)	3	9	17
U_k-cost (β_{gk})	3/6/12, 3/7/18, 3/9/27	2/4/8, 2/5/12, 2/6/18	2/4/8, 2/5/12, 2/6/18

i.e., IP/optical interface is equal to 4. In this case, the IP-cost = 9, with the same U_k-cost scenarios. Table 15 summarizes the cost values of the IP/MPLS and OTN layers used in this study.

Note that the parameters values for Model (**P2**) are different from those described in Section 6.1 for Model (**P1**). First, the DWDM layer capacity cost is not considered; a small routing cost is considered instead. Second, we consider three different values of IP-cost. For each IP-cost value, we determine the U_1 cost and then according to the U_k-cost scenarios we compute the U_ks cost values. Third, we considered three sets of cost ratios of network elements; this is different from Section 6.1 where only one set of cost ratio of network elements is considered. Finally, we consider only three U_k signals for this problem: U_1, U_2, and U_3.

We also consider the size of M that 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 described in Section 6.2 to create a set of demands between the LSRs in a network.

We now briefly comment on our cost parameter selection. It may seem natural to consider unit cost per Gbps for IP/MPLS and factor in the other cost parameters. However, we found that considering M explicitly is also important. This is since not only the cost of IP/MPLS layer affects lower layers, but also the size of the capacity module of the IP/MPLS layer.

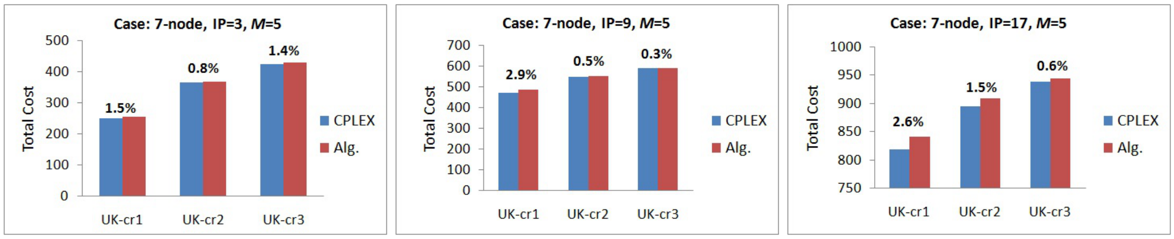
The experiments we conducted for this study with various parameter values allowed us to investigate the impact of each layer cost on other layers and ultimately the overall network cost. We wish to answer a number of questions: For example, how do the IP-cost and size of M influence the types and numbers of U_k signals at the OTN 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_ks needed to satisfy a given set of demands? How does increasing the demands load affect the OTN layer?

8.3 Heuristic vs. Optimal Solutions

To understand the effectiveness of our heuristic, we compared the heuristic with the CPLEX solution for the 7-node problem, by changing a number of parameters. Figure 31 and Figure 32 show that our heuristic is within 3.8% of the optimal solution generated by CPLEX and is often within 1.5% of the optimal solution. Next, we study the results obtained for larger network sizes.

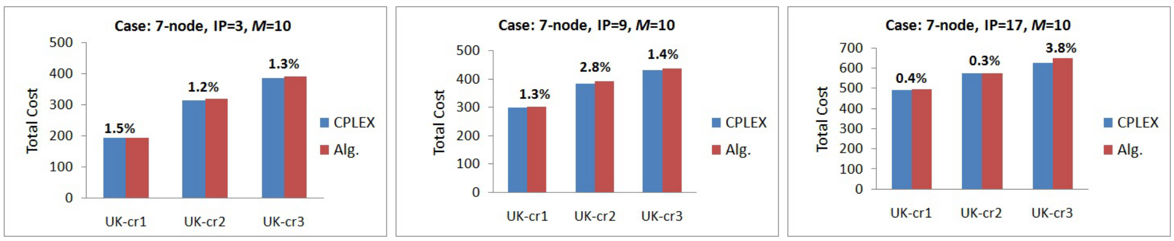
8.4 Study on Larger Networks

We consider two network topologies: a 19-node European optical Network (EON), and a 36-node Sprint continental IP backbone, (Figure 33). Note that, here n-node means n nodes in each layer of the three-layer network architecture. In other words, the 19-node



(a) IP-cost= 3 (b) IP-cost= 9 (c) IP-cost= 17

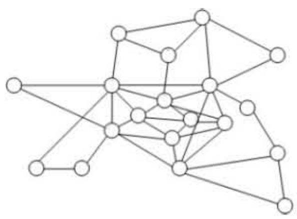
Figure 31: CPLEX vs. Heuristic When $M = 5$ Gbps.



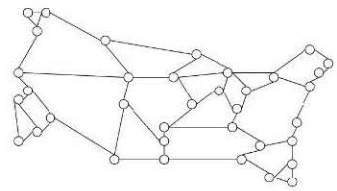
(a) IP-cost= 3 (b) IP-cost= 9 (c) IP-cost= 17

Figure 32: CPLEX vs. Heuristic When $M = 10$ Gbps.

EON has a total of 57 nodes from all layers, and the 36-node Sprint topology has 108 total nodes from all layers. All physical links in these networks are assumed to be bidirectional multi-wavelength fibers, i.e., 10 wavelengths/fiber in EON, and 20 wavelengths/fiber in the Sprint network. Information about network topologies and traffic scenarios are shown in Table 16. 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.



(a) European optical Network (EON)



(b) SPRINT Network

Figure 33: Network Topologies

Table 16: Topology Information and Demands

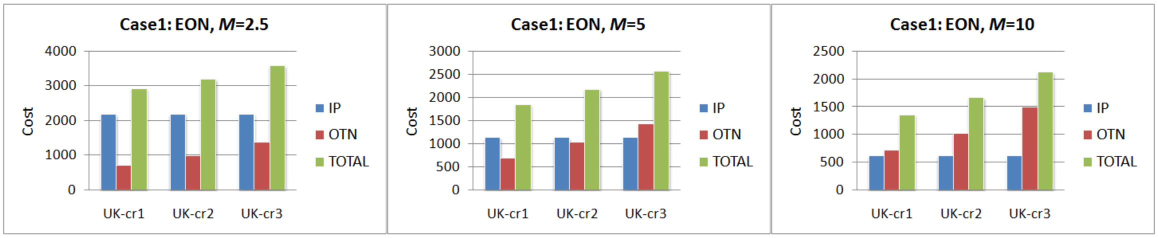
Network	No. of Nodes per Layer	No. of Physical Links (F)	Total load	No. of D	Avg. Load/d
EON	19	35	855	171	5
SPRINT	36	54	3,150	630	5

8.4.1 Numeric Results

8.4.1.1 Interrelated Cost of Both Layers

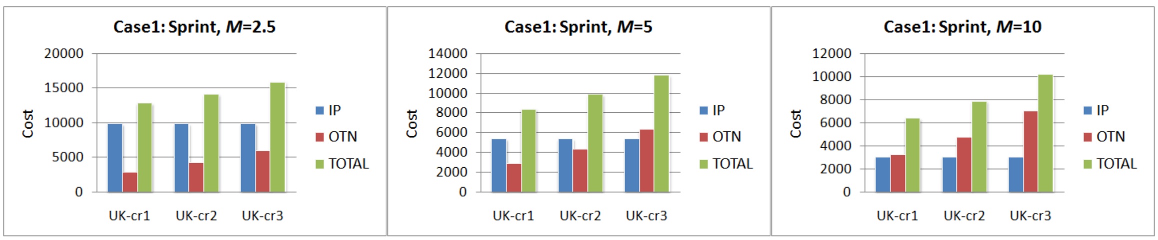
The influential cost depends on the relationship between the IP-cost and the Uk cost, and on the value of M. Figure 34 shows the IP layer, OTN layer, and total cost of Case1 for different values of M in EON. We observe that the IP-cost dominates in Case1 until a turning point at M=5 and UK-cr3 in which the OTN cost becomes dominant. This was also found to be true in the case of the Sprint network as shown in Figure 35.

Figure 36 shows the IP layer, OTN layer, and total cost of Case2 for different values of M in EON. We observe that the IP-cost dominates in Case2 for all scenarios. This was also found to be true for the Sprint network as shown in Figure 37. Similar trend was observed with Case3 as shown in Figure 38 and 39.



(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 34: Costs of Different Components for Different M, Case1 in EON.



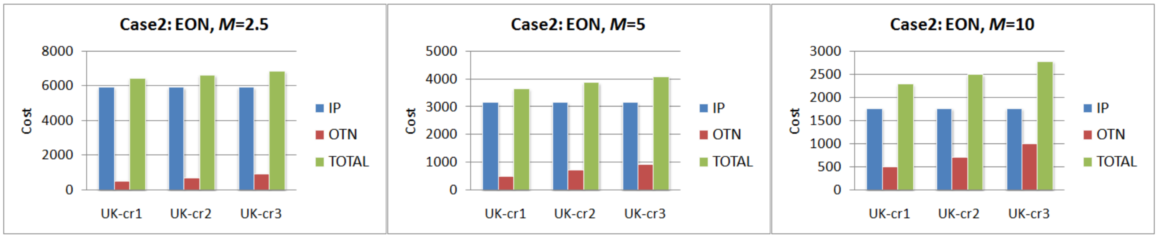
(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 35: Costs of Different Components for Different M, Case1 in Sprint.

This indicates that the influential cost depends on the relationship between the IP-cost and the U_k cost, and on the value of M. The OTN cost is negligible except in Case1 when the IP/optical interface is relatively cheap, M is equal or above the average demand, and U_k-cost:3 $U_k = U_{k+1}$.

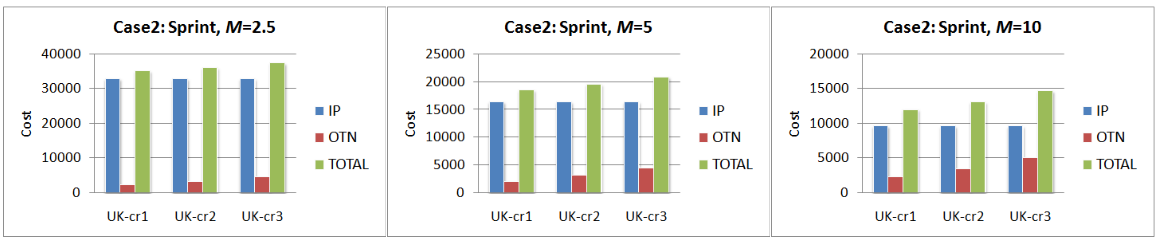
8.4.1.2 IP-Cost vs. OTN-Cost

Here we focus on the IP-cost and the OTN-cost. We can clearly observe the difference cost performance between the two components. Figure 40 shows the IP layer cost vs. the OTN layer cost in EON and Figure 41 shows the same in Sprint. Obviously, the IP-cost is the dominate cost in all cases except in Case1 when $M = 5$ and UK-cr3, and when $M = 10$ for all UK-cr.



(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 36: Costs of Different Components for Different M, Case2 in EON.



(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 37: Costs of Different Components for Different M, Case2 in Sprint.

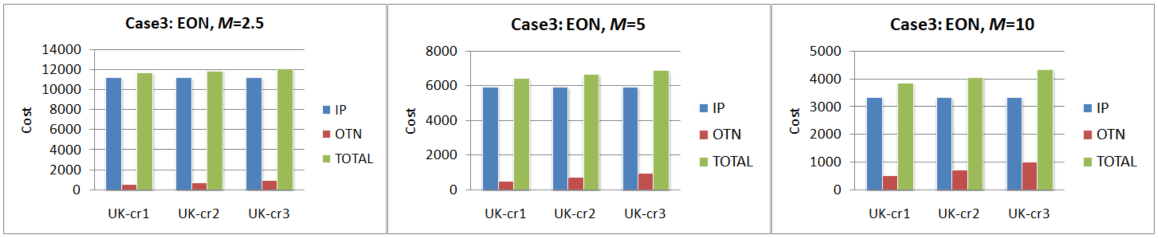
8.4.1.3 IP Layer Cost

Figure 42 shows the total IP cost for different values of M. The cost increases as the IP unit cost increases. Obviously, the case of $M = 10$ yields the lowest IP total cost since we are having more capacity for the same price. We also observe that the difference is widening as we increase the IP unit cost.

8.4.1.4 OTN Layer Cost

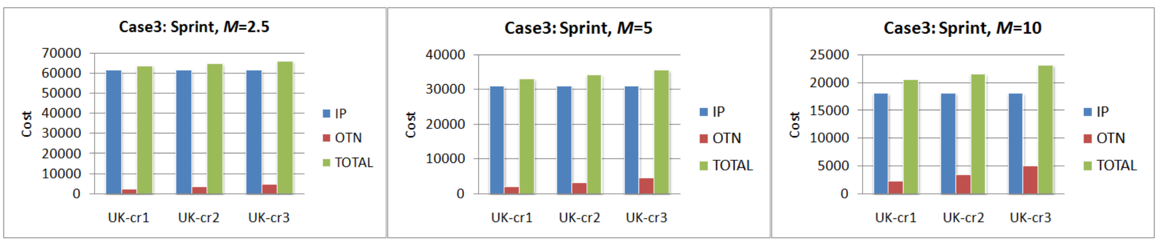
Figure 43 shows the OTN costs for EON and the Sprint network for various values of M, IP, and U_k costs. The cases of IP-cost = 9 and 17 yield the best OTN cost performance when U_k=UK-cr1 for both networks.

Only the case when UK-cr1 indicates that when M is below the average demand



(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 38: Costs of Different Components for Different M, Case3 in EON.

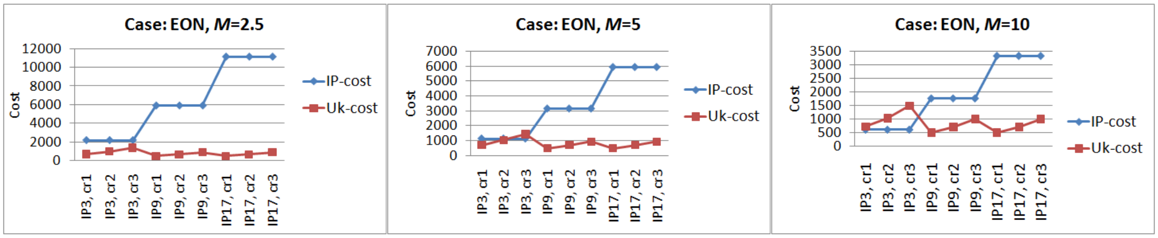


(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 39: Costs of Different Components for Different M, Case3 in Sprint.

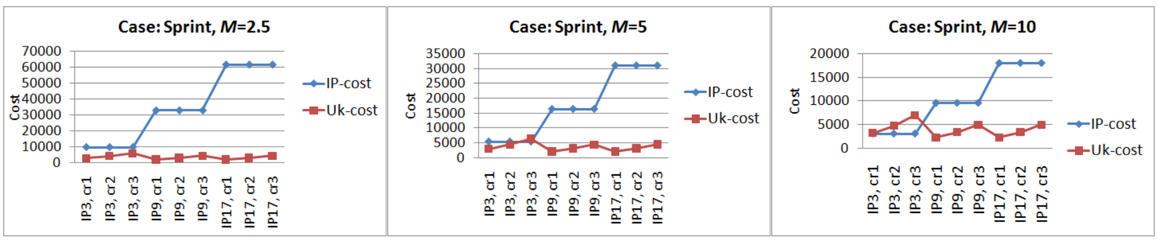
may not the best case to minimize the OTN cost as shown in Figure 43a. Other cases in the EON and the Sprint networks, shown in Figure 43b, clearly point out that a smaller size of M (equal or below the average demand) is the best choice when the goal is to minimize the OTN layer cost. A higher size of M should be avoided if the focus is to reduce the OTN layer cost. Although this case, is the best to achieve the minimum IP layer cost as shown in Figure 42 and the minimum total network costs as shown in Figure 44, it is the worst for the OTN layer cost. This is because when the size of M is large, some of the bandwidth is more than what really is required at the IP/MPLS layers.

If we consider each case of Table 15, we can observe that there is an impact of cost ratio of IP to U_k on the OTN cost. As we increase the IP cost ratio, going from Case1 (Figure 34) to Case2 (Figure 36) and Case3 (Figure 38), we note that the OTN cost is



(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 40: IP-Cost vs. OTN-Cost in All Cases in EON.



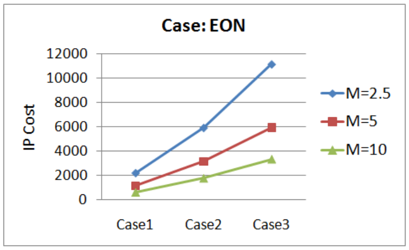
(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Figure 41: IP-Cost vs. OTN-Cost in All Cases in Sprint.

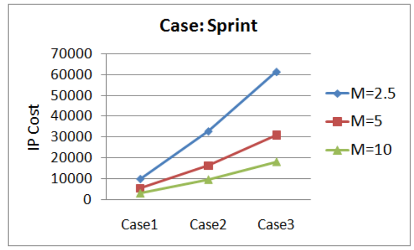
decreasing. For example, consider the case when IP=3 and UK-cr3 in EON. We observe that its OTN cost is higher than the case when IP=9 and UK-cr3 which is also higher than the case when IP=17 and UK-cr3 even though the IP unit cost is increasing. However, we observe the close cost values of Case2 and Case3. In other words, reducing the IP/optical interface by 50% does not have a significant impact on the OTN overall cost for the same U_k-cost. However, it may affect the required signals type and number.

8.4.1.5 Total Network Cost

Now we focus on the total network costs for different scenarios as depicted in Figure 44. Clearly the case of M= 10 has the best cost performance. However, we observe the close performance for Case1. As we increase the IP unit cost we see the performance

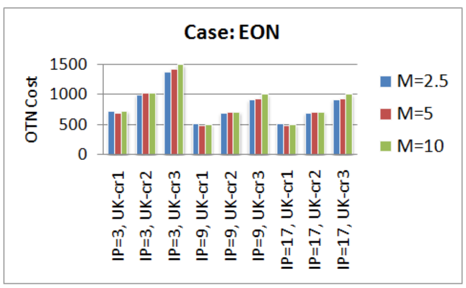


(a) Total IP Cost in EON

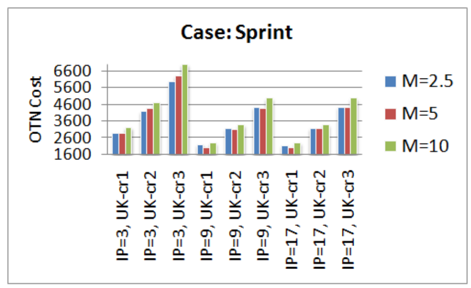


(b) Total IP Cost in SPRINT Network

Figure 42: Total IP Cost of Different M.



(a) Total OTN Cost in EON



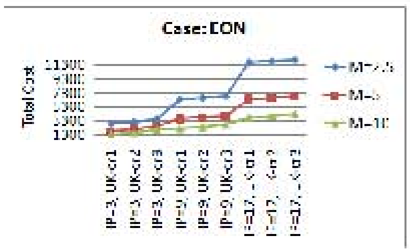
(b) Total OTN Cost in Sprint

Figure 43: Total OTN Cost of Different M and U_k.

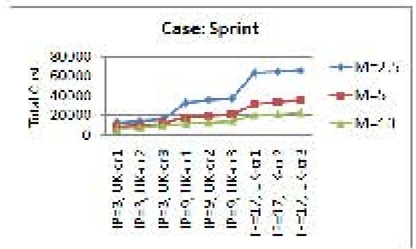
difference is increasing. From this figure and observations in Sections 8.4.1.1 and 8.4.1.4, we infer that this is largely because of the increasing IP unit cost that is the dominant cost in most cases. When the OTN cost is dominant i.e., when M=5, and 10, and UK-cr3 in Case1, we can observe the close performance.

8.4.1.6 No. of Required U_k

No. of U_ks in EON: Figure 45 shows the numbers of U_ks used in EON. We observe that U_1 is not used when M=10. We also observe that U_1 is not used when M=5 and UK-cr1. For all other cases, the numbers of U_1 is larger when M=2.5 as shown in Figure 45a.



(a) Total Cost in EON



(b) Total Cost in Sprint

Figure 44: Total Network Cost of Different M.

For U_2 in Figure 45b, we see a stronger effect of M. The number of U_2s is higher in $M = 2.5$ and $M = 5$ than when $M = 10$. We can also observe the impact of the cost ratio on the numbers of U_2. The number of U_2 increases as we go from Case1 to Case2 to Case3. The number of U_2s is also increased as we go from UK-cr1 to UK-cr3.

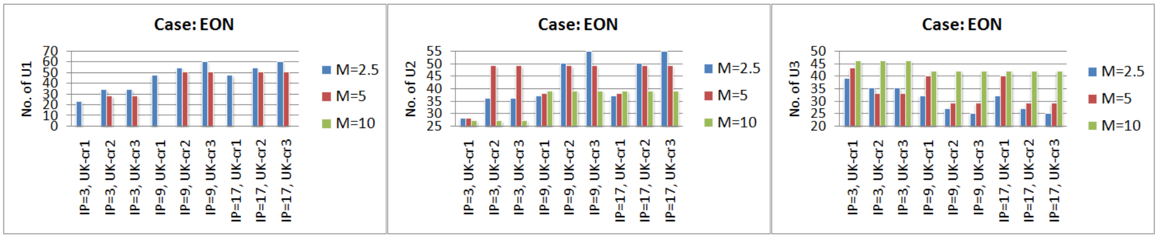
In Figure 45c, we notice similar trends. As we increase M, the numbers of U_3 increase for each case; it is highest in $M = 10$. However, unlike U_2, the numbers of U_3 decrease as we go from Case1 to Case2 to Case3. This shows that while increasing the numbers of U_2, the numbers of U_3 are decreasing.

Results show that the numbers of U_3s are generally higher than the numbers of U_1 or U_2. This is expected as the U_3 size is equal to the maximum capacity of a lightpath. For highly utilized lightpaths, it is cheaper to have one U_3 for each one instead of mixing U_1s and U_2s. For example, suppose a lightpath uses its full 40 Gbps of bandwidth. It is cheaper to have one U_3 than 4 U_2s, 16 U_1s, or a combination of U_1s and U_2s under all U_k-cost scenarios in this study.

Table 17 shows a summary of the patterns of U_ks needed in EON. We make four categories to describe the number of a U_k used in EON: None (-) for zero, Low (L) between 1-15, Medium (M) between 16-30, and High (H) $>$ 30. An up arrow ($\uparrow$) in the table indicates the number of U_k falls in the same previous category but increasing. A down arrow ($\downarrow$) indicates the number of U_k falls in the same previous category but decreasing. Note that we only summarize observations of Case1 (C1) and Case3 (C3) in the table since these are the original elements cost ratio that shows two widely different cost ratios as described earlier.

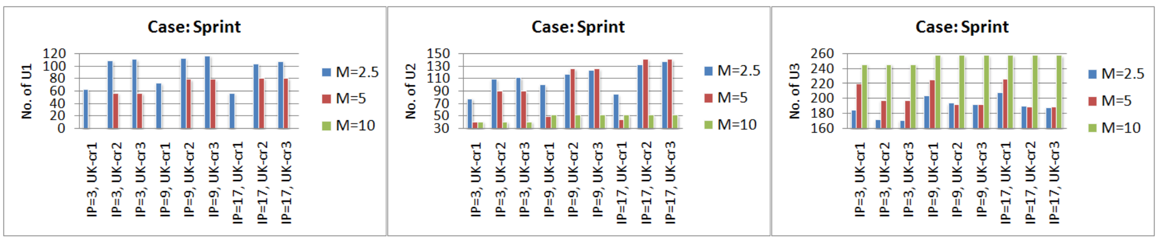
No. of U_ks in the Sprint Network: For the Sprint network (Figure 46), we observe some similarities to EON. First, U_1 is not used when M=10. Second, U_1 is not used when M=5 and UK-cr1. Third, as we increase M, the numbers of U_3 increase for each case. However, there are some differences. The numbers of U_3s increases as we go from Case1 to Case2 and Case3. The numbers of U_2 are considerbly higher when M=2.5 and 5 than when M=10.

Through this discussion we can make two observations. The first is that the sum of all U_ks, in terms of bandwidth, is close for each scenario. What changes is the types and numbers of U_ks used. The second is that the number of required U_ks is mainly determined by two factors: (1) the size of M, and (2) the U_k-cost. We have also observed that the IP unit cost is not as influential as its size M. Again, we make four categories to describe the number of a U_k used in the Sprint topology: None (-) for zero, Low (L) between 1-64, Medium (M) between 65-130, and High (H) $>$ 130. Table 18 shows a summary of patterns for U_ks needed in the Sprint network.



(a) No. of U_1 (b) No. of U_2 (c) No. of U_3

Figure 45: No. of U_k in EON for Different Values of M



(a) No. of U_1 (b) No. of U_2 (c) No. of U_3

Figure 46: No. of U_k in Sprint for Different Values of M

8.4.1.7 Effect of Increasing the Load

Certainly, if we increase the load, the total cost will increase due to more network elements needed to satisfy the load increase. On the other hand, our interest to understand the impact of increasing the load on the OTN U_k types and numbers. We start with the base load, shown in Table 16, and increase the load by 10% up to 50%. This means that we add 0.5 Gbps to the average demand in the network each time we increase the load by 10%. This also means that the case of M=5 is no longer equal to the average demand after the first load increase by 10%. However, when the load is increased by 50%, the average demand will be 7.5 Gbps which is still below the case of M=10.

We summarize our observations per case when the load is increasing as fellows:

Table 17: Summary of The Numbers of U_k for EON

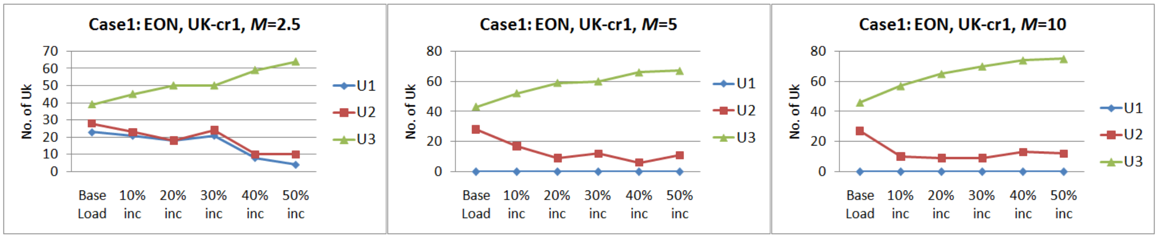
	UK-cr1: 2 U_k = U_{k+1}						UK-cr2: 3 $U_k > U_{k+1}$						UK-cr3: 3 $U_k = U_{k+1}$					
	$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$	
	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3
U_1	M	H	-	-	-	-	H	↑	M	H	-	-	H	↑	M	H	-	-
U_2	M	↓	M	H	M	H	H	↑	H	H	M	H	H	↑	H	H	M	H
U_3	H	↓	H	↓	H	↓	H	M	H	M	H	↓	H	M	H	M	H	↓

Table 18: Summary of The Numbers of U_k for The Sprint Network

	UK-cr1: 2 U_k = U_{k+1}						UK-cr2: 3 $U_k > U_{k+1}$						UK-cr3: 3 $U_k = U_{k+1}$					
	$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$		$M = 2.5$		$M = 5$		$M = 10$	
	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3	C1	C3
U_1	L	↓	-	-	-	-	M	↓	L	M	-	-	M	↓	L	M	-	-
U_2	M	↑	L	↑	L	↑	M	H	L	↑	M	H	M	H	M	H	L	↑
U_3	H	↑	H	↑	H	↑	H	↑	H	↓	H	↑	H	↑	H	↑	H	↑

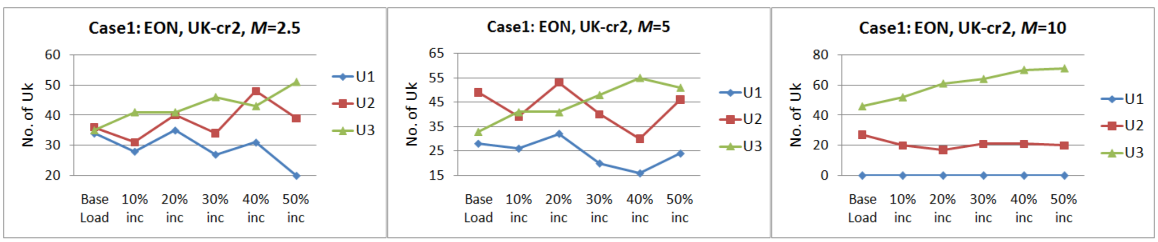
- EON, UK-cr1 (Figure 47): U3 always increases, U1, and U2 decrease, but U1 is still not used when M =5, and 10.
- EON, UK-cr2 (Figure 48): U3 always increases, U1, and U2 fluctuate, but U1 is still not used $M = 10$.
- EON, UK-cr3 (Figure 49): U3 generally increases, U1, and U2 fluctuate, but U1 is still not used $M = 10$.
- Sprint, all UK-cr (Figure 50, Figure 51, and Figure 52): U3 always increases, U1, and U2 fluctuate but generally increasing, and U1 is still not used when M =5, in UK-cr1 and when $M = 10$ in all UKcr.

Figure 53 and Figure 54 shows the effects of the load increase on the IP and OTN layer cost relationship. We observe that the difference between the two cost components



(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

Figure 47: Increasing The Load in EON for Different Values of M, Case1, UK-cr1



(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

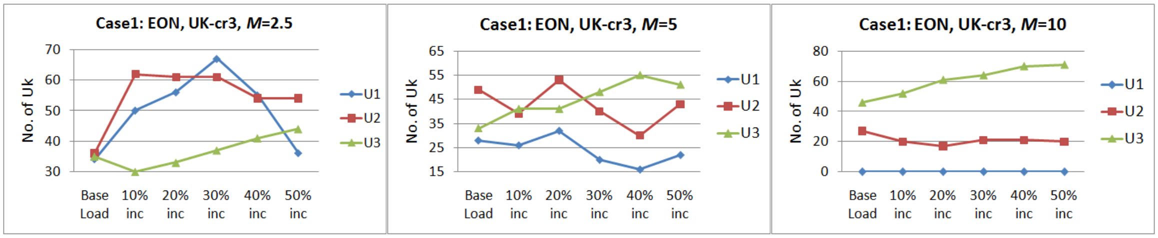
Figure 48: Increasing The Load in EON for Different Values of M, Case1, UK-cr2

are kept within ± 2 as the load increases.

8.4.2 Summary Observations

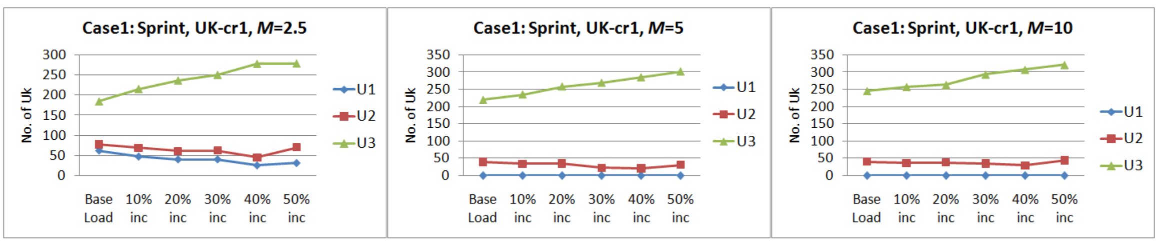
We now present our summary observations and also attempt to answer the questions raised in Section 8.2.

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 that this is the best case that minimizes the cost of this layer (Figure 42). This is also the best case that minimizes the overall network cost as shown in Figure 44. However, the case when M is below or equal the average demand is the best case that minimizes the OTN layer cost in Sprint and EON. From this discussion, we can observe that some parameter values may be the best for reducing the



(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

Figure 49: Increasing The Load in EON for Different Values of M, Case1, UK-cr3



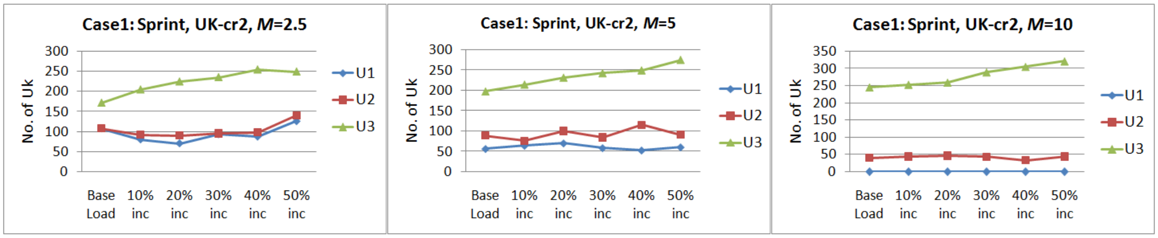
(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

Figure 50: Increasing The Load in Sprint for Different Values of M, Case1, UK-cr1

cost of an individual layer but these are not for minimizing the overall network cost, and vice versa.

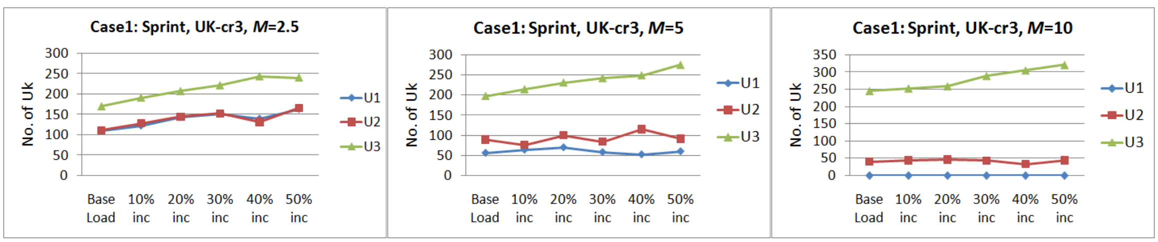
We have observed that the cost ratio of IP-cost to U_k-cost has a clear impact on the OTN layer cost. As we increase the cost ratio, going from Case1 to Case2 and Case3, we note that the OTN layer cost decreases. At the same time we note the close cost performance of Case2 and Case3, which indicates that reducing the IP/optical interface by 50% does not have a significant impact on the OTN overall cost for the same U_k-cost.

The numbers and types of U_k needed to satisfy the demands are noticeably influenced by two elements: the size of M, and the U_k-cost. The number of U_1s is generally larger when M is below the average demand. Increasing the size of M results in higher numbers of U_2s and U_3s to a point where U_1 is not used when M is above the average



(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

Figure 51: Increasing The Load in Sprint for Different Values of M, Case1, UK-cr2



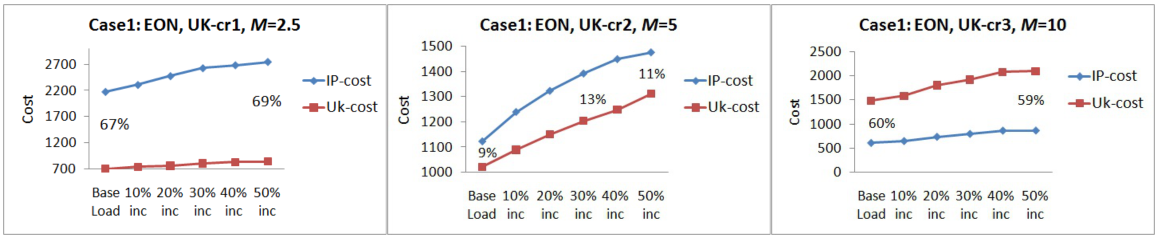
(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

Figure 52: Increasing The Load in Sprint for Different Values of M, Case1, UK-cr3

demand. The U_k-cost has a clear impact especially when M is above the average demand. The number of $U2$s increases as we go from Case1 to Case2 to Case3 of the U_k-cost while the number of U_3s decreases. In case of load increase, a third element is to be considered: the amount of the increase. Generally, increasing the demands will lead to either more U_1s or U_2s (depending on the size of M, the U_k-cost, and the network topology) and U_3s.

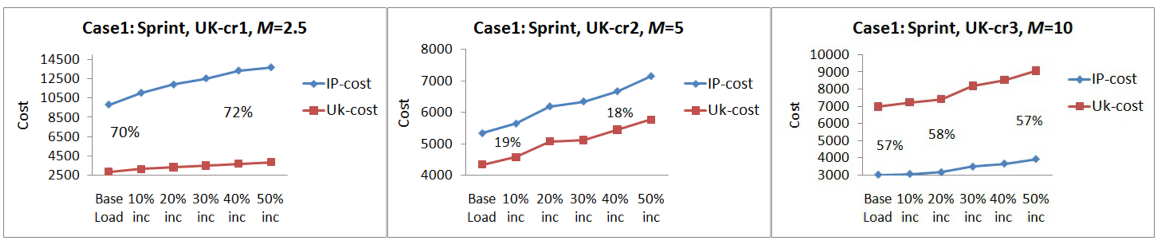
8.5 Conclusion

We have presented in this Chapter results of Model (**P2**) where the DWDM layer capacity is fixed and we focus on the IP/MPLS and OTN layers. Since the problem is NP-hard and to understand three-layer interaction under a number of parameters in large networks, we have modified our heuristic that performs very well compared to CPLEX.



(a) $M = 2.5$, UK-cr1 (b) $M = 5$, UK-cr2 (c) $M = 10$, UK-cr3

Figure 53: Increasing The Load in EON for Different Values of M



(a) $M = 2.5$, UK-cr1 (b) $M = 5$, UK-cr2 (c) $M = 10$, UK-cr3

Figure 54: Increasing The Load in Sprint for Different Values of M

We have experimented with various network parameters values to examine how they impact the network and each layer performance. We have analyzed the results and observed that while some parameters values are the best to optimize the cost of a specific layer, they may be the worst for other layers. OTN layer will be more bandwidth efficient and hence its cost is reduced if the IP/MPLS capacity module is below the average demand in the network. This contradicts the best size of the IP/MPLS capacity module that results in an optimized IP/MPLS layer when its size is above the average demand. The OTN layer cost and the number of U_ks required are significantly influenced by the size of M, the U_k unit cost, and the demand volume. Generally, increasing load will be served with more U_3s. In summary, our study quantifies and shows how the IP layer resources and various costs can impact the neighboring OTN layer and the overall network performance.

CHAPTER 9

OPTIMIZING NODE CAPACITY

Both Models (**P1**) and (**P2**), presented in Sections 4.4 and 7.2 respectively, do not consider the actual representation of the routing and switching nodes. In this Chapter, 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 consume significant power; under the umbrella of green computing, such goals are important to consider in large ISP networks. Unlike Models (**P1**) and (**P2**), Model (**P3**) presented in this Chapter aims to optimize the capacity of LSRs and OXCs, rather than the links capacity at each network layer.

We wish to clarify that power modeling is not the focus of this Chapter; rather, we consider instead the optimizing node capacity problem that can help reduce power consumption. We present an explicit networking optimization Model (**P3**) 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.

9.1 Problem Formulation

We now present the optimization model (**P3**). The notations used in this model are summarized in Tables 19 and 20. The objective in our design model (**P3**) is to minimize the total of LSRs and OXCs node capacity, which can be written as:

Table 19: List of Notations (P3 Given Entities)

Indices:

d = 1, 2, ..., D demands between source-destination pairs of the IP/MPLS layer.
p = 1, 2, ..., P_d 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, ..., Q_e candidate paths of OTN layer for realizing capacity of link e.
g = 1, 2, ..., G links of the OTN layer.
z = 1, 2, ..., Z_g 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.

Constants:

h_d: Volume of demand d.
δ_{edp}: =1 if link e belongs to path p realizing demand d; 0, otherwise.
γ_{geq}: =1 if link g belongs to path q realizing capacity of link e; 0, otherwise.
ϑ_{fgz}: =1 if link f belongs to path z realizing capacity of link g; 0, otherwise.
θ_{ve}: =1 if link e is incident with LSR v; 0, otherwise.
ϕ_{rg}: =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.
U_k: Module size for OTN layer link capacities $k = 1, 2, 3$.
N: Module size for DWDM layer link capacities.
b_f: Number of modules N to be installed on link f in the DWDM layer (non-negative integral).
σ_v: Weight factor of a LSR v.
ρ_r: Weight factor of an OXC r.

Table 20: List of Notations (P3 Variables)

Variables:

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

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

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

y_e: 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.

w_{gk}: Number of modules U_k to be installed on link g in the OTN layer (non-negative integral).

Y_r^o: Capacity of OXC r.

$$\text{Minimize} \qquad \sum_{v=1}^{V} \sigma_v Y_v^l + \sum_{r=1}^{R} \rho_r Y_r^o \tag{9.1}$$

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 (9.1) 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 (**P3**) are as follows:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{9.2}$$

IP demand d is assumed to be carried over a single MPLS tunnel out of the set of paths P_d; this is captured in (9.2).

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \le M y_e \qquad e = 1, 2, ..., E \tag{9.3}$$

The IP/MPLS layer capacity feasibility constraints are given in (9.3) 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.

$$\sum_{e=1}^{E} \theta_{ve} M y_e \leq AY_v^l \qquad v = 1, 2, ..., V \tag{9.4}$$

Next, constraints (9.4) define the capacity Y_v of each LSR v in the IP/MPLS layer, expressed as the maximum of the link capacity connected to the router.

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{9.5}$$

The constraints (9.5) 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.

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \qquad g = 1, 2, ..., G \tag{9.6}$$

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

$$\sum_{k=0}^{4} \phi_{rg} U_k w_{gk} \leq CY_r^o \qquad g = 1, 2, ..., G \;\; r = 1, 2, ..., R \tag{9.7}$$

We then show constraints (9.7) 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.

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4, \;\; g = 1, 2, ..., G \tag{9.8}$$

Next, constraints (9.8) 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.

$$\sum_{g=1}^{G}\sum_{k=0}^{4}U_k\sum_{z=1}^{Z_g}\vartheta_{fgz}s_{gkz} \leq Nb_f \qquad f=1,2,...,F \tag{9.9}$$

Finally, constraints (9.9) 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.

All variables are non-negative while some are integer variables as described in Table 20.

Note that Model (**P1**), presented in Section 4.4, 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 (**P3**) on the other hand explicitly attempts to optimize the required capacity at each routing node v and switching node r. That is, Model (**P3**) 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 (**P3**). 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 10.2.2.2.

9.2 Model P3

To make it more readable and illustratable, the entire Model (**P3**) is summarized below.

$$\text{Minimize} \qquad \sum_{v=1}^{V} \sigma_v Y_v^l + \sum_{r=1}^{R} \rho_r Y_r^o \tag{9.10}$$

Subject to:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{9.11}$$

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \leq M y_e \qquad e = 1, 2, ..., E \tag{9.12}$$

$$\sum_{e=1}^{E} \theta_{ve} M y_e \leq A Y_v^l \qquad v = 1, 2, ..., V \tag{9.13}$$

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{9.14}$$

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \qquad g = 1, 2, ..., G \tag{9.15}$$

$$\sum_{k=0}^{4} \phi_{rg} U_k w_{gk} \leq C Y_r^o \qquad g = 1, 2, ..., G \;\; r = 1, 2, ..., R \tag{9.16}$$

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad k = 0, 1, 2, 3, 4, \;\; g = 1, 2, ..., G \tag{9.17}$$

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f \qquad f = 1, 2, ..., F \tag{9.18}$$

Note that the variables of Model (**P3**) are defined in Table 20.

CHAPTER 10

STUDY AND RESULTS FOR (P3)

10.1 A Case Study: 7-node per Layer Network

Problem (**P3**) has $D+2E+V+G(R+4)+F$ constraints and $P\times D+E(Q+1)+V+R+3G(Z+1)$ integer variables, 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 (**P3**) can be solved using CPLEX 8.11 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 three-layer network. We use the demand model described in Section 6.2 to generate demand volume between LSRs. 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 55.

Figure 56 shows the case when we increase the base load by 10% each run until a

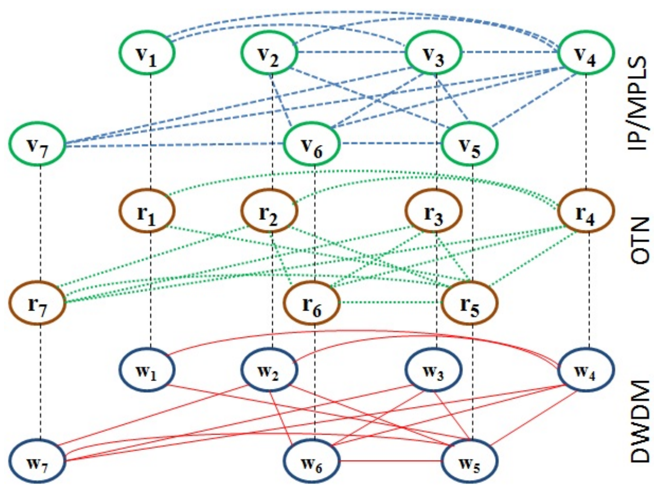


Figure 55: IP/MPLS over OTN over DWDM Network

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 57 shows the required total capacity of the LSRs and the OXCs of the three weight ratios. We observe that on average $\simeq$ 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 $\simeq$ 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

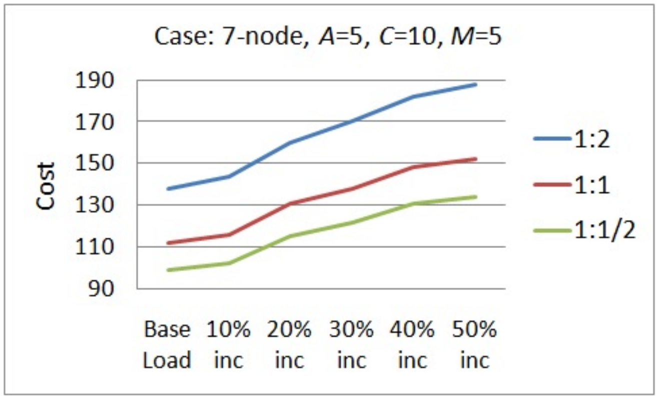


Figure 56: Network Cost with Increase in Load

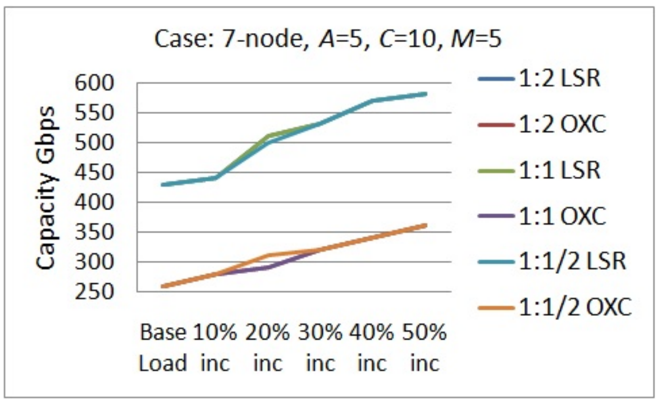


Figure 57: Node Capacity with Increase in Load

the base load is increased by 20%, to highlight the differences. This case is shown in Figure 58 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 59 shows the required capacity at each OXC that shows differences in OXC capacity for two nodes r_2 and r_4. In addition, Figure 58 and Figure 59 show that the weight ratio of 1:1/2 has the most effect on the results.

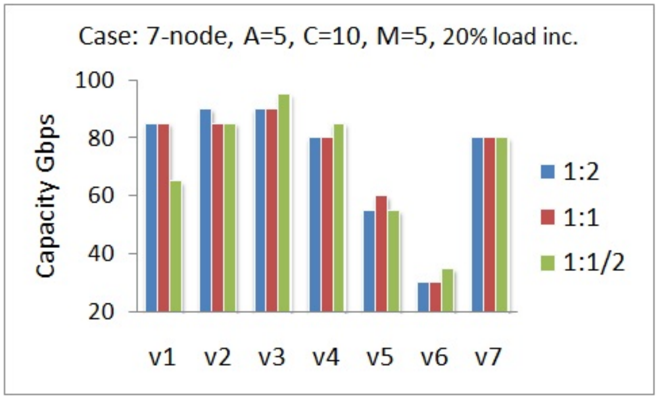


Figure 58: LSRs Capacity for Different Weight Factors (load: 20% inc)

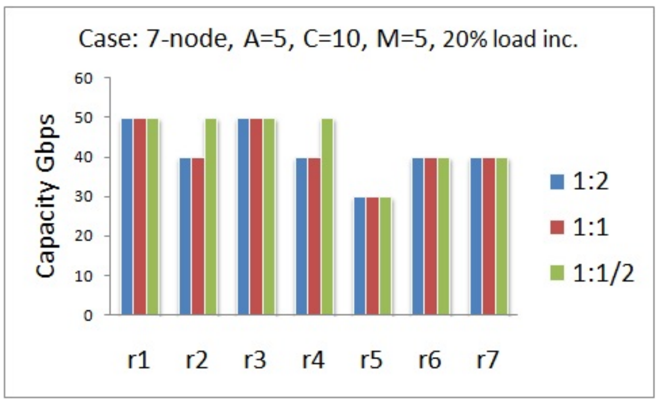


Figure 59: OXCs Capacity for Different Weight Factors (load: 20% inc)

10.2 A Study on a Larger Network

10.2.1 Study Environment

Although we can not solve problem (**P3**) 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. This can be achieved by limiting the number of nodes to be visited in the branch and cut tree to 500,000 by declaring `set mip limits nodes 500000`. Thus, for this study we consider the 14-node per layer NSFNET as shown in Figure 60.

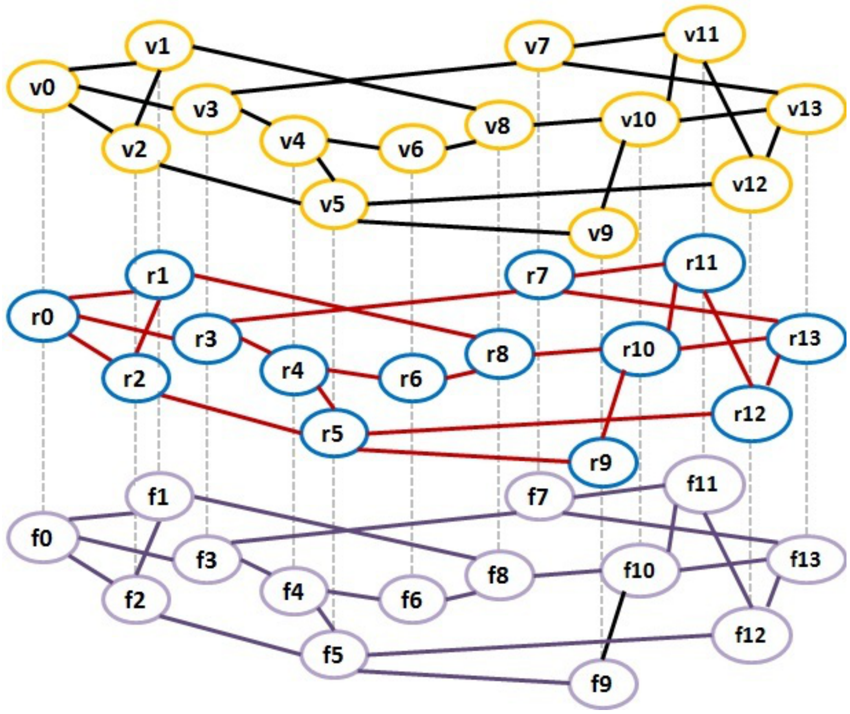


Figure 60: 14-node per Layer NSFNET

Table 21: Topology Information and Demands

Network	No. of Nodes per Layer	No. of Physical Links (F)	Total load	No. of D	Avg. Load/d
NSFNET	14	21	455	91	5

Table 21 shows the network topology and demand volume used in this study. In addition, table 22 shows the considered values of each parameter of Model (**P3**). 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.

Table 22: 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

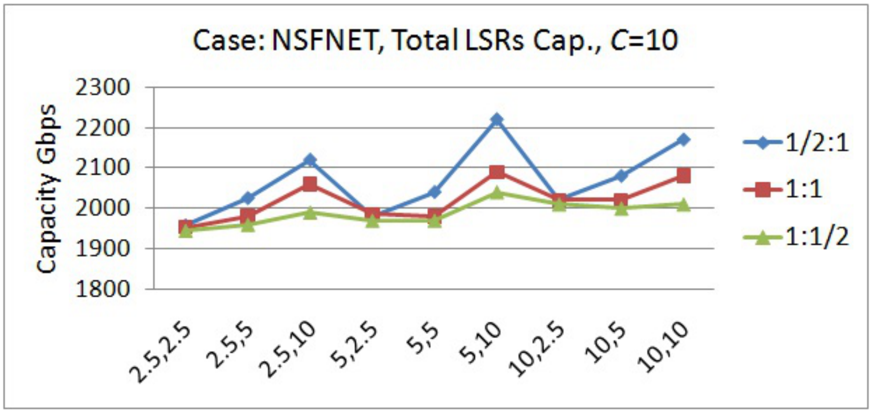


Figure 61: Total LSRs Capacity for Different sizes of M,A in NSFNET

10.2.2 Illustrative Numerical Results

10.2.2.1 Total LSRs and OXCs Capacity

Figure 61 shows the total LSRs capacity for different cases of M and A. Similarly, Figure 62 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 61. 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

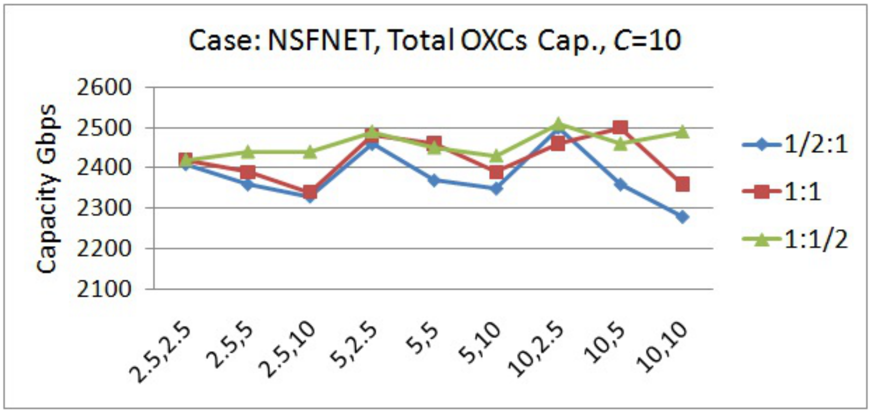


Figure 62: Total OXCs Capacity for Different sizes of M,A in NSFNET

in our study on the 7-node per layer network in Section 10.1.

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 62 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 61. These are as the following:

a. 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).

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

c. 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).

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

e. 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 10.1 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.

10.2.2.2 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 63 shows the each individual LSR capacity and Figure 64 shows the each individual OXC capacity.

We previously observed from Figure 61 and Figure 62 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 63 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

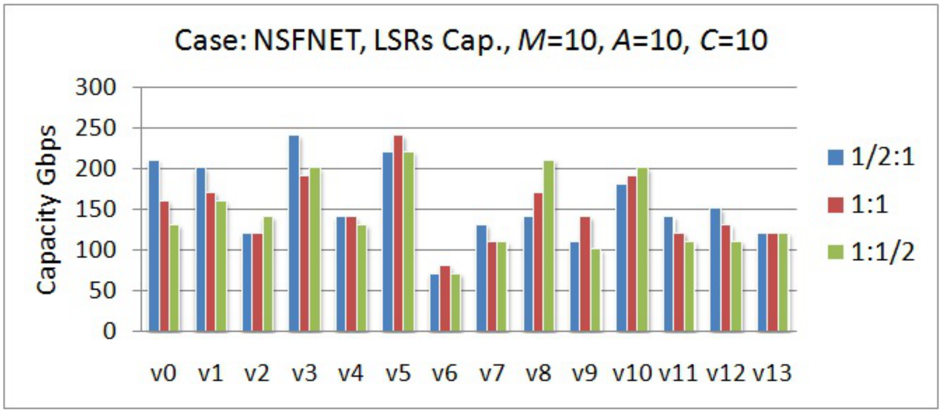


Figure 63: Individual LSRs Capacity when M=10, A=10, and C=10 in NSFNET

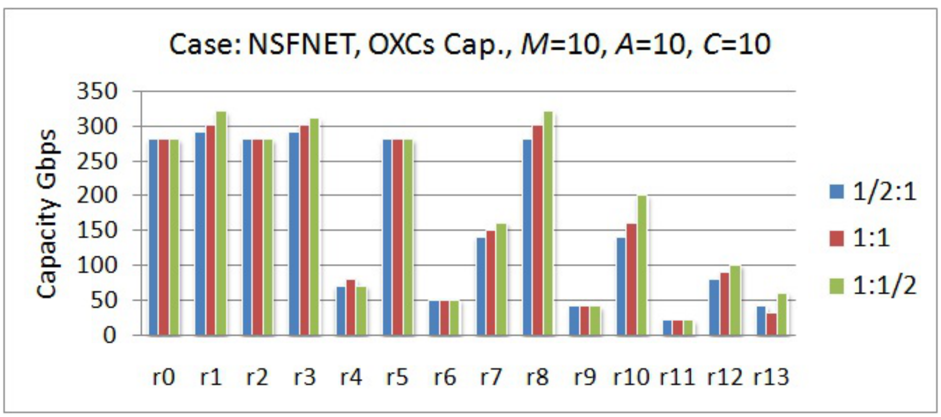


Figure 64: Individual OXCs Capacity when M=10, A=10, and C=10 in NSFNET

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.

We can observe the opposite behaviors as we consider the individual OXC node capacity in Figure 64. 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.

10.2.2.3 Objective Comparison

In this section we focus on the objective comparison of the 27 scenarios studied in NSFNET. Figure 65 shows that the weight ratio 1/2:1 yields the minimum objective values in all scenarios. We observe that as the value of A increases, the objective value decreases. We also note that the objective values become closer as the value of A increases. For example, the objective difference between ratio 1/2:1 and 1:1 in (2.5, 2.5) is 400, while the difference between the two ratios in (2.5, 10) shrinks to 110.

From this figure and previous observations made in Section 10.2.2.1 we can define the impact of A. As the size of A increases, the total required LSRs capacity increases, the total required OXCs capacity decreases, and the objective value decreases. This indicates

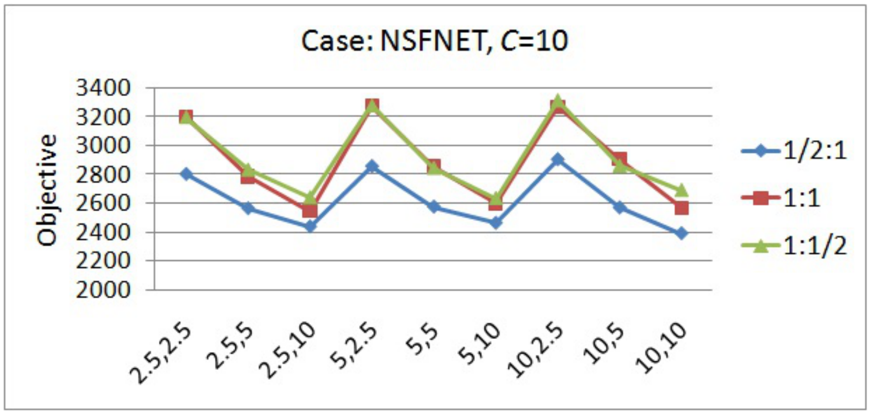


Figure 65: Objective Comparison for Different sizes of M,A in NSFNET

that the objective decreases as we increase the size of the capacity module A of the LSRs while keeping the weight fixed.

10.3 Summary and Future Work

In Chapter 9 we present an optimization model for optimizing node capacity in a multilayer network that consists of IP/MPLS, OTN, and DWDM layers. In this Chapter we present a study on two different networks and results to show that the capacity is impacted as the network load is increased, and how the node capacity requirement at different layers may differ when viewed from the perspective of each node at different layers. We also observed the significant impact of A when this value is equal or above the average demand in the network.

In the future, we plan to develop a heuristic algorithm and provide a comprehensive analysis of results for larger networks. For instance, we plan to study the impact of the different network parameters such as modularity on optimizing the node capacity at different layers. We anticipate drawing a similar conclusion for large multilayer networks. That is, the different weight ratios do not affect the overall required capacity of each layer when the LSR module capacity is low, but the weight ratios may influence the required capacity at each individual node. In addition, when the LSR module capacity is not small, weight ratios influence the overall required capacity of each layer. The scope of our detailed study will be to quantify and understand the extent of the influence.

CHAPTER 11

MULTILAYER NETWORK PROTECTION

In Model (**P1**), Section 4.4, we consider the capacity design problem in the three-layer network. Model (**P2**) in Section 7.2 allows us to focus on the IP/MPLS and OTN layer interrelation while the DWDM capacity is fixed. In Model (**P3**), Section 9.2, we address the problem of optimizing the routing and switching nodes capacity. However, previous Models do not provide any protection to recover from network failures. In this Chapter we present Model (**P4**) that addresses the survivability aspect of the IP/MPLS over OTN over DWDM multilayer networks.

Multilayer network survivability has been an important research topic in recent years as network traffic keeps rising. A survivable network, in general, is a network that provides some ability to recover ongoing traffic disrupted by a network failure. Large ISPs need to ensure their networks can meet customer satisfaction and expectation. In addition, in today's world where businesses rely heavily on computer networks, network failures can severely affect their revenues. Thus, network survivability has always been a vital factor in designing current and future communication networks.

In two-layer networks such as IP-over-WDM, a single recovery mechanism could be provided at either layer. In this design, a critical question arises: where do we provide the protection mechanism? The benefits of an upper layer protection are: (1) in case of failure (either at the upper or lower layer), the network could be fully recovered, (2) since the upper layer often carries differentiated services with different QoS requirements, it is generally easier to offer differentiated survivability at the upper layer. Nonetheless, recovery at the upper layer has some disadvantages: (1) recovery time at the upper layer is usually higher than recovery time at the lower layer due to the nature of IP, (2) in case of failure at the lower layer, there could be a huge amount of upper layer traffic affected by the failure in which case a great amount of recovery process at the upper layer is required. On the other hand, recovery at the lower layer has some advantages. It is faster than recovery at the upper layer and it requires considerably fewer actions due to the coarser granularity of the lower layer. The drawback, however, is that some failures (e.g. an IP router failure) can not be handled by the lower layer. The above discussion elucidates the need for a recovery mechanism to be deployed at each layer of the network to recover from various network failures.

In this Chapter, we consider a survivability design specifically for a three-layer IP/MPLS-over-OTN-over-DWDM network where only the normal flow of each layer is a 100% protected against a single link failure. In this architecture, the label switched routers (LSRs) in the IP/MPLS layer are physically connected to optical transport networks that are slated on top of optical cross-connects (OXCs) that are interconnected by a DWDM fiber transmission medium at the physical level. In this setting, we present the network capacity (Normal and protection) design model and a study based on various network parameters.

11.1 Protection Mechanisms

Resource protection can be performed in different layers of a multilayer network. In our architecture, the IP/MPLS layer is protected in the underlying OTN layer which is protected by the DWDM layer. In this case, a failure in a lower layer can not be seen by the upper layer. For instance, the IP/MPLS layer does not see the failure of the OTN link. Several protection and restoration mechanisms have been introduced in literature [18]. The choice of which method to implement in a network depends on the requirements of the ISP and whether a method is technologically meaningful. In this section, we present our selection of the protection mechanism used per layer of the multilayer network and explain why we selected each one of them.

MPLS tunnels can be set up to carry demand volumes for different traffic demand types that require different QoS. This indicates that the MPLS layer can provide transport services through the use of tunnels. In our design model, we assume that each IP demand d can be carried over a single end-to-end primary tunnel. In this case, one of the suitable protection mechanisms from the service provider standpoint is the hot-standby path protection. In this method, a demand is carried over the primary path only, while the protection path is reserved for future use in case that the primary path gets failed. This is a 1:1 protection technique. Note that the protection capacity for one path is not shared with the protection capacity used for other paths that fail in other failure situations. In addition, each failed flow is restored on one single protection path.

Since each OTN link carries U_k signals, we provide a protection for each U_k by using a link restoration on a single path. In this mechanism, the entire capacity of the failed U_k is restored on a single path between the end nodes of the failed OTN link.

For the DWDM layer, we provide protection at the aggregate signal level. A common method of protection, at this lambda layer, is protection by using fixed back-up paths. In this method, a copy of data signal is transmitted respectively on a primary and a protection path that are link-disjoint and node-disjoint. Based on the signal quality, the receiver can make a decision to accept which copy of signal. This is a 1+1 protection technique.

11.2 An Integrated Capacity (Normal and Protection) Model (P4)

Figure 66 shows how we approach the problem. First, we have an IP/MPLS layer normal capacity and its protection capacity. Both must be realized by the OTN layer. However, the OTN layer will only protect its normal capacity that is needed to realize the normal IP/MPLS capacity to avoid protecting the IP/MPLS layer capacity twice; one in the IP/MPLS layer and one in the OTN layer. Then, all OTN layer capacities will be realized by the DWDM layer. Again, only the normal capacity of the DWDM layer is protected to avoid protecting the OTN layer capacity twice; one in the OTN layer and one in the DWDM layer. Note the difference between Figure 66 and Figure 2 of Chapter 4 in which Model (**P1**) has no protection capacity. Tables 23, 24, 25 and 26 list the notations used in our formulation.

11.2.1 Constraints

Since protection will be provided to the normal capacity of each layer, we have separated the capacity components at each layer. In our formulation, there are two general

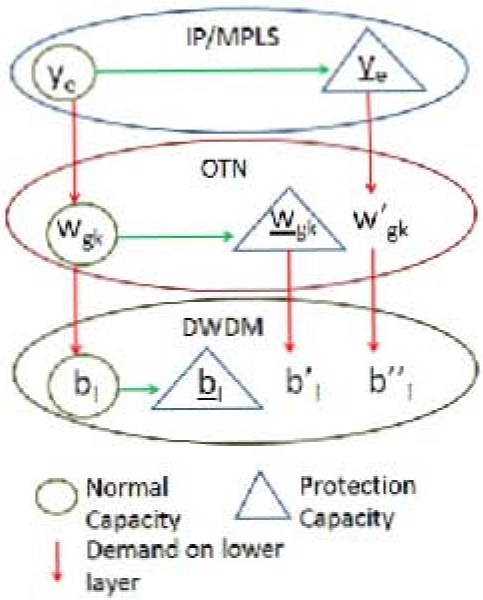


Figure 66: Capacity Components of IP/MPLS over OTN over DWDM Network

sets of constraints. The first is the set of capacity feasibility constraints that assures all flows routed on a particular link do not exceed the capacity of the link. The second is the set of demand constraints that specifies how the capacity of each upper layer link is realized by means of flow allocated to its candidate paths from the routing list in the lower layer. Thus, Model (**P4**) has the following sets of constraints (they will be explained afterward):

IP/MPLS flows:

$$\sum_{p=1}^{P_d} x_{dp} = 1 \qquad d = 1, 2, ..., D \tag{11.1}$$

IP/MPLS normal capacity feasibility:

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \delta_{edp} x_{dp} \leq M y_e \qquad e = 1, 2, ..., E \tag{11.2}$$

Table 23: List of Notations (P4 Given Entities) 1

Indices:

d = 1, 2, ..., D demands between source-destination pairs of the IP/MPLS layer.
p = 1, 2, ..., P_d candidate pair of (primary, protection) paths ($\mathbb{P}_{dp}$, $\mathbb{R}_{dp}$) for realizing demand d.
e = 1, 2, ..., E links of the IP/MPLS layer.
q = 1, 2, ..., Q_e candidate paths of OTN layer for realizing capacity of link e.
g, l = 1, 2, ..., G links of the OTN layer.
r = 1, 2, ..., R_g candidate restoration paths for link g.
z = 1, 2, ..., Z_g candidate pair of (primary, protection) paths ($\mathbb{Z}_g$, $\mathbb{A}_g$) of DWDM layer for realizing capacity of link g.
v = 1, 2, ..., V_g 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.

IP/MPLS protection capacity feasibility:

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \mu_{edp} x_{dp} \leq M \underline{y}_e \qquad e = 1, 2, ..., E \tag{11.3}$$

OTN flow realizing IP/MPLS normal capacity:

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{11.4}$$

OTN flow realizing IP/MPLS protection capacity:

$$\sum_{q=1}^{Q_e} m'_{eq} = \underline{y}_e \qquad e = 1, 2, ..., E \tag{11.5}$$

OTN normal capacity feasibility:

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \leq \sum_{k=0}^{4} U_k w_{gk} \quad g = 1, 2, ..., G \tag{11.6}$$

OTN capacity feasibility of IP/MPLS protection capacity:

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m'_{eq} \leq \sum_{k=0}^{4} U_k w'_{gk} \quad g = 1, 2, ..., G \tag{11.7}$$

Table 24: List of Notations (P4 Given Entities) 2

Constants:

h_d: Volume of demand d.
δ_{edp}: =1 if link e belongs to the primary path $\mathbb{P}_{dp}$ realizing demand d; 0, otherwise.
μ_{edp}: =1 if link e belongs to the protection path $\mathbb{R}_{dp}$ protecting path $\mathbb{P}_{dp}$ of demand d; 0, otherwise.
γ_{geq}: =1 if link g belongs to path q realizing capacity of link e; 0, otherwise.
ϑ_{fgz}: =1 if link f belongs to primary path $\mathbb{Z}_g$ realizing capacity of link g; 0, otherwise.
θ_{fgz}: =1 if link f belongs to the protection path $\mathbb{A}_g$ protecting path $\mathbb{Z}_g$ of link g; 0, otherwise.
π_{fgv}: =1 if link f belongs to the path v realizing capacity of link g; 0, otherwise.
Δ_{lgkr}: =1 if link l belongs to path r restoring OTN interface k on link g; 0, otherwise.
M: Module size for IP/MPLS layer.
U_k: Module size for OTN layer link capacities $k = 0, 1, 2, 3, 4$.
N: Module size for DWDM layer link capacities.
η_e: Cost of one capacity unit of module M of IP/MPLS layer link e.
β_{gk}: Cost of one capacity unit of type U_k of OTN layer link g.
ξ_f: Cost of one capacity unit of module N of WDM layer link f.

OTN protection mechanism:

$$\sum_{r=1}^{R_g} c_{gkr} = w_{gk} \qquad g = 1, 2, ..., G \;\; k = 0, 1, 2, 3, 4 \tag{11.8}$$

$$\sum_{r=1}^{R_g} u_{gkr} = 1 \qquad g = 1, 2, ..., G \;\; k = 0, 1, 2, 3, 4 \tag{11.9}$$

$$c_{gkr} \le U_k u_{gkr} \qquad g = 1, 2, ..., G \;\; k = 0, 1, 2, 3, 4, \quad r = 1, 2, ..., R_g \tag{11.10}$$

$$\sum_{r=1}^{R_g} \Delta_{lgkr} c_{gkr} \le \underline{w}_{lk} \qquad k = 0, 1, 2, 3, 4, \quad l = 1, 2, ..., G, \;\; g = 1, 2, ..., G \;\; l \ne g \tag{11.11}$$

DWDM flow realizing OTN normal capacity:

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad g = 1, 2, ..., G \;\; k = 0, 1, 2, 3, 4 \tag{11.12}$$

Table 25: List of Notations (P4 Variables) 1

Variables:

x_{dp}: IP/MPLS flow allocated to path pair p ($\mathbb{P}_{dp}$, $\mathbb{R}_{dp}$) of demand d (non-negative, binary).

m_{eq}: OTN flow allocated to path q realizing normal capacity of link e (non-negative integral).

m'_{eq}: OTN flow allocated to path q realizing protection capacity of link e (non-negative integral).

y_e: Number of modules M to be installed on link e for normal capacity of the IP/MPLS layer (non-negative integral).

$\underline{y}_e$: Protection capacity on link e.

w_{gk}: Number of modules U_k to be installed on link g in the OTN layer (non-negative integral).

$\underline{w}_{gk}$: Protection capacity of link g (non-negative integral).

w'_{gk}: Number of modules U_k to be installed on link g in the OTN layer for realizing IP/MPLS layer protection capacity (non-negative integral).

c_{gkr}: flow restoring normal capacity of interface k of link g on restoration path r.

u_{gkr}: binary flow variable associated with c_{gkr}.

DWDM flow realizing OTN protection capacity:

$$\sum_{v=1}^{V_g} s'_{gkv} = \underline{w}_{gk} \qquad g = 1, 2, ..., G \;\; k = 0, 1, 2, 3, 4 \tag{11.13}$$

DWDM flow realizing OTN capacity that realizes IP/MPLS protection capacity:

$$\sum_{v=1}^{V_g} \overline{s}_{gkv} = w'_{gk} \qquad g = 1, 2, ..., G \;\; k = 0, 1, 2, 3, 4 \tag{11.14}$$

DWDM normal capacity feasibility:

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z}^{Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f \qquad f = 1, 2, ..., F \tag{11.15}$$

DWDM protection capacity feasibility:

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \theta_{fgz} s_{gkz} \leq N \underline{b}_f \qquad f = 1, 2, ..., F \tag{11.16}$$

Table 26: List of Notations (P4 Variables) 2

Variables:
s_{gkz}: DWDM flow allocated to path pair z ($\mathbb{Z}_g$, $\mathbb{A}_g$) realizing normal capacity of link g of interface k (non-negative integral).
s'_{gkv}: DWDM flow allocated to path v realizing protection capacity of link g of interface k (non-negative integral).
$\overline{s}_{gkv}$: DWDM flow allocated to path v realizing OTN capacity of link g of interface k that realizes protection capacity of the IP/MPLS layer (non-negative integral).
b_f: Number of modules N to be installed on link f in the DWDM layer (non-negative integral).
$\underline{b}_f$: Protection capacity on link f in the DWDM layer (non-negative integral).
b'_f: Number of modules N to be installed on link f in the DWDM layer for realizing OTN layer protection capacity (non-negative integral).
b''_f: Number of modules N to be installed on link f in the DWDM layer for realizing OTN capacity that realizes IP/MPLS layer protection capacity (non-negative integral).

DWDM capacity feasibility of OTN protection capacity:

$$\sum_{g=1}^{G}\sum_{k=0}^{4} U_k \sum_{v=1}^{V_g} \pi_{fgv} s'_{gkv} \leq N b'_f \qquad f = 1, 2, ..., F \tag{11.17}$$

DWDM capacity feasibility of OTN capacity that realizes IP/MPLS protection capacity:

$$\sum_{g=1}^{G}\sum_{k=0}^{4} U_k \sum_{v=1}^{V_g} \pi_{fgv} \overline{s}_{gkv} \leq N b''_f \qquad f = 1, 2, ..., F \tag{11.18}$$

In this architecture, we assume that an IP demand d can be carried over a single pair of primary and protection paths ("pp-path-pair") out of the set of candidate pairs of paths P_d. We define x_{dp} as a binary decision variable for selection of a pp-path-pair for demand d. This can be expressed as in constraints (11.1). Constraints (11.2) are the capacity feasibility constraints of the normal flows routed on link e where M is the allowable granularity of each MPLS tunnel. Here, δ_{edp} determines if link e belongs to the primary path $\mathbb{P}_{dp}$ carrying the normal flow of demand d. Protection in the IP/MPLS layer is achieved using a hot-standby path for each primary path. Constraints (11.3) are the capacity feasibility constraints of the protection flows on link e. Here, μ_{edp} determines if link e belongs to the protection path $\mathbb{R}_{dp}$ that protects the primary path $\mathbb{P}_{dp}$. Constraints (11.4) are the demand constraints that specify how the normal 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. Similarly, Constraints (11.5) are the demand constraints of the protection capacity of the IP/MPLS layer.

The OTN layer normal capacity feasibility constraints are expressed in (11.6). These constraints assure that all normal flows routed on each OTN layer link g do not exceed their capacity that is allocated in modules of sizes U_k that represent the five modular interfaces of OTN. Likewise, constraints (11.7) are the OTN layer protection capacity feasibility constraints.

Protection in the OTN layer is achieved using a link restoration on a single path. Constraints (11.8)–(11.11) assure that only normal capacity of each link g can be restored using only the protection capacity of the remaining links $l(l \neq g)$ on a single restoration path r. Note that we avoid double protection of the IP/MPLS spare capacity by protecting only the capacity w_{gk} required for m_{eq} flow of the IP/MPLS normal capacity y_e. Note that constrains (11.8) to (11.10) force that $c_{gkr} = u_{gkr}w_{gk}$, but the right-hand side cannot be used directly in the formulation because it is a term containing a multiplication of two variables. Also, constraints (11.11) assure that normal capacity of each OTN interface k can be restored using only the protection capacity of the remaining links $l(l \neq g)$.

Constraints (11.12) and (11.13) are the OTN over DWDM demand constraints for the normal, and protection capacity, respectively. They specify how the capacity of each OTN layer interface k of link g is realized by means of flow allocated to its candidate paths from the routing list in the DWDM layer. Note that we separated the normal capacity w_{gk} from spare capacity $\underline{w}_{gk}$ to avoid protecting the OTN signals twice, once in the OTN layer and once in the DWDM layer. Constrains (11.14) are the OTN over DWDM demand constraints for the OTN capacity required to realize the IP/MPLS protection capacity.

Protection in the DWDM layer is achieved using fixed back-up paths. Constraints (11.15) to (11.18) are the DWDM layer capacity feasibility constraints. They assure that the capacity of each physical link f 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 wavelength capacity, and b_f would be the normal number of wavelengths to be installed on link f. At this layer, we have four capacity components: b_f for the normal DWDM layer capacity, $\underline{b}_f$ for the protection capacity, b'_f for the capacity required to realize the OTN protection capacity, and b''_f for the capacity required to realize the OTN capacity that realizes the IP/MPLS protection capacity. Figure 66 shows all capacity components at each layer.

11.2.2 Objective and Cost Model

The goal in our design Model (**P4**) is to minimize the total network planning cost of the normal and protection capacity. The objective is given by:

$$\begin{aligned}\mathcal{F} = \sum_{e=1}^{E} \eta_e(y_e + \underline{y}_e) + \sum_{g=1}^{G}\sum_{k=0}^{4} \beta_{gk}(w_{gk} + w'_{gk} + \underline{w}_{gk}) \\ + \sum_{f=1}^{F} \xi_f(b_f + b'_f + \underline{b}_f + b''_f)\end{aligned} \tag{11.19}$$

This objective function captures the total cost of network resources over all three layers generically, where η_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 67. An advantage of our cost structure model is that this allows to consider a number of different cost combinations that are helpful in understanding inter-layer interactions.

For the IP/MPLS layer, η_e is the unit cost of link e; this is defined as the sum of the interface cost for the upper layer η_e^U and the lower layer η_e^L ends of the connection between the IP/MPLS layer node and the OTN layer node, i.e., $\eta_e = 2\eta_e^U + 2\eta_e^L$, 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 the U_k signal on link g, β_g^U, plus the cost of multiplexing OTN signals β_g^k, i.e., $\beta_{gk} = 2\beta_g^U + 2\beta_g^k$.

For the 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 ξ_f^I, the optical transponders cost ξ_f^t, the OXC ports ξ_f^o, plus a physical link distance cost Δ_f, i.e., $\xi_f = 2(\xi_f^I + \xi_f^t + \xi_f^o) + \Delta_f$.

The capacity (Normal and Protection) optimization problem (**P4**) for the IP/MPLS-over-OTN-over-DWDM multilayer is to minimize the cost $\mathcal{F}$ given by (11.19) subject to the set of constraints (11.1)–(11.18), with variables as defined in Tables 25 and 26.

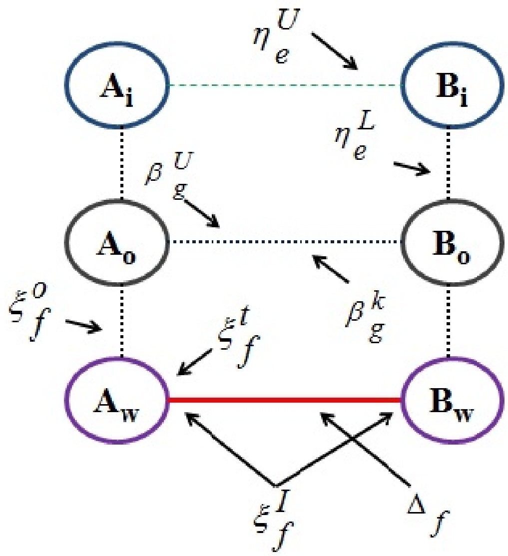


Figure 67: Cost Structure of The Three-Layer Network

11.3 A Three-Phase Solution Approach

Model (**P4**) has a large number of discrete variables and constraints. The number of variables is $P \times D + 2(E(1+Q)) + 8G(1+R) + 12GZ + 4F$, where P denotes the average number of paths for each demand d, and the number of constraints is $D + 4(E + GR + F + G^2) + 22G$. Furthermore, the problem is NP-hard, since simpler forms of network design problems, such as the single-path flow allocation or modular link design, are shown to be NP-hard [38]. It is extremely difficult to solve problem (**P4**) using an ILP solver such as CPLEX even for a small size network. We note, however, that if we decompose the problem into three subproblems, then we can solve the problem for moderate size networks taking a phased approach. Therefore, we solve problem (**P4**) in three phases as follows:

Phase 1: Solve the following design problem:

$$\text{Minimize} \sum_{e=1}^{E} \eta_e(y_e + \underline{y}_e) + \sum_{g=1}^{G}\sum_{k=0}^{4} \beta_{gk}(w_{gk} + w'_{gk}) \tag{11.20}$$

subject to the set of constraints (11.1)–(11.7). Then, w_{gk} will be a constant in the phase 2.

Phase 2: Solve the following design problem:

$$\text{Minimize} \sum_{g=1}^{G}\sum_{k=0}^{4} \beta_{gk}\underline{w}_{gk} + \sum_{f=1}^{F} \xi_f b'_f \tag{11.21}$$

subject to the set of constraints (11.8)–(11.11), (11.13), and (11.17).

Phase 3: Solve the following design problem:

$$\text{Minimize} \sum_{f=1}^{F} \xi_f(b_f + \underline{b}_f + b''_f) \tag{11.22}$$

subject to the set of constraints (11.12), (11.14)–(11.16), and (11.18). Note that w_{gk} and w'_{gk} are constant to this phase made by solving phase 1.

Figure 68 shows the phases of the solution. Note that even by breaking the original problem into three subproblems, each one of the them is still NP-hard on its own. We have managed to reduce the magnitude of its complexity but it is still hard to solve for large networks.

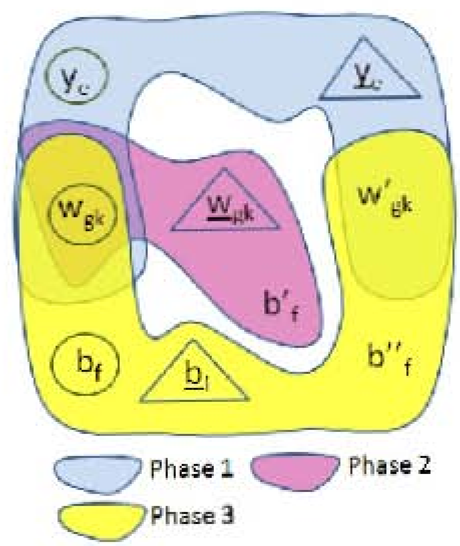


Figure 68: Phases of the Solution Approach

CHAPTER 12

STUDY AND RESULTS FOR (P4)

12.1 Study Environment

In the formulation of problem (**P4**), η_e is defined as the cost of one unit of module M of the IP/MPLS layer link e. In our study, this is also referred to as the IP-cost. Likewise, β_{gk} is the cost of one capacity unit of module type U_k of the OTN layer link g. We refer to this cost as the U_k-cost for ($k = 0, 1, 2, 3, 4$). 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 W-cost.

According to [6], 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 photopic OXC port, respectively. Based on our cost model in Section 11.2.2, 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 plus a physical distance cost; we assume this is a fixed cost of 66. This means when the IP/MPLS layer cost is 3, the DWDM cost is 84. We transform this value so that 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. Specifically, for the

IP-cost we vary the cost starting from IP-cost$= 5$ and double the cost to IP-cost$= 10$, 20, and 40 to study the impact of different IP-cost scenarios while the W-cost is fixed.

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

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

To represent them, we consider the following U_k 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 U_ks are not as important as the relationships between them. Note that we avoid unrealistic U_k cost relationships such as when U_k = U_{k+1} or when $4U_k$ = U_{k+1}. The former indicates an equal cost of two different OTN units, and the latter follows one of the signal multiplexing rules we explained in Chapter 3. We summarize each layer's cost values in Table 27.

Table 27: Summary of Cost Values for Each Layer.

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 (ξ_f)	140

The experiments we conducted for this study with various parameter values allowed us to examine the impact of each layer cost and IP/MPLS modularity on other layers and ultimately the overall network cost. We wish to answer a number of questions.

For instance, how do the IP-cost and the size of M influence the required protection capacity at each layer and the overall network cost? How does the cost of each U_k scenario affect the final types and numbers of U_ks needed to satisfy a given set of demands?

In this work, we study the 14-node NSFNET topology in the three-layer setting. In our three-layer case, the NSFNET is considered as 14 nodes in *each layer* that results in 42 total nodes, and the number of physical fiber links F is 21. We assume that the virtual topologies of the IP/MPLS and OTN layers follow the connectivity of the physical layer, hence $E = G = 21$ resulting in 63 total links. The total number of demands is 91 bidirectional demands assuming a demand between every LSRs pair where the average demand 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 the network. Demands between the LSRs in the network are generated according to the demand model described in Section 6.2. For each demand, five primary paths and five protection paths are available at each layer. Figure 69 shows the multilayer design of NSFNET when IP-cost=5, M=2.5 Gbps, and the Uk-cost is UK-cr1 using our phased design approach. Here, a black link indicates that all capacity components of the layer are present on the link. If not a black link at the OTN layer, we use a blue dashed link to indicate the normal capacity, a green dashed link for the protection capacity, and a red dashed link for the capacity that realizes the IP/MPLS protection capacity. At the DWDM layer, we use the same colors to relate this layer's capacity with the OTN capacity components except that the orange dashed link is used for the DWDM layer protection capacity.

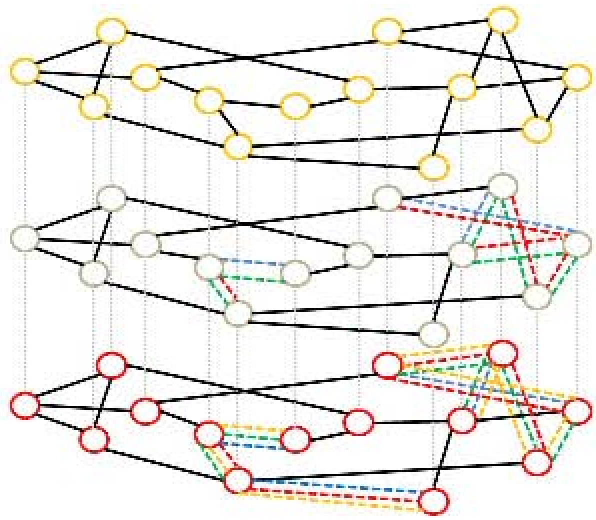


Figure 69: 14-node per Layer Protected NSFNET Design

All results are close-to-optimal derived by solving the three phases of problem (**P4**) as described in Section 11.3 using the CPLEX 12.2 optimization package where we limit the number of nodes to be visited in the branch and cut tree to 500,000 by declaring `set mip limits nodes 500000`.

Table 28: Notation and Abbreviation Mapping.

Notation	Abbreviation	Discreption
y_e	N-IP	Normal IP capacity
$\underline{y}_e$	P-IP	Protection IP capacity
w_{gk}	N-OTN	Normal OTN capacity
$\underline{w}_{gk}$	P-OTN	Protection OTN capacity
w'_{gk}	P-IP-OTN	OTN capacity of P-IP
b_f	N-W	Normal fiber capacity
$\underline{b}_f$	P-W	Protection fiber capacity
b'_f	P-OTN-W	Fiber capacity of P-OTN
b''_f	P-IP-OTN-W	Fiber capacity of P-IP-OTN

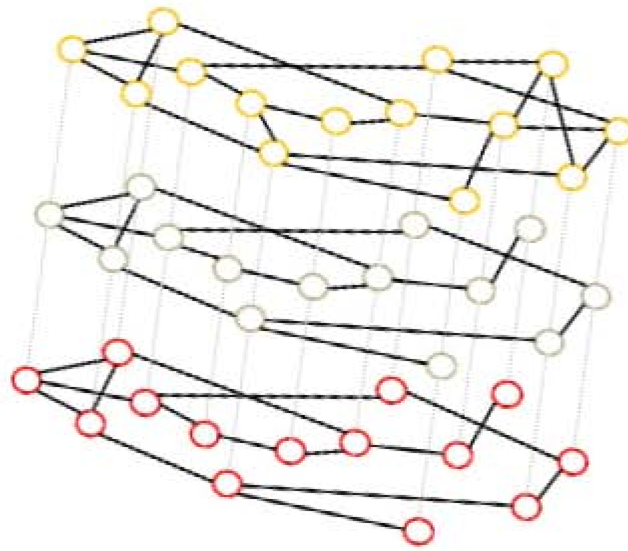


Figure 70: 14-node per Layer Unprotected NSFNET Design

12.2 Illustrative Numerical Results

12.2.1 Unprotected vs. Protected Network

To make it easier to follow the results, we present Table 28 that maps each capacity notation in the formulation to an abbreviation. Using our phased design approach, we run the same scenario of Figure 69 but with no protection components. That is, only y_e, w_{gk}, and b_f are present for the normal capacity of the IP/MPLS, OTN, and DWDM layers, respectively.

Figure 70 shows the unprotected multilayer design of NSFNET when IP-cost=5, M=2.5 Gbps, and the Uk-cost is UK-cr1. By comparing the results of the unprotected and protected networks, we observe that the N-IP cost and bandwidth are identical in both cases. N-OTN and N-W costs and bandwidths are very close. Table 29 presents the results of both networks.

Table 29: Unprotected vs. Protected NSFNET.

Cost	Unprotected NSF	Protected NSF
N-IP	2025	2025
P-IP	-	4825
N-OTN	824	820
P-OTN	-	1556
P-IP-OTN	-	1812
N-W	3920	4060
P-W	-	21280
P-OTN-W	-	7000
P-IP-OTN-W	-	8400
Total	6769	51778

12.2.2 Total Network Cost

Figure 71 shows the total network cost for each considered scenario. We observe that when the IP-cost is fixed, M=2.5 is more expensive than M=5 which is also more expensive than M=10. This is because as we fix the IP-cost, the larger the M the more demands it can satisfy without increasing the cost. We also observe the cost increase as we increase the IP-cost from 5 to 40. By observing the effects of M and its cost, we note that both are essential to be considered jointly in multilayer networks. For instance, the cost of the case when IP=20 and M=2.5 is higher than when IP=40 and M=10. This is simply comparing the costs per Gbps (8 vs. 4). However, not only the cost per Gbps is important to consider but also the size of M as this parameter will impact the lower layers. Obviously when M and the IP-cost are fixed, the case of UK-cr3 is the most expensive followed by UK-cr2 and UK-cr1. This is because the gap between the U_k-cost is the largest in UK-cr3. Moreover, the cost gap between UK-cr3 and UK-cr2 is larger than between UK-cr2 and UK-cr1. We will explain the reason in Section 12.2.5.

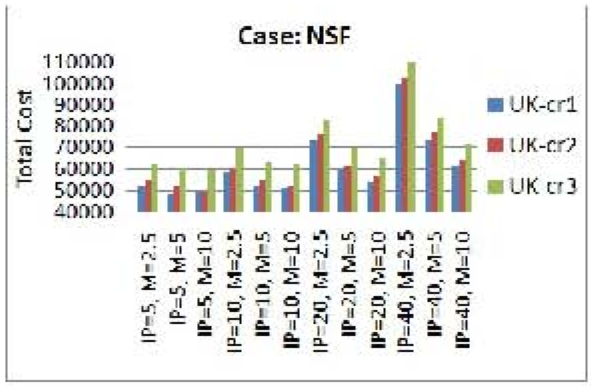


Figure 71: Total Network Cost

12.2.3 Capacity of Different Components

Figure 72 shows the capacity required for each component when the IP-cost=5 and UK-cr1. We note that the protection capacity of each layer is larger than its normal capacity. Furthermore, the gap between the normal capacity and its protection capacity is increased as we go down in the network's layers. That is, the gap between N-IP and P-IP is less than the gap between the N-OTN and P-OTN, which is also less than the gap between N-W and P-W. This is primarily due to the larger granularity of the lower layers and the longer the protection paths. The gap is the largest in the DWDM layer where each wavelength bit rate N=100 Gbps (compared to M=2.5, 5, or 10 Gbps for the IP/MPLS layer) and the protection paths are usually longer than the primary paths. We note the same trends for different IP-cost and UK-cost scenarios but figures are not shown due to space limitation.

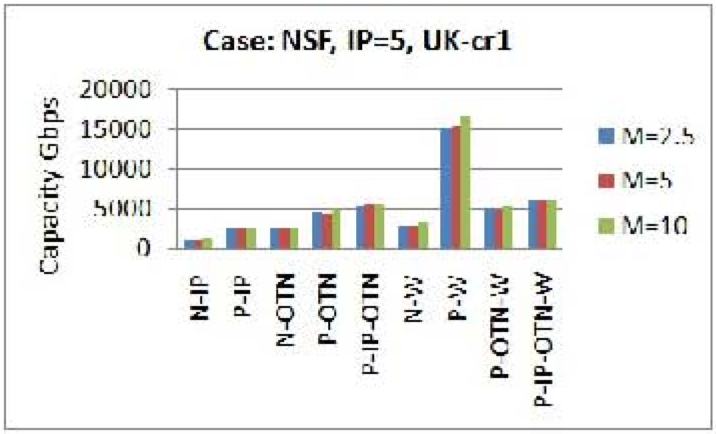


Figure 72: Capacity of Different Components when IP=5 and UK-cr1

12.2.4 Protection Capacity

In this section, we present the protection capacity required for each individual layer. Figure 73 depicts the required P-IP for each scenario. We observe that the cases when M=10 requires more protection capacity than when M=2.5 and 5. M=2.5 is the best case to minimize P-IP. An interesting observation is that the IP-cost is not a significant factor when the M=2.5. Increasing the IP-cost when M=2.5 does not significantly change the required capacity. This is unlike the case when the impact of the IP-cost is noticeable in M=10 scenarios.

Figure 74 depicts the required P-OTN for each scenario. In this capacity component, the smallest required protection capacity is usually achieved under UK-cr3 and the largest is under UK-cr2. Moreover, the case when M=2.5 is often the case that minimizes P-OTN. This suggests that when M is below the average demand, it is often the best case to minimize the required protection capacity at the OTN layer.

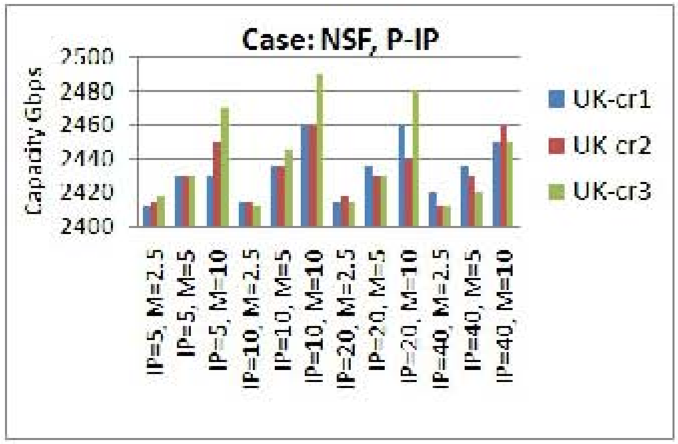


Figure 73: Protection Capacity of the IP/MPLS Layer

Figure 75 shows the required P-W under different scenarios. We note that UK-cr3 is the best case to minimize this capacity component along with M=2.5. The largest capacity is required under UK-cr1 and M=10.

12.2.5 No. of OTN Signals for P-OTN

Figure 76 shows the OTN layer U_k signals required in the P-OTN component. We observe that in UK-cr3 scenarios, only U_0 and U_3 are used. This is because the cost of 2 U_3s is less than the cost of a U_4. And since 2 U_3s take only 80 Gbps of the wavelength, the rest is filled with U_0s. We observe that U_4 is used in UK-cr2 but with fewer numbers than U_3. It is only in UK-cr1 that U_4 becomes higher than U_3 due to the small gap between their costs. We also observe the low numbers of U_1s and U_2s in all cases suggesting their limited benefits in these scenarios. That is, the IP/MPLS demands will largely be served by U_0s and U_3s under UK-cr3 or a mix of U_4, U_3, with very low numbers of U_0s, U_1s, and U_2s,under UK-cr1 and UK-cr2.

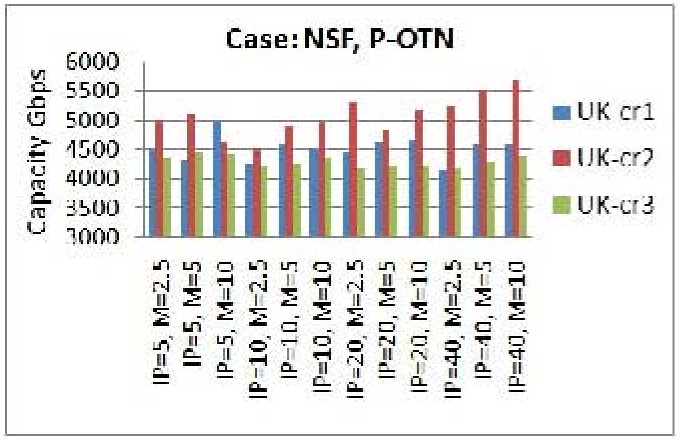


Figure 74: Protection Capacity of the OTN Layer

The same general trends can be observed when varying the IP-cost or for different OTN capacity components. However, the numbers of U_ks in P-OTN are higher than those in N-OTN which explains the larger capacity required for P-OTN as shown in Figure 72. We stated in Section 12.2.2 that the cost gap between UK-cr3 and UK-cr2 is larger than between UK-cr2 and UK-cr1. This is because of the costs of the U_ks used in each U_k-cost scenario. Consider this example, if we want to consume the full capacity of an OTN link (100 Gbps) under UK-cr1, then the optimal solution would be to use 1 U_4, which costs 32. Under UK-cr2, the optimal solution would also be 1 U_4 which costs 50. In UK-cr3, $U4$ is not the optimal solution since $2U_3 + 16U_0 = 140 < 162$, the cost of a U_4. We note that the gap between UK-cr1 and UK-cr2 in this example is ($50 - 32 = 18$, or about a 56% increase). on the other hand, the gap between UK-cr2 and UK-cr3 is ($140 - 50 = 90$, or about a 180% increase).

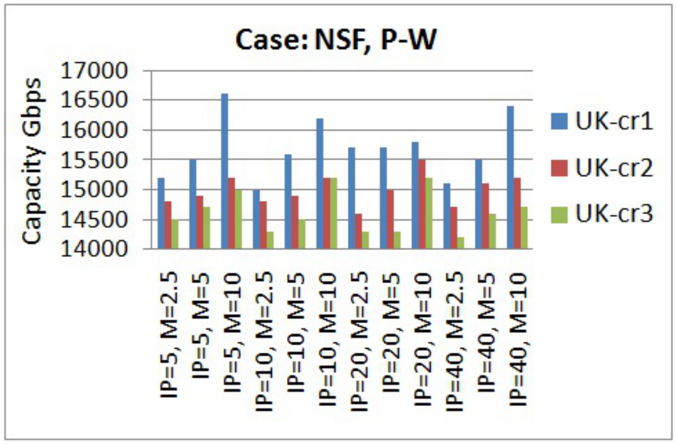


Figure 75: Protection Capacity of the DWDM Layer

12.2.6 Cost vs. Protection Capacity

We mentioned in Section 12.2.2 that the case when M=10 achieves the lowest overall network cost performance when the IP-cost is fixed. This may seem contradictory to the observations pointed out in Section 12.2.4 that more capacity is often required for protection when M=10 leads to more cost for protection. However, it is important to note that the overall network cost is determined by all capacity components not just the protection components. More important, the cost per Gbps plays a significant role in the IP/MPLS layer. To illustrate, when the IP-cost=40, the costs per Gbps are 16 and 4 for the cases M= 2.5 and 10, respectively. To carry a 10 Gbps demand on a link, 4 Ms are required when M=2.5 is clearly more expensive than 1 M required when M=10. From a cost perspective, the higher the size of M, the better. However, if we look from a capacity standpoint, a higher size of M implies more capacity needed at each layer.

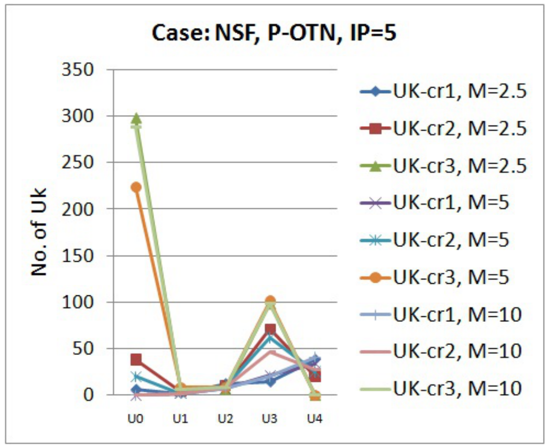


Figure 76: No. of U_ks of P-OTN OTN Layer Components When IP=5

12.3 Summary and Future Work

In this Chapter we presented a network protection design model for a IP/MPLS over OTN over DWDM three-layer network. In this architecture, we explicitly considered the OTN layer as a distinct layer with its own technological constraints. The survivability design provides protection only for the normal capacity of each layer to reduce the protection resources while maximizing the protection. We present a heuristic solution to the problem by solving it in three phases to reduce the complexity of the problem in order to solve it for moderate size networks.

We next presented a study based on various network parameters to understand their effects especially on the protection capacity and overall cost. We find that even though the case when M=10 (above the average demand) would be the best case to reduce the overall network cost, it is often the one that requires more protection capacity. The case when M=2.5 (below the average demand) would achieve the lowest amount of capacity needed for protection at each layer. We observed that the protection capacity of each layer is larger than its normal capacity, noticeably at the lowest layer (DWDM layer), due to the longer protection paths and the larger granularity of this layer. We also noted the limited usage of OTN layer U_1 and U_2 signals. Mainly, the IP/MPLS demands will be accommodated by U_0s and U_3s under UK-cr3 or a mix of U_4, U_3, with very low numbers of U_0s, U_1s, or U_2s, under UK-cr1 and UK-cr2.

For future work, we plan to expand our study by developing a heuristic algorithm to solve the problem for large size networks and provide an extensive analysis. We also would like to consider other protection mechanisms and compare their performance under the three-layer architecture.

CHAPTER 13

CONCLUSION AND FUTURE WORK

13.1 Summary

In this dissertation, we have considered four related problems in IP/MPLS over OTN over DWDM multilayer networks. These are: the capacity design problem, the IP/MPLS and OTN layers interrelation, the optimization of node capacity, and the survivability design. We have presented the optimization models, heuristic algorithms, and studies and analyses for the problems considered.

A principal contribution in this work is that the OTN sublayer technological constraints are explicitly considered. We have also defined comprehensive cost models that cover a broad set of cost components in each layer in the network. Because of the way we define the cost structure at the OTN layer, we were able to significantly reduce the number of constraints of each OTN signal quantum and consider them jointly. Moreover, we have addressed the modularity of each layer and proposed a heuristic algorithm based on the notion of the multilayer shortest path to solve the problem for large size networks.

Label switched routers (LSRs) are 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 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 is based on the separation of the capacity components of each layer to provide protection to the normal traffic and hence avoid double or triple protection in the three-layer networks.

Based on our cost models, we have presented extensive studies through various costs and network parameters values. 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.

Our analysis shows that our heuristic is efficient in most cases especially when 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 in the best overall network performance. However, this case is often the worst case if the goal is to consider either the OTN or DWDM layer cost separately. We have also noted the impact of the OTN signals cost and relationship on the final numbers of required 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, not the cost of that capacity. We have seen that there are three factors that have evident effects on the OTN layer signals. These are: the size of the IP/MPLS layer capacity module, the cost relationship of the OTN signals, and the demand volumes.

13.2 Limitations

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 are given. 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 lightpath allowed.

Another 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 focus in this research on the capacity design and believe that those are 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. That is, once we know the available capacity of the DWDM layer, we can then solve the allocation problems and determine where to place the wavelength converters or how the wavelengths are assigned per lightpath. We have done some work in the past in [25] and [27] that consider the wavelength continuity constraints and the wavelength converter placement for the reconfigurable optical WDM layer.

13.3 Lessons Learned

Through extensive experiments conducted in this research with varying network parameters and costs, we have learned some fundamental lessons. These are as follows:

- What works good for a particular layer maybe in conflict with the ultimate goal.
- Be economical even when resources are inexpensive.
- Demand volume is an important factor in resource usage (e.g. OTN signals).
- IP layer plays a decisive role in multilayer networks.
- Cost and Capacity: different perspectives.

13.4 Future Work

We plan to continue to investigate multilayer networks and emerging technologies. This will benefit future communication networks by creating more efficient and resilient network designs, deployment, and operations. We particularly plan to: (1) consider load balancing in the IP layer and the optical layer, while minimizing the cost of the overall network, and (2) consider the effects of the dynamic demand of the IP/MPLS layer and reconfigurability of the optical layer on the network performance.

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 consumption, and leading to less CO_2 emission.

APPENDIX A

SAMPLE INPUT/OUTPUT FILES

All sample input/output files are based on a partially connected 7-node per layer network.

Sample Parameters File

This file specifies the input parameters to the heuristic. It has the following format: Version 0.1

LINKFILE 7nodeLink.dat

DEMANDFILE 7nodeDemand.dat

SORTDEMAND YES

WAVELENGTHPERFIBER 10

KSHORTESTPATH 4 PRINTPATHS

MPLSCAPACITY 10000

IPCOST 5

FIBERCOST 140

U1COST 4

U2COST 8

U3COST 16

Sample Link File

This file specifies the topology considered. Each entry has the following format: Link ID, Link Type, Source Node ID, Source Node Name, Source Node Type, Destination Node ID, Destination Node Name, Destination Node Type, Capacity of the Link, Link Cost.

Version 0.1

0 IP-I 0 I0 IP-MPLS 7 O7 OTN 0 80000 0

1 IP-I 1 I1 IP-MPLS 8 O8 OTN 0 80000 0

2 IP-I 2 I2 IP-MPLS 9 O9 OTN 0 80000 0

3 IP-I 3 I3 IP-MPLS 10 O10 OTN 0 80000 0

4 IP-I 4 I4 IP-MPLS 11 O11 OTN 0 80000 0

5 IP-I 5 I5 IP-MPLS 12 O12 OTN 0 80000 0

6 IP-I 6 I6 IP-MPLS 13 O13 OTN 0 80000 0

7 OTN-I 7 O7 OTN 14 W14 OXC 0 80000 0

8 OTN-I 8 O8 OTN 15 W15 OXC 0 80000 0

9 OTN-I 9 O9 OTN 16 W16 OXC 0 80000 0

10 OTN-I 10 O10 OTN 17 W17 OXC 0 80000 0

11 OTN-I 11 O11 OTN 18 W18 OXC 0 80000 0

12 OTN-I 12 O12 OTN 19 W19 OXC 0 80000 0

13 OTN-I 13 O13 OTN 20 W20 OXC 0 80000 0

14 Fiber 14 W14 OXC 20 W20 OXC 3 40000 0

15 Fiber 14 W14 OXC 16 W16 OXC 3 40000 0

16 Fiber 15 W15 OXC 16 W16 OXC 3 40000 0

17 Fiber 15 W15 OXC 17 W17 OXC 3 40000 0

18 Fiber 15 W15 OXC 19 W19 OXC 3 40000 0

19 Fiber 15 W15 OXC 20 W20 OXC 3 40000 0

20 Fiber 16 W16 OXC 18 W18 OXC 3 40000 0

21 Fiber 17 W17 OXC 19 W19 OXC 3 40000 0

22 Fiber 18 W18 OXC 20 W20 OXC 3 40000 0

Sample Demand File

In this input demand file, each entry has the following format: Pair, ON, Source Node ID, Destination Node ID, Service Type, Demand Volume. Note that currently Service Type is not used.

Version 0.1

Pair ON 1 2 S1 17500

Pair ON 0 2 S1 15800

Pair ON 2 6 S1 15100

Pair ON 1 3 S1 13300

Pair ON 1 6 S1 11900

Pair ON 3 4 S1 11100

Pair ON 0 6 S1 10800

Pair ON 4 6 S1 10800

Pair ON 3 6 S1 9900

Pair ON 3 5 S1 8700

Pair ON 2 3 S1 8500

Pair ON 0 1 S1 5700

Pair ON 2 4 S1 5200

Pair ON 1 4 S1 5100

Pair ON 0 3 S1 4000

Pair ON 1 5 S1 3200

Pair ON 0 4 S1 2700

Pair ON 2 5 S1 1800

Pair ON 5 6 S1 1700

Pair ON 4 5 S1 1600

Pair ON 0 5 S1 800

Sample Output File

Multilayer Network simulation version 0.1

Total wavelengths: 90

Used wavelengths: 13

Wavelength utilization: 14 %

No. of Lightpath: 12

DWDM cost: 1820

OTN usage:

U1: 0 U2: 5 U3: 8

OTN cost: 168

IP/MPLS capacity units: 32 cost: 160

Total Model cost: 2148

Links (IP/MPLS, OTN, DWDM) after running the algorithm:

Link(14) Src 14 Dst 20 Link Type Fiber Initial Capacity 10 Current Capacity 9 Link Utilization 10

Link(15) Src 14 Dst 16 Link Type Fiber Initial Capacity 10 Current Capacity 7 Link Utilization 30

Link(16) Src 15 Dst 16 Link Type Fiber Initial Capacity 10 Current Capacity 8 Link Utilization 20

Link(17) Src 15 Dst 17 Link Type Fiber Initial Capacity 10 Current Capacity 8 Link Utilization 20

Link(18) Src 15 Dst 19 Link Type Fiber Initial Capacity 10 Current Capacity 10 Link Utilization 0

Link(19) Src 15 Dst 20 Link Type Fiber Initial Capacity 10 Current Capacity 8 Link Utilization 20

Link(20) Src 16 Dst 18 Link Type Fiber Initial Capacity 10 Current Capacity 9 Link Utilization 10

Link(21) Src 17 Dst 19 Link Type Fiber Initial Capacity 10 Current Capacity 9 Link Utilization 10

Link(22) Src 18 Dst 20 Link Type Fiber Initial Capacity 10 Current Capacity 9 Link Utilization 10

Link(23) Src 8 Dst 9 Link Type LightPath Initial Capacity 40000 Current Capacity 0 Link Utilization 100

Link(24) Src 1 Dst 2 Link Type MPLS Total Capacity 40000 Current Capacity 2900 Link Utilization 92

Link(25) Src 7 Dst 9 Link Type LightPath Initial Capacity 40000 Current Capacity 0 Link Utilization 100

Link(26) Src 0 Dst 2 Link Type MPLS Total Capacity 40000 Current Capacity 9100 Link Utilization 77

Link(27) Src 7 Dst 13 Link Type LightPath Initial Capacity 40000 Current Capacity 0 Link Utilization 100

Link(28) Src 0 Dst 6 Link Type MPLS Total Capacity 40000 Current Capacity 8400 Link Utilization 79

Link(29) Src 8 Dst 10 Link Type LightPath Initial Capacity 40000 Current Capacity 0 Link Utilization 100

Link(30) Src 1 Dst 3 Link Type MPLS Total Capacity 40000 Current Capacity 5700 Link Utilization 85

Link(31) Src 8 Dst 13 Link Type LightPath Initial Capacity 40000 Current Capacity 0 Link Utilization 100

Link(32) Src 1 Dst 6 Link Type MPLS Total Capacity 40000 Current Capacity 7400 Link Utilization 81

Link(33) Src 9 Dst 11 Link Type LightPath Initial Capacity 40000 Current Capacity 20000 Link Utilization 50

Link(34) Src 2 Dst 4 Link Type MPLS Total Capacity 20000 Current Capacity 1000 Link Utilization 95

Link(35) Src 11 Dst 13 Link Type LightPath Initial Capacity 40000 Current Capacity 20000 Link Utilization 50

Link(36) Src 4 Dst 6 Link Type MPLS Total Capacity 20000 Current Capacity 2500 Link Utilization 87

Link(37) Src 10 Dst 12 Link Type LightPath Initial Capacity 40000 Current Capacity 20000 Link Utilization 50

Link(38) Src 3 Dst 5 Link Type MPLS Total Capacity 20000 Current Capacity 2200 Link Utilization 89

Link(39) Src 8 Dst 10 Link Type LightPath Initial Capacity 40000 Current Capacity 10000 Link Utilization 75

Link(40) Src 1 Dst 3 Link Type MPLS Total Capacity 30000 Current Capacity 8400 Link Utilization 72

Link(41) Src 7 Dst 8 Link Type LightPath Initial Capacity 40000 Current Capacity 30000 Link Utilization 25

Link(42) Src 0 Dst 1 Link Type MPLS Total Capacity 10000 Current Capacity 3400 Link Utilization 66

Link(43) Src 7 Dst 9 Link Type LightPath Initial Capacity 40000 Current Capacity 30000 Link Utilization 25

Link(44) Src 0 Dst 2 Link Type MPLS Total Capacity 10000 Current Capacity 5500 Link Utilization 45

Link(45) Src 8 Dst 13 Link Type LightPath Initial Capacity 40000 Current Capacity 30000 Link Utilization 25

Link(46) Src 1 Dst 6 Link Type MPLS Total Capacity 10000 Current Capacity 6700 Link Utilization 33

Total Demand: 21 Bandwidth: 165200 Demand Satisfied: 165200 100

Demand(0) Src 1 Dst 2 Bandwidth 17500

Path Taken:

Links(1 [IP-I], 8 [OTN-I], 16 [Fiber], 9 [OTN-I], 2 [IP-I])

Demand(1) Src 0 Dst 2 Bandwidth 15800

Path Taken:

Links(0 [IP-I], 7 [OTN-I], 15 [Fiber], 9 [OTN-I], 2 [IP-I])

Demand(2) Src 2 Dst 6 Bandwidth 15100

Path Taken:

Links(26 [MPLS], 0 [IP-I], 7 [OTN-I], 14 [Fiber], 13 [OTN-I], 6 [IP-I])

Demand(3) Src 1 Dst 3 Bandwidth 13300

Path Taken:

Links(1 [IP-I], 8 [OTN-I], 17 [Fiber], 10 [OTN-I], 3 [IP-I])

Demand(4) Src 1 Dst 6 Bandwidth 11900

Path Taken:

Links(1 [IP-I], 8 [OTN-I], 19 [Fiber], 13 [OTN-I], 6 [IP-I])

Demand(5) Src 3 Dst 4 Bandwidth 11100

Path Taken:

Links(30 [MPLS], 24 [MPLS], 2 [IP-I], 9 [OTN-I], 20 [Fiber], 11 [OTN-I], 4 [IP-I])

Demand(6) Src 0 Dst 6 Bandwidth 10800

Path Taken:

Links(28 [MPLS])

Demand(7) Src 4 Dst 6 Bandwidth 10800

Path Taken:

Links(4 [IP-I], 11 [OTN-I], 22 [Fiber], 13 [OTN-I], 6 [IP-I])

Demand(8) Src 3 Dst 6 Bandwidth 9900

Path Taken:

Links(30 [MPLS], 32 [MPLS])

Demand(9) Src 3 Dst 5 Bandwidth 8700

Path Taken:

Links(3 [IP-I], 10 [OTN-I], 21 [Fiber], 12 [OTN-I], 5 [IP-I])

Demand(10) Src 2 Dst 3 Bandwidth 8500

Path Taken:

Links(24 [MPLS], 1 [IP-I], 8 [OTN-I], 17 [Fiber], 10 [OTN-I], 3 [IP-I])

Demand(11) Src 0 Dst 1 Bandwidth 5700

Path Taken:

Links(28 [MPLS], 32 [MPLS])

Demand(12) Src 2 Dst 4 Bandwidth 5200

Path Taken:

Links(34 [MPLS])

Demand(13) Src 1 Dst 4 Bandwidth 5100

Path Taken:

Links(32 [MPLS], 36 [MPLS])

Demand(14) Src 0 Dst 3 Bandwidth 4000

Path Taken:

Links(0 [IP-I], 7 [OTN-I], 15 [Fiber], 16 [Fiber], 8 [OTN-I], 1 [IP-I], 40 [MPLS])

Demand(15) Src 1 Dst 5 Bandwidth 3200

Path Taken:

Links(40 [MPLS], 38 [MPLS])

Demand(16) Src 0 Dst 4 Bandwidth 2700

Path Taken:

Links(0 [IP-I], 7 [OTN-I], 15 [Fiber], 9 [OTN-I], 2 [IP-I], 34 [MPLS])

Demand(17) Src 2 Dst 5 Bandwidth 1800

Path Taken:

Links(44 [MPLS], 42 [MPLS], 40 [MPLS], 38 [MPLS])

Demand(18) Src 5 Dst 6 Bandwidth 1700

Path Taken:

Links(38 [MPLS], 40 [MPLS], 1 [IP-I], 8 [OTN-I], 19 [Fiber], 13 [OTN-I], 6 [IP-I])

Demand(19) Src 4 Dst 5 Bandwidth 1600

Path Taken:

Links(36 [MPLS], 46 [MPLS], 40 [MPLS], 38 [MPLS])

Demand(20) Src 0 Dst 5 Bandwidth 800

Path Taken:

Links(42 [MPLS], 40 [MPLS], 38 [MPLS])

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