Comparison of Network Protection in three-layer IP/MPLS-over-OTN-over-DWDM Networks

Helder M. N. S. Oliveira[1], Iyad Katib[2], Nelson L. S. da Fonseca[1], and Deep Medhi[3]
[1]University of Campinas, Brazil [2] King Abdulaziz University, KSA, [3]University of Missouri-Kansas City, USA

***Abstract*—In multilayer networks, protection can be accomplished in any of the layers. However, which layer to protect most remains an important problem. In this paper, we consider a three-layer with IP/MPLS-over-OTN-over-DWDM in which we consider an optimization modeling framework incorporating modularization of its capacity for protection in any layer. Our resulting study, conducted on two topologies, shows that the cost ratio of different layers is an important factor in answering this question, as well as the actual modular values of the capacity used. Furthermore, we found that the cost providing protection in the OTN layer is highly influenced by the network connectivity.**

Keywords—Survivability, WDM Optical Network, Multilayer.

I. Introduction

Protection design for survivability of multilayer networks has been a topic of great interest for a long time. Most of the works so far have considered a two-layer network architecture such as an IP-over-WDM network. In a two-layer environment, an important question is: where should we provide the protection mechanism? This question was posed in [1] generating significant interests in the research community. If we consider protection at the upper layer, a network can recover fully from failure at either layer, although recovery time can be relatively slower compared to the lower layer [2]. On the other hand, if the protection is done at the lower layer, restoration is typically faster, although not all types of failures can be recovered from, such as from the failure of an upper layer node such as an IP router. Thus, it is generally understood that if the failures are of different types, then a protection mechanism at a particular layer may not address all such failure types.

While such comparisons are understandable, it still begs the question on how best a protection design is at any layer, if we consider the level playing field of failures that can be addressed by any layer. Considering this angle, we seek to answer the question: which layer would result in the most cost effective protection design, and how does the modularization of capacity and unit cost influence this choice? We seek to answer this question in a three-layer setting with IP/MPLS-over-OTN-over-DWDM. In this architecture, the label switched routers (LSRs) in the IP/MPLS layer are 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. There are a number of factors to consider in pursuing this question. How does the unit cost structure at each layer matter? Secondly, how does modularization of the capacity at each layer factor in, so to answer the posed question?

To our knowledge, this question has not been addressed for three-layered networks with modularized capacity. Our approach builds on an earlier work [2]. We adapt this model appropriately to answer our question on protection design at each layer separately.

This paper is organized as follows. Section II reviews related work. Section III reviews the model in [2] and adapt this formulation for our study. In Section IV, we consider the three independent protection models, catered to protection at each layer separately. In Section V, we evaluate the performance of the proposed models and Section VI concludes the paper.

II. Related Work

The existing literature is abundant with survivability mechanisms for two-layer networks; for example, see [3]–[6]. Fumagalli and Valcarenghi, in [1], reviewed 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.

The question on which layer to provide fault management in a two-layer IP/WDM setting was discussed in [7]. Kubilinskas and Pióro [8] also presented two design problems providing protection in either the WDM layer or the IP layer. Zhang and Durresi, in [9], investigated the necessity, methods, and advantages to coordinate multilayer survivability in the IP over WDM networks. Lei et al. in [10], and Qin et al. in [11], investigated and studied joint multilayer survivability in IP/WDM networks. In [12], Bigos et al. compared single layer and multilayer survivability in MPLS over optical transport networks. In [13], [14], the impact of GMPLS on multi-layer survivability has been addressed. [15] noted that restoration can be well accomplished with a good balance of protection in each of the two layers by invoking dynamic routing after a failure.

It may be noted that most works so far ignored the OTN layer in considering network protection. In [2], a protection design model for three-layer networks was addressed. Mainly, the benefit of employing a protection mechanism in each layer was emphasized leading to a fully survivable and recoverable network. On the other hand, this model results in provisioning of multiple protection capacities at OTN and DWDM layers (see Fig. 1a) leading to over-provisioning. In any case, this model serves as our basis since we can address the protection mechanism at *each* layer separately in this framework.

III. Review: An Integrated Capacity (Normal and Protection) Optimization Model

In this section, we first review the optimization formulation presented in [2] and depicted in Fig. 1a since this forms the important basis for our study; we will then discuss how to adapt this formulation to consider the remaining models shown

Table I: List of Notations (Given entities)

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.
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 $k = 0, 1, 2, 3, 4$ for 1.25, 2.5, 10, 40, and 100 Gbps, respectively
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.

Table II: List of Notations (Variables)

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).
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).
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}.
y_e: Number of modules M to be installed on link e for normal capacity of the IP/MPLS layer (non-negative integral).
$\underline{y}_e$: Number of modules M to be installed for protection capacity of link e.
w_{gk}: Number of modules U_k to be installed on link g for normal capacity in the OTN layer (non-negative integral).
$\underline{w}_{gk}$: Number of modules U_k to be installed for 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).
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).

in Fig. 1. Notations used in this model are summarized in Tables I and II.

In this architecture, it is assumed 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 (primary, protection) paths that are numbered $1, 2, ..., P_d$. Here, x_{dp} represents the binary decision variable for selection of a pp-path-pair for demand d. This is captured below:

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

Constraints (2) are the capacity feasibility constraints of the *normal* flows routed on link e where M is the allowable granularity of each MPLS tunnel.

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

Constraints (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 $\mathbb{P}_{dp}$.

$$\sum_{d=1}^{D} h_d \sum_{p=1}^{P_d} \mu_{edp} x_{dp} \le M \underline{y}_e \qquad e = 1, 2, ..., E \tag{3}$$

Constraints (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.

$$\sum_{q=1}^{Q_e} m_{eq} = y_e \qquad e = 1, 2, ..., E \tag{4}$$

Constraints (5) are the demand constraints of the *protection* capacity of the IP/MPLS layer.

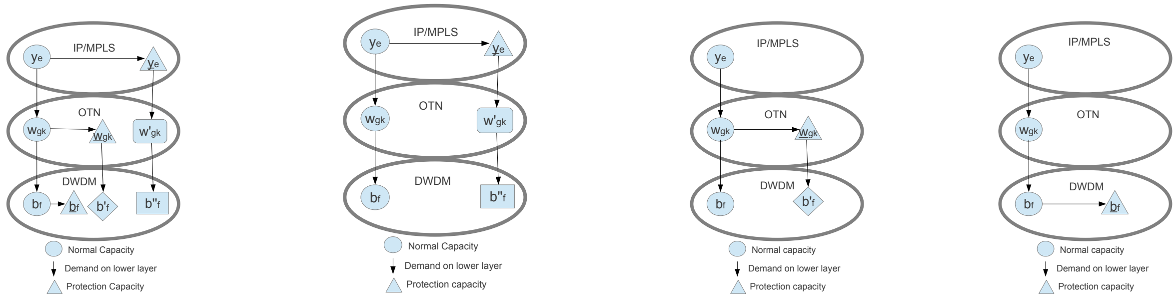
$$\sum_{q=1}^{Q_e} m'_{eq} = \underline{y}_e \qquad e = 1, 2, ..., E \tag{5}$$

The OTN system is structured in layered networks consisting of several optical data unit (ODU) sublayers that are defined at five bit-rate client signals, i.e., 1.25, 2.5, 10, 40, and 100 Gbps that are referred to as Uk ($k = 0, 1, 2, 3, 4$), in the rest of the paper. The OTN layer's *normal* capacity feasibility constraints are expressed in (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.

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m_{eq} \le \sum_{k=0}^{4} U_k w_{gk} \quad g = 1, 2, ..., G \tag{6}$$

Similarly, constraints (7) are the OTN layer *protection* capacity feasibility constraints.

$$M \sum_{e=1}^{E} \sum_{q=1}^{Q_e} \gamma_{geq} m'_{eq} \le \sum_{k=0}^{4} U_k w'_{gk} \quad g = 1, 2, ..., G \tag{7}$$



(a) IP/MPLS over OTN over DWDM Network

(b) Representation of Model 1 (IP/MPLS Protection)

(c) Representation of Model 2 (OTN Protection)

(d) Representation of Model 3 (DWDM Protection)

Figure 1: Influence of Protection: a pictorial view

Protection in the OTN layer is achieved using a link restoration on a single path. Constraints (8)–(11) assure that only the 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.

$$\sum_{r=1}^{R_g} c_{gkr} = w_{gk} \qquad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4 \tag{8}$$

$$\sum_{r=1}^{R_g} u_{gkr} = 1 \qquad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4 \tag{9}$$

$$c_{gkr} \leq U_k u_{gkr} \qquad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4, \quad r = 1, 2, ..., R_g \tag{10}$$

$$\sum_{r=1}^{R_g} \Delta_{lgkr} c_{gkr} \leq \underline{w}_{lk} \qquad k = 0, 1, 2, 3, 4, \quad l = 1, 2, ..., G, \quad g = 1, 2, ..., G \quad l \neq g \tag{11}$$

Constraints (12) and (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 protection capacity $\underline{w}_{gk}$ to avoid protecting the OTN signals twice, once in the OTN layer and once in the DWDM layer.

$$\sum_{z=1}^{Z_g} s_{gkz} = w_{gk} \qquad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4 \tag{12}$$

$$\sum_{v=1}^{V_g} s'_{gkv} = \underline{w}_{gk} \qquad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4 \tag{13}$$

Constraints (14) are the OTN over DWDM demand constraints for the OTN capacity required to realize the IP/MPLS protection capacity.

$$\sum_{v=1}^{V_g} \overline{s}_{gkv} = w'_{gk} \qquad g = 1, 2, ..., G \quad k = 0, 1, 2, 3, 4 \tag{14}$$

Protection in the DWDM layer is achieved using fixed back-up paths. Constraints (15) to (18) are the DWDM layer capacity feasibility constraints.

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z}^{Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f \qquad f = 1, 2, ..., F \tag{15}$$

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{z=1}^{Z_g} \theta_{fgz} s_{gkz} \leq N \underline{b}_f \qquad f = 1, 2, ..., F \tag{16}$$

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{v=1}^{V_g} \pi_{fgv} s'_{gkv} \leq N b'_f \qquad f = 1, 2, ..., F \tag{17}$$

$$\sum_{g=1}^{G} \sum_{k=0}^{4} U_k \sum_{v=1}^{V_g} \pi_{fgv} \overline{s}_{gkv} \leq N b''_f \qquad f = 1, 2, ..., F \tag{18}$$

The goal in this design model is to minimize the total network cost of the normal and protection capacity. The objective is given by:

$$\mathcal{F} = \sum_{e=1}^{E} \eta_e (y_e + \underline{y}_e) + \sum_{g=1}^{G} \sum_{k=0}^{4} \beta_{gk} (w_{gk} + w'_{gk} + \underline{w}_{gk}) + \sum_{f=1}^{F} \xi_f (b_f + b'_f + \underline{b}_f + b''_f) \tag{19}$$

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.

In summary, Figure 1a shows how components are related for the above problem. First, there is the IP/MPLS layer normal capacity and its protection capacity. Both must be supported by the OTN layer. However, the OTN layer will 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 provided 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 that by separating the capacity components and protecting the normal capacity of each layer, the multilayer network can fully survive three link failures at minimum in case a single link fails in each layer simultaneously.

IV. Protection Design at Each Layer Independently

First, it should be clear from the model presented in Section III and Figure 1a that the multi-layer model ends up providing multiple levels of protection. We consider protection design models at each layer independently based on the model presented in Section III. These protection design models will be referred to as Model-IP/IMLS (or Model 1), Model-OTN (or Model 2), and Model-DWMD (or Model 3).

Model 1 (Figure 1b) considers protection done at the IP/MPLS layer. In this model, there is no additional protection either at the OTN nor the DWDM layer; these layers provide normal capacity for the upper layer demands. Model 1 is accomplished by minimizing the objective function (20) given by

$$F=\sum_{e=1}^{E}\eta_e(y_e+\underline{y}_e)+\sum_{g=1}^{G}\sum_{k=0}^{4}\beta_{gk}(w_{gk}+w'_{gk})+\sum_{f=1}^{F}\xi_f(b_f+b''_f) \quad (20)$$

while satisfying the following constraints: (1), (2), (3), (4), (5), (6), (7), (8), (9), (10), (12), (14), (15) and (18). The other constraints are not needed as there is no protection at the OTN or the DWDM layer.

Model 2 is shown in Figure 1c in which the protection is done at the OTN layer. In this model we have normal capacity in IP/MPLS layer. This normal capacity is protected by the OTN layer. As the normal capacity of the OTN layer is protected both normal capacity and protection capability has to be provided by the DWDM layer. In this model, there is no additional protection either at the OTN or the DWDM layer; these layers provide normal capacity for the upper layer demands. Model 2 is accomplished by minimizing the objective function (21) given by

$$F=\sum_{e=1}^{E}\eta_e y_e+\sum_{g=1}^{G}\sum_{k=0}^{4}\beta_{gk}(w_{gk}+\underline{w}_{gk})+\sum_{f=1}^{F}\xi_f(b_f+b'_f) \quad (21)$$

while satisfying the following constraints: (1), (2), (4),(6), (8), (9), (10),(11), (12), (13), (15) and (17).

Model 3 is shown in Figure 1d in which the protection is done simply at the DWDM layer, while normal capacity in IP/MPLS layer and the OTN layer. Model 3 is accomplished by minimizing the objective function (22) given by

$$F=\sum_{e=1}^{E}\eta_e y_e+\sum_{g=1}^{G}\sum_{k=0}^{4}\beta_{gk}w_{gk}+\sum_{f=1}^{F}\xi_f(b_f+\underline{b}_f) \quad (22)$$

The objective is minimized subject to satisfying the constraints: (1), (2), (4), (6), (12), (15), and (16).

V. Cost Comparison Study

We performed a cost comparison study of the three models by various a number of parameters. In all models, there are three unit cost parameters in the objective functions, η_e, β_{gk} and ξ_f, each associated with different layers as specified in Table III. In our study, we fixed the W-cost at 140 and adjusted the other units costs to evaluate the impact due to change of the cost ratio at different layers. The IP-cost can be 5, 10, 20, and 40. Which represent approximately 3.5, 7, 14, and 28% of the W-cost, respectively. We varied M to 2.5, 5, and 10 Gbps.The cost of the OTN layer can be of three different types 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}

For UK-cr1, UK-cr2 and UK-cr3 the following U_k cost ($k = 0, 1, ..., 4$) were considered, 2/4/8/16/32, 2/5/13/20/50, and 2/6/18/54/162. Indeed the actual values of U_ks are not as important as the relationships between them. 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 (Table III).

Table III: Cost values in 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

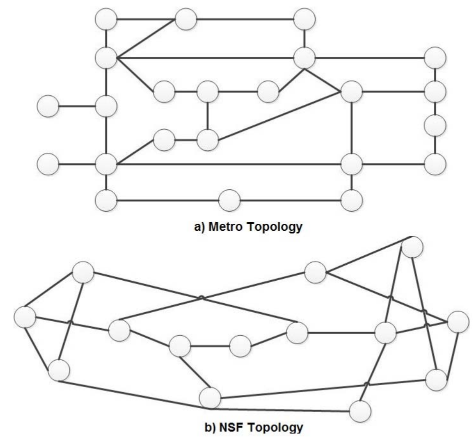


Figure 2: Topologies

Two network topologies were employed in our study: the NSF topology with 14 nodes and 21 links (see Fig. 2 a) and the Metro topology with 23 nodes and 30 links (see Fig. 2 a), with the aim to assess the impact of network size and connectivity on the total cost of the network (figures are not included due to space limitations; they can be found in [2]). The three models were solved by extending the phased approach described in [2]. The network cost, the normal capacity, and the protection capacity, are evaluated as a function of the module size for the IP/MPLS layer in Gbps (M) and the IP-cost (η_e) for each protection model. Due to space constraints, only the result of UK-cr2 OTN signals is shown; the UK-cr1 and UK-cr3 costs show a similar pattern when using UK-cr2. The solver CPLEX 12.6 was employed to generate numerical results. For all demand generation in this paper we use the demand model presented in [16].

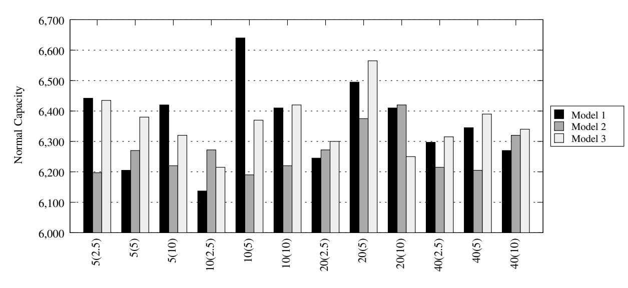


Figure 3: Normal capacity of three models for NSF Topology (UK-cr2)

Figures 3 to 5 show the total cost, the normal capacity and the protection capacity, respectively, for the NSF topology, while Figures 6 to 8 are for the Metro topology.

Figure 3 displays the normal capacity required by the three layers. The IP-cost and M value have a slight impact on the demand of normal capacities for each model, as can be seen by the small range of variability of the normal capacity. The low node connectivity in the NSF topology leads to a low number of primary paths with small length variations. Moreover, the demanded capacity for protection also influences the small difference of normal capacity demand. Protection paths are typically longer than normal paths and therefore, demand more capacity. The NSF topology can operate with great diversity of signals U_k.

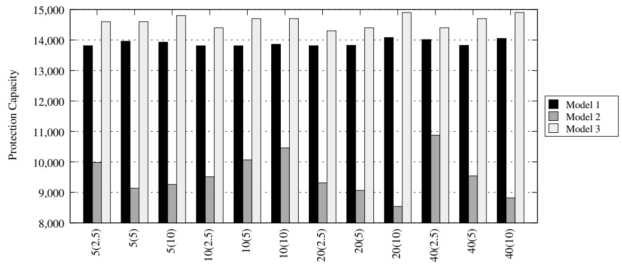


Figure 4: Protection capacity comparison for NSF Topology (UK-cr2)

Figure 4 displays the required protection capacity by the three layers for the three models. The number of components of the model does not affect the required protection capacity (Figures 1b to 1d), Model 1 has a higher number of components followed by Model 2 and Model 3; however, Model 3 has the highest demand of protection capacity followed by Model 1 and Model 2. The required protection capacity of Model 2 is the lowest one due to path sharing at the OTN layer. The required protection capacity of Model 1 is smaller than that required by Model 3 due to the larger granularity of the DWDM layers.

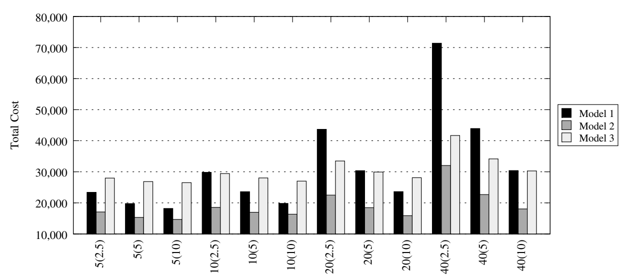


Figure 5: Total cost of the three models for NSF Topology, and UK-cr2

The total cost of Model 1 is influenced by both the IP-cost and the value of M (Figure 5). The total cost increases roughly 30% when the IP-cost doubles and it increases from 13% to 50% when the value of M doubles. The total cost of Model 2 is smaller than that of Model 1, since the cost of Model 2 is influenced by the signals U_k required rather than the values of the IP-cost and M since the protection provided by Model 2 is at the OTN layer. The total cost of Model 2 increases 18% when the IP-cost doubles and 7 to 30% when the value of M doubles. Model 2 employs the signals U_0, U_1, U_2, U_3, and U_4, but signals U_0 e U_1 are less employed, which makes the cost of Model 2 the lowest one. The total cost of Model 3 increases on average 12% when the IP-cost doubles and 0.3 to 17% when the values of M doubles. For a fixed IP-cost, the total cost increases as a function of the value of M since a higher number of large demands can be satisfied. The total cost also increases when the IP-cost varies from 5 to 40. Both the values of the IP-cost and M impact the total cost.

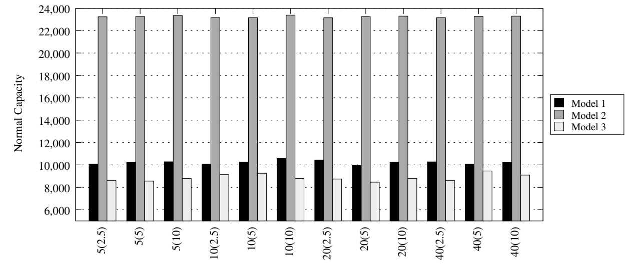


Figure 6: Normal capacity comparison of three models for Metro Topology, for UK-cr2

Figure 6 presents the normal capacity required by the three models for the Metro topology. The value of the IP-cost and M have a slight impact on the normal capacity demand. The higher connectivity of the Metro topology, when compared to the NSF connectivity implies in diverse primary path length and consequently diverse demands of normal capacity. The required normal capacity of Model 1 is 18% higher than that required by Model 3 and 57% lower than that of Model 2. Signals U_0, U_1, U_2 are not required at the OTN layer in Model 2; thus, by employing only signals U_3 and U_4, the normal capacity demand of Model 2 is considerably larger than those of the two other models. The values of M and IP-cost do not influence the normal capacity demand, with a impact of less than 1%.

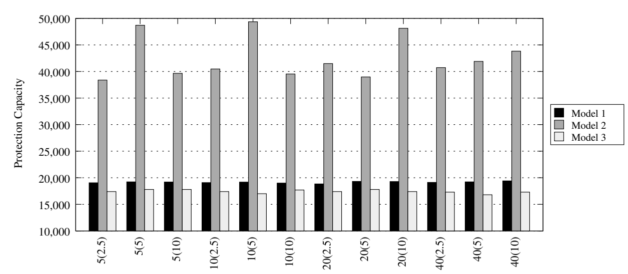


Figure 7: Protection capacity comparison of three models for Metro Topology, for UK-cr2

Figure 7 shows the required protection capacity by the three layers for the three models. The required protection capacity of Model 2 is the highest one due to low path sharing at the OTN layer and because only the signals U_3 and U_4 are used. The required protection capacity of Model 1 is smaller than that required by Model 3 due to the larger resource granularity of the DWDM layers. We also note that the protection capacity demand for each individual component is greater than the normal capacity demand, due to longer protection paths. Furthermore, the gap between the normal capacity and the protection capacity demand increases as we more towards the lower layers of the networks.

Figure 8 shows the total network cost for the Metro topology. Similarly to NSF topology, the total cost of Model

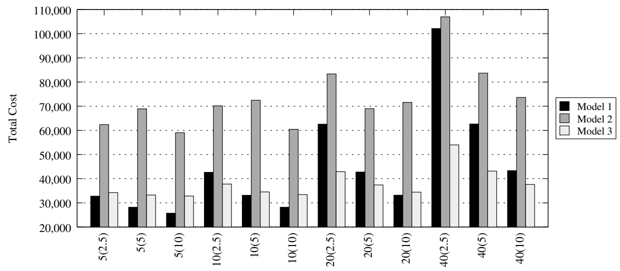


Figure 8: Cost comparison of three models for Metro Topology, for UK-cr2

1 is influenced by the values of the IP-cost and M. The total cost increases roughly 32% when the IP-cost doubles and it increases 12% to 54% when M doubles. The total cost of Model 2 is more influenced by the number of U_k used than it is influenced by the values of IP-cost and M. However, differently than the NSF topology, the cost of Model 2 was higher than that of Models 1 and 3, since only U_3 and, U_4 are used, moreover U_4 was used with greater intensity. The total cost of Model 2 increases 16% when the IP-cost doubles and 0.3 to 20% when the value of M doubles. The total cost of the Model 3 is influenced by the values of the IP-cost and M. The total cost of Model 3 increases on average 14% when the IP-cost doubles and 0.2 to 20% when the values of M doubles. For the fixed IP-cost, the smaller the value of M, the greater is the network cost, since the larger the M value, the higher is the number of demands than can be satisfied. The total cost also increases when the IP-cost varies from 5 to 40.

To summarize, we found that for both topologies, Model 1 and Model 3 had similar behaviors. Overall, for both topologies we also observed the total cost is highest when the IP-cost = 40 and M = 2.5 and the lowest when the IP-cost = 5 and M = 10, which is clear when we compare the ratio between IP-cost and M (16 vs 0.5). For both topologies, the protection capacities are roughly twice that of the nominal capacity. The cost of providing protection at the OTN layers is highly influenced by the network connectivity. For networks with low node connectivity (e.g., NSFnet), providing protection at the OTN layer is feasible. However, for networks with large node connectivity, the cost of such protection is too high.

The difference between normal and protection capacities increases when the protection is provided at the lower layers. For example, the difference between the protection and normal capacities of Model 1 is greater than it is in Model 2, and it is also greater than in Model 3.

Increasing the value of IP and M strongly impacts the protection of the top layers. For example, when the IP-cost or M double, the impact on the total cost was higher for Model 1 than it was for Model 2, followed by Model 3.

VI. Conclusions

In this paper, we presented network protection design models for the IP/MPLS over OTN over DWDM three-layer network. The proposed scheme provides protection at only one layer. Signals U_0, U_1, and U_2 are not used for protecting the Metro topology and the number of paths shared is small, which makes the protection of the OTN layer more expensive than the protection provided at the IP/MPLS layer. On the other hand, providing protection at the IP/MPLS layer is more expensive than providing protection at the DWDM layer. The signals U_0, U_1, U_2 are used for the NSF topology. The use of lower performing protection signals at the OTN layer reduces the total cost, making the protection of the OTN layer more advantageous than at the IP/MPLS or DWDM layer.

Acknowledgement

This work has been partially supported by NSF Grant # CNS-1217736 and CNPq.

References

[1] A. Fumagalli and L. Valcarenghi, "Ip restoration vs. wdm protection: is there an optimal choice?" *Network, IEEE*, vol. 14, no. 6, pp. 34–41, Nov 2000.

[2] I. Katib and D. Medhi, "Network protection design models, a heuristic, and a study for concurrent single-link per layer failures in three-layer networks," *Computer Communications*, vol. 36, no. 6, pp. 678 – 688, 2013, reliable Network-based Services.

[3] P. Demeester, M. Gryseels, A. Autenrieth, C. Brianza, L. Castagna, G. Signorelli, R. Clemenfe, M. Ravera, A. Jajszczyk, D. Janukowicz, K. Van Doorselaere, and Y. Harada, "Resilience in multilayer networks," *Communications Magazine, IEEE*, vol. 37, no. 8, pp. 70–76, Aug 1999.

[4] S. De Maesschalck, D. Colle, A. Groebbens, C. Develder, U. Lievens, P. Lagasse, M. Pickavet, P. Demeester, F. Saluta, and M. Quagliatti, "Intelligent optical networking for multilayer survivability," *Communications Magazine, IEEE*, vol. 40, no. 1, pp. 42–49, Jan 2002.

[5] D. Medhi, "A unified approach to network survivability for teletraffic networks: models, algorithms and analysis," *Communications, IEEE Transactions on*, vol. 42, no. 234, pp. 534–548, Feb 1994.

[6] M. Pióro and D. Medhi, *Routing, Flow, and Capacity Design in Communication and Computer Networks.* Morgan Kaufmann Publishers, July 1, 2004.

[7] L. Sahasrabuddhe, S. Ramamurthy, and B. Mukherjee, "Fault management in ip-over-wdm networks: Wdm protection versus ip restoration," *Selected Areas in Communications, IEEE Journal on*, vol. 20, no. 1, pp. 21–33, Jan 2002.

[8] E. Kubilinskas and M. Pióro, "Two design problems for the ip/mlps over wdm networks," in *Design of Reliable Communication Networks, 2005. (DRCN 2005). Proceedings.5th International Workshop on*, Oct 2005, pp. 241–248.

[9] H. Zhang and A. Durresi, "Differentiated multi-layer survivability in ip/wdm networks," in *Network Operations and Management Symposium, 2002. NOMS 2002. 2002 IEEE/IFIP*, 2002, pp. 681–694.

[10] L. Lei, A. Liu, and Y. Ji, "A joint resilience scheme with interlayer backup resource sharing in ip over wdm networks," *Communications Magazine, IEEE*, vol. 42, no. 1, pp. 78–84, Jan 2004.

[11] Y. Qin, L. Mason, and K. Jia, "Study on a joint multiple layer restoration scheme for ip over wdm networks," *Network, IEEE*, vol. 17, no. 2, pp. 43–48, Mar 2003.

[12] W. Bigos, B. Cousin, S. Gosselin, M. Le Foll, and H. Nakajima, "Survivable mpls over optical transport networks: Cost and resource usage analysis," *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 5, pp. 949–962, June 2007.

[13] P. Pongpaibool and H. Kim, "Impacts of gmpls on topology design and protection planning of survivable ip-over-optical networks," in *Global Telecommunications Conference Workshops, 2004. GlobeCom Workshops 2004. IEEE*, Nov 2004, pp. 352–356.

[14] J. Zhao, S. Wang, and Z. Tang, "Integrated multi-layer network survivability based on gmpls to improve fault recovery time," in *Computer Engineering and Technology, 2009. ICCET '09. International Conference on*, vol. 2, Jan 2009, pp. 126–130.

[15] D. Medhi and R. Khurana, "Optimization and performance of restoration schemes for wide-area teletraffic networks," *Journal of Network and Systems Management*, vol. 3, no. 3, pp. 265–294, 1995.

[16] B. Fortz and M. Thorup, "Internet traffic engineering by optimizing ospf weights," in *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 2, 2000, pp. 519–528 vol.2.