A Study on Layer Correlation Effects Through a Multilayer Network Optimization Problem

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***Abstract*—Multilayer network design has received significant attention over the years. Despite this, the explicit modeling of three-layer networks such as IP/MPLS-over-OTN-over-DWDM in which the OTN layer is specifically considered has not been addressed before. In this paper, we present an optimization model for network planning of such multilayer networks that consider the OTN layer as a distinct layer with its unique technological sublayer constraints. More importantly, 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. Focusing on the interrelation between the IP/MPLS and OTN layers, we present a detailed numeric study that considers various cost parameter values of each layer in the network and analyzes their impacts on individual layers and overall network cost.**

I. Introduction

Multilayer network design has received considerable attention over the years. The focus has primarily been on the design of two-layer networks [1]–[6]. In two-layer networks, such as IP-over-DWDM, 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. 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 optical transport networks (OTN) serving as an intermediary 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 (Fig. 1). 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. This is beneficial from an effective management of resources and in failure detection.

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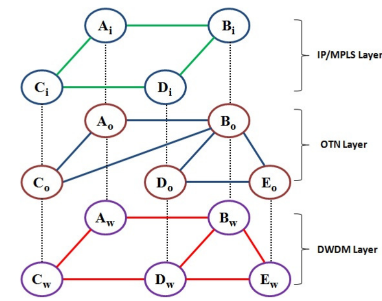

Fig. 1. IP/MPLS over OTN over DWDM Network

As of now, there is, however, limited work on understanding three-layer networks such as IP-over-OTN-over-DWDM, especially how unit costs of each layer and modular capacity impact the multilayer correlation. The scope of our work is to present an optimization model for the operational planning of a three-layer IP/MPLS over OTN over DWDM networks, and more importantly, to shed some light on multilayer correlation effects.

The rest of this paper is organized as follows. In Section II, we present the optimization problem formulation. In Section III, we present a comprehensive study. Finally, in Section IV, we present our summary.

II. A Multilayer Optimization Model

In this section, we present a three-layer network optimization model 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 functionality of OTN is described from a network level viewpoint in [7]. The interfaces of OTN to be used within and between subnetworks of the optical networks are defined in [8]. For this work, we use the rates 2.5, 10, and 40 Gbps, referred to as ODU1, ODU2, and ODU3, respectively. In the rest of the paper, U_k denotes ODUk for $k = 1, 2, 3$.

The list of notations is shown in Table I. The first constraint represents IP demand d carried on a single tunnel out of a set of possible tunnel paths P_d where we define x_{dp} as a binary decision variable for selection of a tunnel for demand d

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

For each IP/MPLS layer link e that IP/MPLS tunnels x_{dp} traverse, the capacity allocated in modules of size M must

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TABLE I
LIST OF NOTATION

Indices:
D: Set of demands between source-destination pairs of the IP/MPLS layer.
P_d: Set of candidate paths for demand $d \in D$.
E: Set of links in the IP/MPLS layer.
Q_e: Set of candidate paths at the OTN layer for $e \in E$.
G: Set of links in the OTN layer.
Z_g: Set of candidate paths of DWDM layer for for $g \in G$.
F: Set of links at the DWDM layer.
$K = \{1, 2, 3\}$: Set of 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 $k \in K$.
N: Module size for DWDM layer link capacities.
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.
b_f: Number of modules N to be installed on link f in the DWDM layer (non-negative integral).
Variables:
x_{dp}: IP/MPLS flow 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).
w_{gk}: Number of modules U_k to be installed on link g in the OTN layer (non-negative integral).

be satisfied

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

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

$$\sum_{q \in Q_e} m_{eq} = y_e, \qquad e \in E. \tag{3}$$

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 with demand is satisfied

$$M \sum_{e \in E} \sum_{q \in Q_e} \gamma_{geq} m_{eq} \leq \sum_{k \in K} U_k w_{gk} \qquad g \in G. \tag{4}$$

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

$$\sum_{z \in Z_g} s_{gkz} = w_{gk}, \qquad k \in K \quad g \in G. \tag{5}$$

Finally, we consider the DWDM layer capacity feasibility

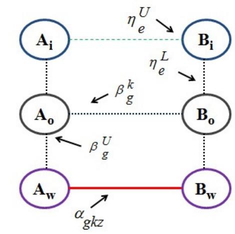


Fig. 2. Cost Structure of The multilayer Network

constraints that assure that the capacity of each physical link f is not exceeded by the flow using this DWDM link.

$$\sum_{g \in G} \sum_{k \in K} U_k \sum_{z \in Z_g} \vartheta_{fgz} s_{gkz} \leq N b_f, \qquad f \in F. \tag{6}$$

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. Note that from constraints (4)–(6), several U_ks may occupy a single wavelength subject to the multiplexing rules defined in [8]. The objective is to minimize the three layers cost that can be written as:

$$\sum_{e \in E} \eta_e y_e + \sum_{g \in G} \sum_{k \in K} \beta_{gk} w_{gk} + \sum_{g \in G} \sum_{k \in K} \sum_{z \in Z_g} \alpha_{gkz} s_{gkz}. \tag{7}$$

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 work [9] on the multilayer formulation where the DWDM capacity is also unknown.

Note that each layer has a different cost structure. 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 (**P**) 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 Fig. 2.

Thus, the overall optimization problem (**P**) is to minimize (7) subject to the set of constraints (1)–(6). The final solution gives us the optimal number of capacity modules (IP/MPLS layer), and signals (OTN layer), needed to satisfy the demands.

III. STUDY AND RESULTS

The main scope of this study is to understand three-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). A difficulty with the model is that it is an integer linear programming (ILP) model. Except for a 7-node model (i.e., 7-node in each layer for a total of 21 nodes in three layers), an ILP solver such as CPLEX cannot solve large network problems. Thus, we have developed a heuristic to solve larger networks, again with the main focus being understanding the correlation between layers. Due to space limitation, we skip the details of the heuristic, which is described in [10, Chapter 8]. 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. We found 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 focus on the details of the parameter values we considered for larger network problems.

A. *Parameter Values*

In the formulation of problem (**P**), M refers to the capacity of the interface cards at the LSRs and 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 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 *U_k unit cost for $k \in K$*, or simply as U_k-cost. According to [5], one of the cost ratios of future network elements is 8, 0.5, and 1 representing costs of a DWDM transponder (10 Gbps), IP/optical interface card (10 Gbps), and a photopic OXC port, respectively. Based on our cost model in Section II, 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. Note that we set the multiplexing cost ($\beta_g^k = 1$). For the OTN layer cost parameter values, we consider the following scenarios:

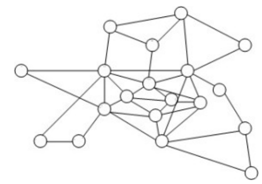
- UK-cr1: 2 U_k = U_{k+1}
- UK-cr2: 3 $U_k > U_{k+1}$
- UK-cr3: 3 U_k = U_{k+1}

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. Considering these issues, we choose three representative values to reflect the above three scenarios: 3/6/12, 3/7/18 and 3/9/27, to reflect $U_1/U_2/U_3$ costs.

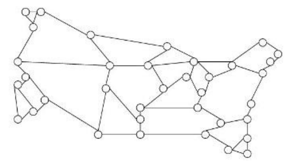
For the DWDM layer cost α_{gkz} we choose to assign 10% of the basic U_1 signal. That is, we fixed α_{gkz} to be equal to 0.3. This is a small routing cost at the DWDM layer and is not associated with the capacity used at this layer. Another cost ratio of network elements reported in [5], is 1, 8, and 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 the IP-cost, we also define another network elements cost ratio in which the IP/optical interface is reduced by 50%, i.e., IP/optical interface is equal to 4. In this case,

TABLE II
SUMMARY OF COST VALUES FOR EACH LAYER.

	Unit Cost Values		
Cost Notation	Case-1	Case-2	Case-3
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



(a) European optical Network (EON)



(b) Sprint Network

Fig. 3. Network Topologies.

the IP-cost = 9, with the same U_k-cost scenarios. Table II summarizes the cost values of the IP/MPLS and OTN layers used in this study.

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 of [11] 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 the 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?

B. *Network Study*

We consider two network topologies: a 19-node European optical Network (EON), and a 36-node Sprint continental IP backbone, (Fig. 3). Note that, here n-node means n nodes in each layer of the three-layer network architecture. In other words, the 19-node EON has a total of 57 nodes from all

TABLE III
TOPOLOGY INFORMATION AND DEMANDS

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

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 where each wavelength is 40 Gbps. Information about network topologies and traffic scenarios are shown in Table III. 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, average, and above average demand in these networks.

C. Numeric Results

1) Interrelated Cost of Both Layers: Fig. 4 shows the IP layer, OTN layer, and total cost of Case-1 for different values of M in EON. We observe that the IP-cost dominates in Case-1 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.

Fig. 5 shows the IP layer, OTN layer, and total cost of Case-2 for different values of M in EON. We observe that the IP-cost dominates in Case-2 for all scenarios. This was also found to be true for the Sprint network. A similar trend was observed with Case-3 as shown in Fig. 6.

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 Case-1 when the IP/optical interface is relatively cheap, M is equal or above the average demand, and U_k-cost follows UK-cr3. Note that the IP total cost is the same under different U_k-cost. This is because when the U_k-cost changes, the IP/MPLS layer still has to satisfy the same IP demands. Thus, the IP total cost is only affected by M.

2) IP Layer Cost: Fig. 7 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.

3) OTN Layer Cost: Fig. 8 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.

When M is below the average demand, the UK-cr1 indicates that this may not be the best case to minimize the OTN cost as shown in Fig. 8a. Other cases in the EON and the Sprint networks, shown in Fig. 8b, 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 Fig. 7 and the minimum total network costs as shown in Fig. 9, 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 II, we can observe that the OTN cost is decreasing going from Case-1 (Fig. 4) to Case-2 (Fig. 5) and Case-3 (Fig. 6). However, we observe the close cost values of Case-2 and Case-3. This 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.

4) Total Network Cost: Now we focus on the total network costs for different scenarios as depicted in Fig. 9. Clearly the case of M= 10 has the best cost performance. However, we observe the close performance for Case-1. As we increase the IP unit cost we see the performance difference is increasing. From this figure and observations in Sections III-C1 and III-C3, 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 Case-1, we can observe the close performance.

5) No. of Required U_k:

No. of U_ks in EON:

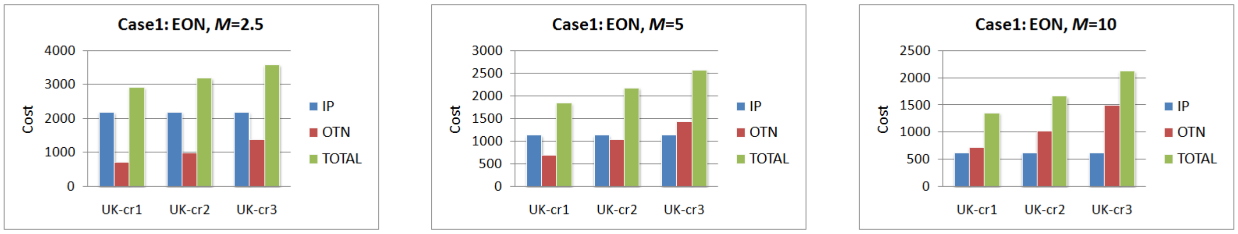
Fig. 10 shows the numbers of U_ks used in EON. We observe that U_1 is not used when M=10. We also observe that U_1 is not used when M=5 and UK-cr1. For all other cases, the numbers of U_1 is larger when M=2.5 as shown in Fig. 10a.

For U_2 in Fig. 10b, 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 Case-1 to Case-2 to Case-3. The number of U_2s also increases as we go from UK-cr1 to UK-cr3.

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.

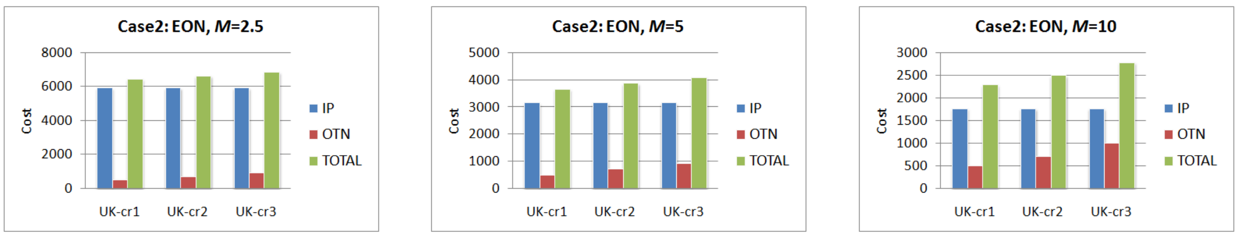
Table IV shows a summary of the patterns of U_ks needed in EON. We make four categories to describe the number of a U_k used in EON: None (-) for zero, Low (L) between 1-15, Medium (M) between 16-30, and High (H) > 30. An up arrow (↑) in the table indicates the number of U_k falls in the same previous category but increasing. A down arrow (↓) indicates the number of U_k falls in the same previous category but decreasing. Note that we only summarize observations of Case-1 (C1) and Case-3 (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 (Fig. 11), 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.



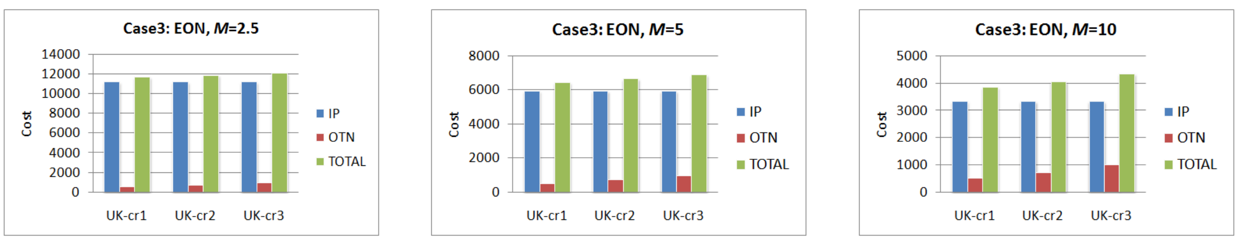
(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Fig. 4. Costs of Different Components for Different M, Case-1 in EON.



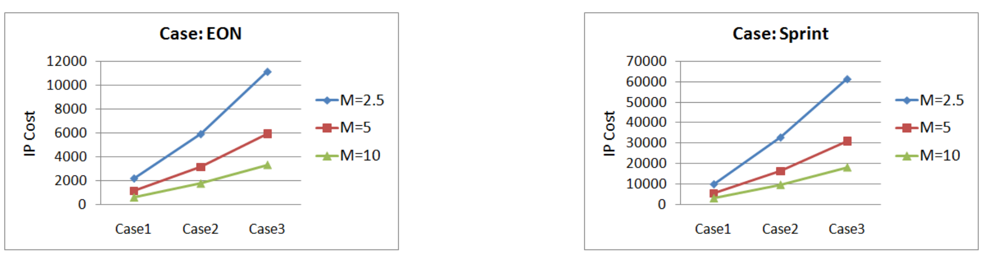
(a) $M = 2.5$ Gbps (b) $M = 5$ Gbps (c) $M = 10$ Gbps

Fig. 5. Costs of Different Components for Different M, Case-2 in EON.



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

Fig. 6. Costs of Different Components for Different M, Case-3 in EON.



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

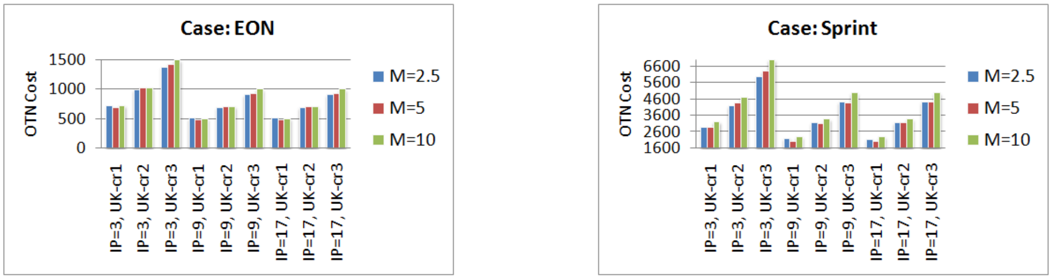
Fig. 7. Total IP Cost of Different M.

The numbers of U_3s increase as we go from Case-1 to Case-2 and Case-3. The numbers of U_2 are considerably higher when M=2.5 and 5 than when M=10.

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 V shows a summary of patterns for U_ks needed in the Sprint network.

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 case. What changes is the types and numbers of U_ks used. We find that if the IP-cost and M are fixed, the difference of bandwidth due to changing the U_k-cost is often within 2%. 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.

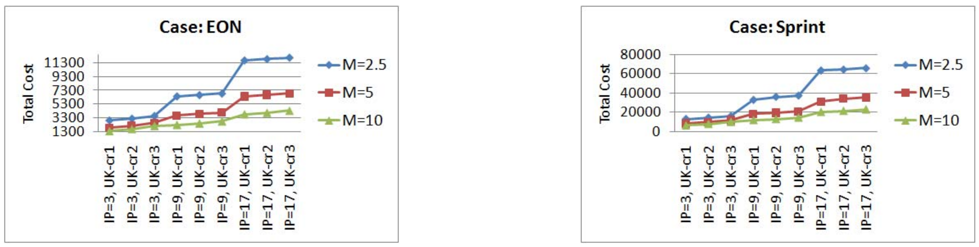
6) Effect of Increasing the Load: Certainly, if we increase the load, the total cost will increase due to more network elements needed to satisfy the load increase. On the other



(a) Total OTN Cost in EON

(b) Total OTN Cost in Sprint

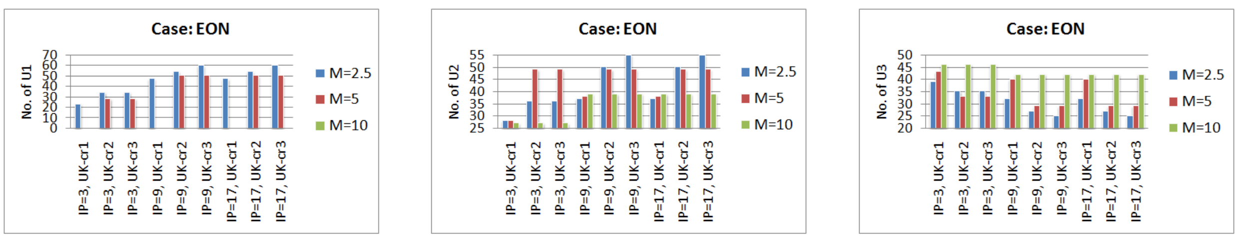
Fig. 8. Total OTN Cost of Different M and U_k.



(a) Total Cost in EON

(b) Total Cost in Sprint

Fig. 9. Total Network Cost of Different M.

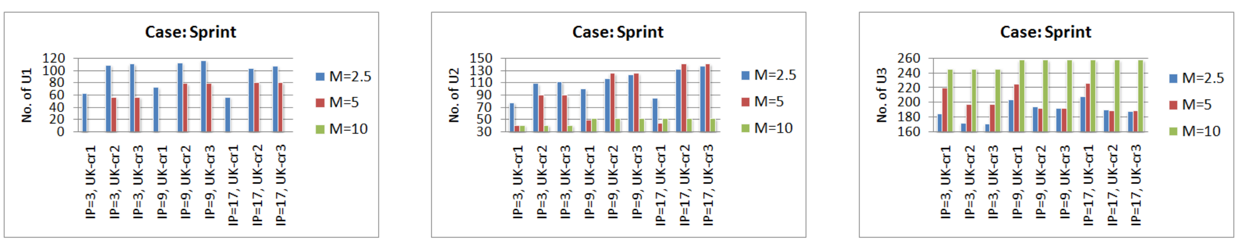


(a) No. of U_1

(b) No. of U_2

(c) No. of U_3

Fig. 10. 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

Fig. 11. No. of U_k in Sprint for different values of M

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 III, and increase the load by 10% up to 50%.

Fig. 12, 13, and 14 depict a representative subset to help visualize the impact of load increase for the EON and Sprint networks. We summarize our observations per case when the load is increasing as fellows:

- EON, UK-cr1: U_3 always increases, U_1, and U_2 decrease, but U_1 is still not used when M =5, and 10.
- EON, UK-cr2: U_3 always increases, U_1, and U_2 fluctuate, but U_1 is still not used $M = 10$.
- EON, UK-cr3: U_3 generally increases, U_1, and U_2 fluctuate, but U_1 is still not used $M = 10$.
- Sprint, all UK-cr: U_3 always increases, U_1, and U_2 fluctuate but generally increasing, and U_1 is still not used when M =5, in UK-cr1 and when $M = 10$ in all UKcr.

We conclude that the expected numbers of required U_ks due

TABLE IV
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 V
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	↑

to the load increase that minimizes the network cost depends on three factors. They are the size of M, the U_k-cost, and the magnitude of the load increase. Primarily, however, the load increase will be served by a considerable increase in U_3s.

D. Summary Observations

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

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 (Fig. 7). This is also the best case that minimizes the overall network cost as shown in Fig. 9. 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 cost of an individual layer but not for minimizing the overall network cost, and vice versa.

We have observed that the the OTN layer cost is affected more by the U_k-cost than by the IP-cost. We note that the OTN layer cost decreases as we go from Case-1 to Case-2 and Case-3. At the same time we note the close cost performance of Case-2 and Case-3, 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.

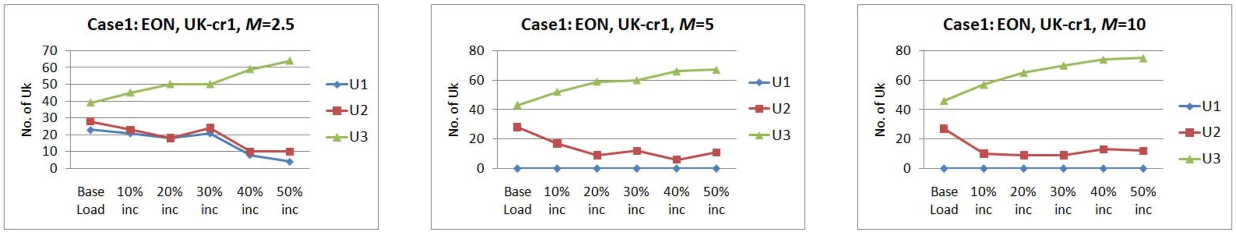
The numbers and types of U_k needed to satisfy the demands are noticeably influenced by two elements: the size of M, and the U_k-cost. The number of U_1s is generally larger when M is below the average demand. Increasing the size of M results in higher numbers of U_2s and U_3s to a point where U_1 is not used when M is above the average 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 Case-1 to Case-2 to Case-3 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.

IV. CONCLUSION

We have described in this paper a three-layer network design problem whose middle layer, the OTN layer, has not been explicitly investigated in the context of multilayer networks. We have considered the OTN sublayer technological constraints in our model to minimize the network cost over the three layers. In our design problem, the DWDM layer capacity is fixed and we focus on the IP/MPLS and OTN layers.

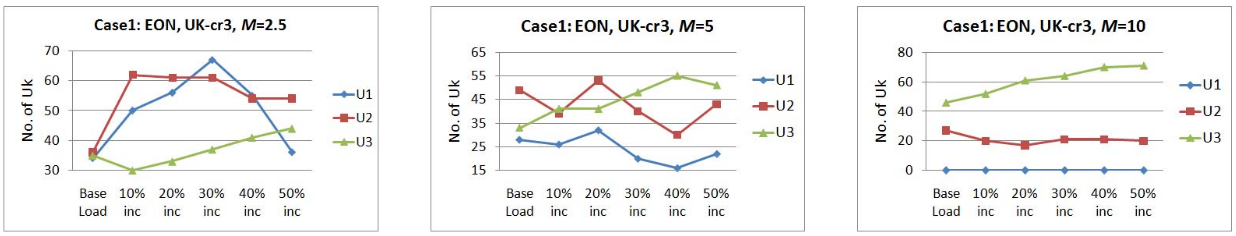
We have experimented with various network parameters values to examine how they impact the network and each layer performance. We have analyzed the results and observed that while some parameters' values are the best to optimize the cost of a specific layer, they may be the worst for other layers. The 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.

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. Often, at the planning phase, specific knowledge of the details of the demand routing may not be required. For such a case, we plan to develop analytical descriptions of the optimized solutions



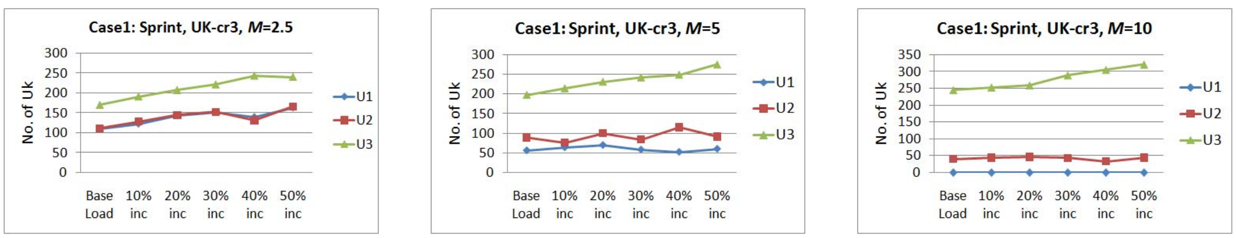
(a) $M = 2.5$ (b) $M = 5$ (c) $M = 10$

Fig. 12. Increasing the Load in EON for different values of M, Case-1, UK-cr1



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

Fig. 13. Increasing the Load in EON for different values of M, Case-1, UK-cr3



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

Fig. 14. Increasing the Load in Sprint for different values of M, Case-1, UK-cr3

as described in [12] and compare the results with our current solutions.

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