A Network Optimization Model for Multi-Layer IP/MPLS over OTN/DWDM Networks

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Abstract. The operational model for large Internet service providers is moving to a multi-layer architecture consisting of IP/MPLS coupled with OTN/DWDM. While there has been significant work on multi-layer networks, the explicit modeling in IP/MPLS over OTN/DWDM has not been addressed before. In this paper, we present a detailed network optimization model for the operational planning of such an environment that considers OTN as a distinct layer with defined restrictions.

1 Introduction

With the proliferation of Internet traffic caused by new Internet users and applications that require high bandwidth and QoS guarantees, the current IP backbone network is facing new challenges. Optical Transport Network (OTN), defined in [1, 2], is a new-generation transmission layer technology that supports high-speed optical signals, and is emerging as promising for the next-generation transport networks featuring large-granule broadband service transmissions. It combines the benefits of both SONET (synchronous optical network) and DWDM (dense wavelength-division multiplexing) while offering viable solutions to their shortcomings. Some advantages of OTN include more productive multiplexing and switching of high-bandwidth (around 100 Gbit/s) signals and the capability of cross connect dispatching of wavelengths and sub-wavelengths resulting in efficient wavelength utilization. In addition, OTN offers a "digital wrapper" layer that defines signal overhead to support powerful performance-monitoring, fault detection, and forward error correction (FEC); this is useful to limit the number of required regenerators in the network and hence, extends the transmission distances at a lower cost. For this and many other benefits, large Internet providers are recognizing that IP/MPLS-over-OTN/DWDM is an emerging architecture that bridges integration and interaction between the optical layer and the IP layer [3]. The operational implementation of OTN is slated to be on top of DWDM systems in the future.

Multi-layer networks have been an important research topic in recent years. The vast majority of research considered the two-layer architecture: IP-over-WDM. They mostly concentrated on the resiliency or traffic engineering of the

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network [4–6]. A two-layer network architecture that consists of a traffic layer over a DWDM transport layer, such as IP/MPLS-over-DWDM, suffers from a major limitation. In this architecture, the core routers are connected through the physical optical fibers and DWDM provides the transmission channels. Adding wavelengths to increase the capacity of the backbone network would, in turn, require extending the capacity of the routers. However, approximately 60-70% of the core routers found in this case are to be used for forwarding services instead of processing local add/drop services on the nodes [3]. This is where OTN comes into the picture. The OTN layer, as a middle layer, separates the logical from the physical topologies. IP/MPLS routers will be connected based on the logical topology while OTN/DWDM provides connections based on the physical topology. As a result, a demand that requires more than one logical link at the IP/MPLS layer can be accommodated in a fewer number of links at the OTN/DWDM layer, and thus, significantly reduces the forwarding services that the core routers perform.

On the other hand, previous work that considered the OTN system, such as [7], have embedded the OTN in the DWDM layer implicity. They have not taken into consideration the OTN layer as a separate layer that imposes its own restrictions. This does not reflect a precise view of the next-generation architecture nor does it produce accurate results of the models or simulations based on that assumption. However, the functionalities each technology provides are distinguishable, and this impels us to model each of them separately, i.e., to visualize the relation between the two layers with OTN as the optical logical layer on top of the physical DWDM layer.

In this paper, we introduce an explicit architecture for IP/MPLS-over-OTN-over-DWDM as depicted in Fig1. Considering OTN as a separate layer with its own restrictions, we model this architecture as a three-layer network. Each layer becomes a demand on the layer underneath it. In this architecture, we consider the network operational planning problem and a present an explicit network optimization formulation, including the cost structure for different interfaces. Our formulation uses [8] as the basis of understanding and presents a novel explicit optimization model for IP/MPLS over OTN/DWDM networks.

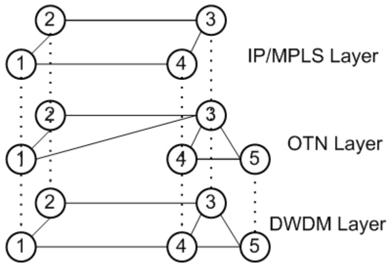

Fig. 1. IP/MPLS over OTN/DWDM Network

The rest of the paper is organized as follows. In section 2, we give a brief overview of the OTN signals bit rates and the multiplexing rules. In section 3, we present the problem formulation; in section 3.1, we discuss the cost model associated with the objective function. Finally, in section 4, we briefly outline our direction for future work.

2 OTN Signals and Multiplexing

The OTN system consists of multiple layers [2]. Each layer is distributed along the network and is activated at its termination points to perform specific activities. For the scope of this paper, we are concerned with the Optical Data Unit (ODU) layer that provides an end-to-end functionality of digital path signals for transporting the client data that can be of diverse formats such as STM-N, Ethernet, IP/MPLS, ATM, etc. The ODU layer supports three bit-rate client signals, i.e. 2.5, 10, and 40 Gbit/s, which are referred to as ODUk ($k = 1, 2, 3$), respectively. We are also interested in the ODUk time division multiplexing. It allows several lower bit-rate signals to be multiplexed and transported over a higher bit-rate optical channel and maintains an end-to-end trail for the lower bit-rate signals. This may occur when a client signal does not occupy an entire wavelength. The multiplexing of signals is defined as follows: up to 16 ODU1s or 4 ODU2s can be multiplexed to an ODU3, and 4 ODU1s can be multiplexed to an ODU2. While it is possible to mix ODU1s and ODU2s in an ODU3, only one stage multiplexing is allowed to reduce the overall network complexity. For example, it is possible to perform the multiplexing of (ODU1 → ODU2) or (ODU1 and ODU2 → ODU3), but not (ODU1 → ODU2 → ODU3).

Let U_1, U_2, and U_3, denote ODU1, ODU2, and ODU3, respectively. Then for the multiplexing process we can say: $4U_1 = U_2$, $4U_2 = U_3$, and $16U_1 = U_3$. Furthermore, U_1 and U_2 can be multiplexed into a U_3 signal according to the following rule: $U_3 = SU_2 + (4 - S)4U_1$ where $(0 \leq S \leq 4)$.

Table 1 shows the OTN different signals bit-rate, and how OTN signals can be carried over a single wavelength assuming that the maximum wavelength bit rate is 40 Gbit/s.

ODU Signal	Bit-Rate (Gbit/s)	Max. ODUs in a wavelength
ODU1	2.5	16
ODU2	10	4
ODU3	40	1

Table 1. OTN Signals, Data Rates and Multiplexing

3 Problem Formulation

In this section, we provide a link-path formulation to describe the multi-layer network optimization problem. The key point of the model is that each upper layer imposes demands on the neighboring lower layer, while explicitly considering all technological restrictions. In our example of Fig. 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. 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. Table 2 lists the notations used in our formulation. We first discuss each constraint separately.

Table 2. Notations used in Multi-layer Network Optimization Formulation

Notation	Discription
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 of the IP/MPLS layer
Q_e	Set of candidate paths of OTN layer for realizing capacity of link $e \in E$
G	Set of links of the OTN layer
Z_g	Set of candidate paths of DWDM layer for realizing capacity of link $g \in G$
F	Set of links of the DWDM layer
J	Set of modular interfaces of OTN $1, 2, 3$
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_j	Module size for OTN layer link capacities $j \in J$
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_{gj}	Cost of one capacity unit of module type U_j of the OTN layer link g
ξ_f	Cost of one capacity unit of module N of the 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)
k_{gjz}	DWDM flow variable allocated to path z realizing capacity of link g of interface j (non-negative integral)
y_e	Number of modules M to be installed on link e in the IP/MPLS layer (non-negative integral)
w_{gj}	Number of modules U_j 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)

Constraints:

We assume that an IP demand $d \in D$ can be carried over different tunnels P_d, and the fraction of the demand volume for d to be carried on tunnel p is x_{dp}. This can be expressed as follows:

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

defining the IP/MPLS layer demands. It may be noted, however, that if each demand is to be carried on a single tunnel, then we can consider the same constraint and define x_{dp} to be a binary decision variable instead. Thus, either requirement on the flow can be captured by the above constraint

Next, we consider the IP/MPLS layer capacity feasibility constraints (2). These assure that for each IP/MPLS layer link $e \in E$, its capacity is allocated in modules of size M and is not exceeded by the flow using this link as shown below:

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

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

The constraints (3) below specify how the capacity of each IP/MPLS layer link $e \in E$ is realized by means of flow m_{eq} and is allocated to its candidate paths from the routing list in the OTN layer.

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

We next consider the OTN layer capacity feasibility constraints, shown below(4). They assure that all flows routed on each OTN layer link $g \in G$ do not exceed their capacity that is allocated in modules of sizes U_j, which represent the three modular interfaces of OTN.

$$M \sum_{e \in E} \sum_{q \in Q_e} \gamma_{geq} m_{eq} \leq \sum_{j \in J} U_j w_{gj} \qquad g \in G \tag{4}$$

The following constraints (5) specify how the capacity of each OTN layer link $g \in G$ is realized by means of flow k_{gjz}, allocated to its candidate paths from the routing list in the DWDM layer.

$$\sum_{z \in Z_g} k_{gjz} = w_{gj} \qquad j \in J, g \in G \tag{5}$$

These next constraints (6) are the DWDM layer capacity feasibility constraints. They assure that for each physical link $f \in F$, 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.

$$\sum_{g \in G} \sum_{j \in J} U_j \sum_{z \in Z_g} \vartheta_{fgz} k_{gjz} \leq N b_f \qquad f \in F \tag{6}$$

The above then completes all the constraints in our multi-layer design model, along with the requirements on the variables as listed in Table 2.

Objective:

The objective in our design model is to minimize the total network cost. Thus, the goal is to

$$\text{Minimize} \qquad \sum_{e \in E} \eta_e y_e + \sum_{g \in G} \sum_{j \in J} \beta_{gj} w_{gj} + \sum_{f \in F} \xi_f b_f \tag{7}$$

subject to the set of constraints (1)–(6).

3.1 Cost Model

Our objective function (7) tries to minimize the cost of network resources over all three layers. The final solution is the optimal number of tunnels (IP/MPLS layer), lightpaths (OTN layer), and fibers (DWDM layer) needed to satisfy the demands. Each layer has a different cost structure. This is now briefly described.

For the IP/MPLS layer, η_e is the unit cost of link $e \in E$; this is defined as the sum of the interface cost for the upper layer (η_e^U) and 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 for both ends. At the OTN layer, β_{gj} is the unit cost of link $g \in G$, and is equal to the cost of establishing a new lightpath on link g (β_g^L) plus the cost of multiplexing OTN signals (β_g^j), i.e., $\beta_{gj} = \beta_g^L + \beta_g^j$. For the DWDM layer, ξ_f is the cost of link $f \in F$, 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) plus a physical link distance cost (Δ_f), i.e., $\xi_f = 2\xi_f^I + \Delta_f$.

4 Future Work

The model presented here has a large number of constraints and variables even for a small network problem. Furthermore, the problem is $\mathcal{NP}$-hard, since simpler forms of network design problems, such as the single-path flow allocation (i.e., x_{dp} is binary) or modular link design, are shown to be $\mathcal{NP}$-hard [8]. Thus, we plan to verify the computational limits of our proposed model and develop efficient heuristic algorithms to solve the problem for large networks. This will be reported in a future work.

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