

Joint operation of packet network and WDM network

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ABSTRACT

In integration of IP and WDM networks, there are two main approaches. One is joint planning approach; the other is joint operation approach. Joint planning typically addresses an optimality problem on total network cost given a certain data traffic pattern and some physical constraints at the network planning stage; while through reconfiguration or real-time setup of lightpaths, joint operation focuses on optimizing network performance or guaranteeing it to a defined level under current network configuration and dynamic data traffic pattern at the network operational stage. On contrary to the (semi-) static virtual topology in joint planning, the joint operation approach maintains a dynamic virtual topology. We propose an integration network model with separated control plane and data plane. Formulations have been studied in building the model, and the initial findings may help in designing the routing and signaling protocols.

Keywords: Joint operation, IP over WDM, dynamic virtual topology, routing and signaling, traffic grooming, cost function

1. INTRODUCTION

Emerging technologies have made possible an evolving optical WDM (wavelength division multiplexing) network underneath legacy transport networks¹. This new network layer features effective exploitation of fiber bandwidth and high flexibility in provisioning of optical path services. In parallel with the bandwidth explosion at backbone, data traffic is increasing exponentially and outpacing the voice traffic. The rapid expansion of Internet has made IP (internet protocol) a standard de facto. New architectures of IP directly over WDM^{2,3} have been proposed to eliminate the bandwidth inefficiency caused by such intermediate layers as ATM, SDH/SONET, etc., to enhance the total network performance and together to lower the total network cost.

However, current and emerging WDM networks are circuit-switched with coarse granularity in nature, while the IP networks are packet-switched, connectionless with finer granularity, it is doubtful whether they can get along well with each other. To bridge their differences, we need to introduce an interaction mechanism.

There are two views in recent studies regarding the interaction issue. First is a planning view. In this view, lightpaths connecting IP routers are set up a priori based on known or expected traffic^{4,5}. These lightpaths form a virtual topology seen from the upper IP layer. The virtual topology is typically determined and maintained through a central entity that collects and stores information of network's long-term traffic distribution and resource utilization in both electrical and optical layers, seeking to perform a global optimization. Such process is essentially static or semi-static, which we call joint planning.

The second view is an operational view. In this view, the packet network and WDM network works jointly to establish connections, i.e., lightpaths are setup on demand and released when traffic demand terminates⁶. This scheme, which we call joint operation, accommodates the WDM network to the dynamic traffic change from the IP network. Currently, two frameworks encompassing joint operation seem promising. One is lambda labeling, which extends MPLS (multi-protocol label switching) to the wavelength domain, named multi-protocol lambda switching (also MPLS)^{7,8}. The other is ASON (automatic switching optical network)¹⁰, which proposes signaling protocols between client and server networks to setup lightpaths in real time.

The common idea of these two frameworks is the separation of a control plane and a data plane. The concept of virtual topology between IP network and WDM network is still useful in the data plane, similar to the planning approach. However in operation, the virtual topology change dynamically under the control of control plane. Routing and signaling protocols are running among control entities in the control plane to achieve quality network performance. These protocols should also solve the issues in granularity gap and switching timescale gap between packet and WDM networks.

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In the next section we discuss the two frameworks of joint operation, and propose a generic model for integration of IP and WDM networks in operation. Section 3 focuses on dynamic virtual topology, and gives more detailed descriptions of interfaces between IP and WDM networks. Section 4 presents a group of formulations in defining the routing and grooming issues to bridge the gap between IP and WDM networks. Section 5 proposes plans for cost function in designing routing and signaling protocols. Section 6 draws conclusion.

2. INTEGRATION OF IP AND WDM NETWORKS

The bottleneck in today's IP router-based infrastructure lies in electronic processing, and especially the routing table lookup process. To eliminate or relieve this bottleneck, some techniques have been adopted to turn the layer 3 routing into a label-based switching, typified by MPLS (multi-protocol label switching)⁹. Within the MPLS framework, regular IP packet is associated with a "label" according to a binding of forward equivalence class (FEC), and then switched and forwarded without further inspection of the IP header along its route till it reaches end or leaves an MPLS-enabled edge-router. Consequently, data streams (flows of IP packets) with various service requirements (bandwidth, delay, loss of packet, jitter, to name a few) can be supported by these fast-forwarded paths called LSP's (label switched paths), in contrast to the single best-effort traffic supported in traditional IP routers.

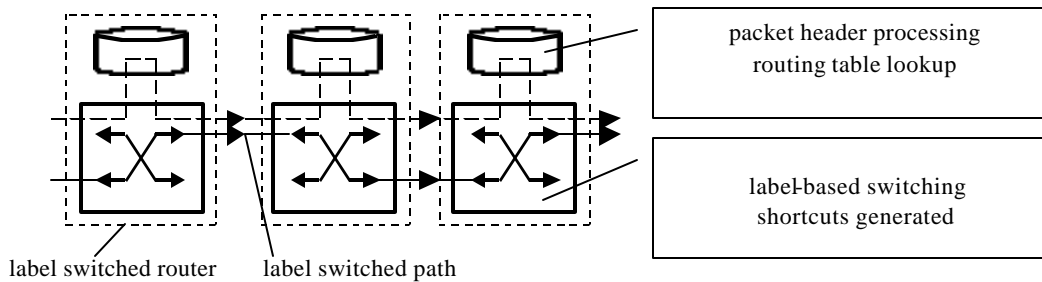


Figure 1 Shortcuts generated by label switched routers

In figure 1, we see that LSP's act as short-cuts to fast-forward the IP packets. However the contributions of MPLS are far more than fast-forwarding (in fact, this benefit has been challenged by recently-deployed wire speed legacy routers). One of the eminent contributions is the idea of separation of forwarding and routing. Label plays a key role in this separation. The basic aim of any switching is to establish connections between input ports and output ports and direct data on those connections. By associating with data, labels act as index entries for finding the corresponding connections established in switches. Labels and I/O port connections are stored in a database called forward information base (FIB). By using labels, the control plane is separated from the data plane. The data plane merely fulfill the task of forwarding according to FIB, while the control plane creates and maintains FIB, allocates and distributes labels according to routing information or other administrative commands (traffic engineering, network management, etc.).

Label is also a good abstraction of switching independent of the switching technique, in that labels can be taken in any form. For example, in classical MPLS network, label is a fixed-bit-length integer; in ATM, label takes the form of VPI/VCI; in SDH/SONET, label the time slot; and finally in WDM optical path networks, label the wavelength. By extending the MPLS into wavelength domain, a new framework for integration of IP and WDM networks is proposed, i.e. multi-protocol lambda switching^{7,8}.

Under this framework, the basic switching entity in WDM networks, or optical cross-connectors (OXC's), are IP addressable devices. Within the optical sub-network, lightpaths are the LSP's and label is wavelength, or lambda. To avoid ambiguity, we call such LSP's O-LSP's, and LSP's created within the electronic domain E-LSP's. Consider the optical networking model as shown in Figure 2, where clients (IP routers or MPLS switches) are attached to an optical core network composed of OXC's partitioned into sub-networks. The control plane is separately drawn. Under MPLS environment, this control plane can well be viewed as an IP control network. O-LSP's are setup, released and modified by RSVP signaling or CR-LDP within the optical sub-network or under the whole IP/MPLS control network.

Figure 2 also conforms to another joint operation framework proposed by T1 committee, automatic switched optical network, or ASON¹⁰. This architecture emphasizes on the automation of the OCh (optical channel) layer network, and proposes use of signaling protocols to setup OCh connections in real time. Client networks request connections in the optical core network (also the server) through signaling across the user-network interface (UNI), while lightpaths crossing optical sub-networks are setup and released via signaling across the network-network interface (NNI).

Despite the similarities, there are significant differences between ASON and MPLS. First MPLS favors a consistent view of topology between packet network and WDM network, while ASON prefers not revealing the topology to each other. The reason for this distinction is that MPLS holds a peer view that all controllers entity corresponding to switches, routers or OXC's are communication peers at the network layer, while ASON resembles the client and server model, in which specific knowledge of client should not be used in computing connections in server, and accordingly there is no service advantage in providing client visibility of server (OTN) topology. Thus the second difference between MPLS and ASON is that MPLS uses a uniform addressing scheme while ASON adopts different addressing schemes for IP and WDM networks. Therefore, in ASON, to the server all client names are translated into the namespace of server in accessing resources pertaining to the optical networks.

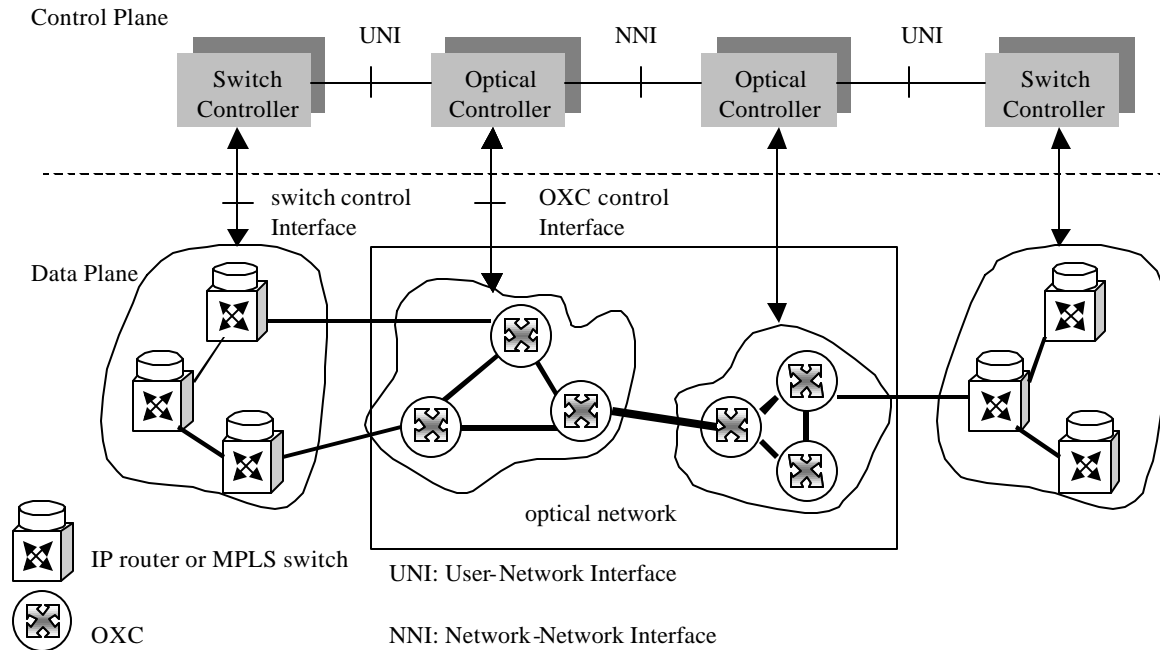


Figure 2 *Integration and internetworking of IP and WDM networks*

In this paper, we address the issue of IP over WDM integration under the model as shown in Figure 2, since it fits well to both MPLS and ASON frameworks albeit their differences. Notice that the key here is the separation of control from data manipulation (transportation). The data plane is layered to support the idea multi-layer switching as illustrated in the next section. The control plane does not necessarily resemble the layered model in data plane. It can be a simple IP network as suggested in MPLS framework or separate networks interconnected with defined interfaces as proposed in ASON framework. Either way, the optical part and the electronic part (part outside the optical core network) of the control plane can talk to each other in some language at the network layer (or layer 3) boundary.

This talk, or interaction happens at both UNI and NNI. At the UNI, the talk includes but is not limited to:

1. Service mapping and negotiation. An agreement between differentiated services model between optical networks and packet networks should be met herein. Usually optical networks have quite different service metrics than packet ones¹¹.
2. Connection or lightpath service. This includes connection setup, release and modification. Also in case of resource constraints, this talk may include scheduling of connection treatment. Diverse connections may also be considered to enhance resilience.
3. Traffic aggregation or merging, also known as traffic grooming. This should be cautiously treated to bridge the bandwidth granularity gap between packet and WDM networks.

At the NNI (within optical networks), the talk includes but is not limited to:

1. Connection maintenance. This includes information exchange of the topology and resource usage.
2. Impairment compensation. This includes compensation information for the nonlinear cumulative impairments such as dispersion, crosstalk, insertion loss, etc.

Thus extensions of current routing scheme or new routing and signaling scheme should be developed to fulfill these talks.

3. DYNAMIC VIRTUAL TOPOLOGY

As mentioned in section 1, a virtual topology optimized for total network cost or other objectives is the main aim of joint planning. In joint operation, virtual topology is also a good abstraction of resources in both optical and electronic layers. By maintaining a dynamic virtual topology, the optical part of the control plane as shown in Figure 2 can lead the whole network into an efficient state in operation. In this section, we discuss in detail relationship between virtual topology and resources in both optical and electronic layer, namely o-layer and e-layer.

To the upper e-layer, virtual topology is a set of connections. These connections are associated with information of connectivity (zero connections mean no connectivity) and available bandwidth for each node pair over the whole optical network. Data ports are the abstraction of interfaces for electronic routers or switches (we call them e-switches hereafter if not specified) attached to the terminals of light paths. These data ports feature fixed or discrete series of bit rates, smart framing and flexible bandwidth aggregation. A connection corresponds to a data link (DL) connecting two data ports from any two nodes. Note that it is possible for a node pair to have multiple links, with diverse or common routes.

To the lower o-layer, virtual topology is a set of lightpaths (LPs). In transparent optical networks, a light path passes through intermediate optical switches (OADMs or OXC's, we call them o-switches hereafter if not specified) without optoelectronic conversion. In opaque optical networks, a light path is regenerated (2R or 3R) at intermediate optical nodes to compensate for such cumulative degradations as crosstalk, dispersion, noise, jitter, etc. We consider a 3R or 2R regenerator (transponder) an optical layer device as long as it does not contribute to upper layer's decisions in traffic grooming or routing. The real optical network is a mixture of transparent and opaque ones, e.g. transparent domains with 3R at borders.

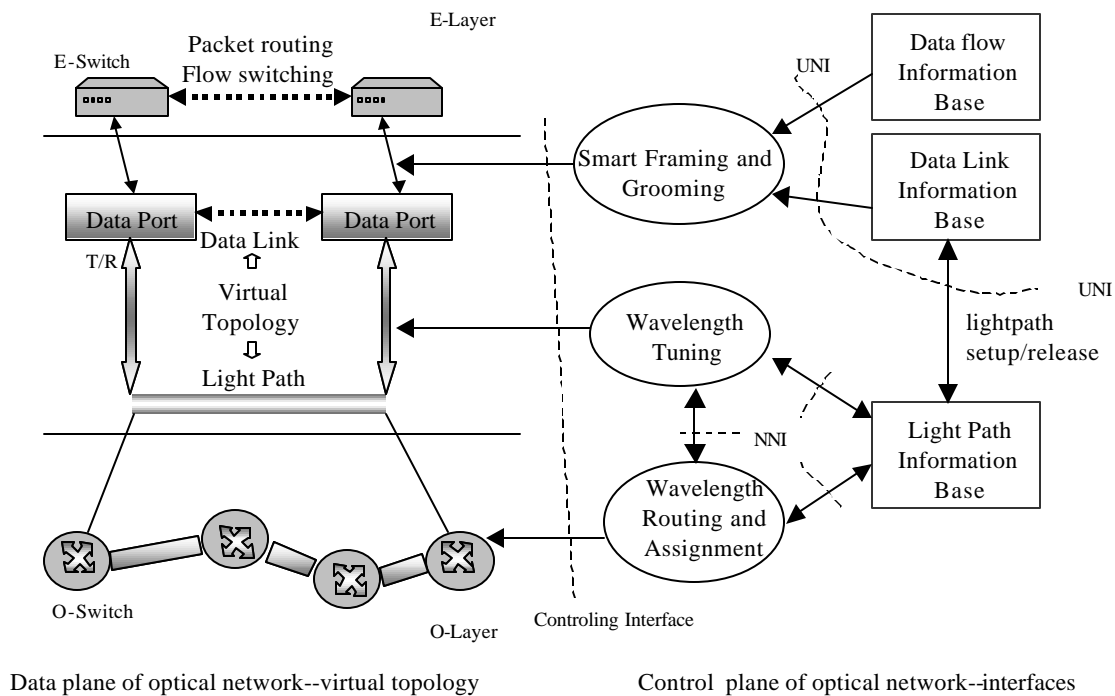


Figure 3 Data plane and control plane of optical network

The relationship between data link and light path is depicted in figure 3. In the data plane of optical networks overlaid by an e-layer, as shown on the left of figure 3, DL's act as logical links between switches from different sites, while light paths are the physical carrier for these DL's. When a light path is setup or released, the corresponding DL is added or reduced. The corresponding exchanges of the pertaining status and command information are initiated at the UNI defined at the rightmost of figure 3. In the control plane, the change of DL's is reflected by the change of connectivity or available bandwidth, and stored in the DL information base, while change of lightpaths stored in the LP information base. New protocols or extensions of existing routing protocols (OSPF etc.) must be employed to dispatch the alteration information as soon to

make these two databases consistent and initiate rerouting of data traffic. The e-layer does not care which LP supports a certain DL, i.e., the wavelength and wavelength path in use. Such information is associated with light paths within the o-layer. Likewise, the o-layer does not care such information as occupied and spare bandwidth associated with the DL supported by a certain light path. Thus DLs and LPs define well the interfaces for e-layer and o-layer within data plane, and also distinguish the UNI and NNI within control plane. Data traffic routing and wavelength routing run in two worlds demarcated by these two interfaces.

The control entity of smart framing and grooming acts as a “bridge and cushion” in solving the problem of granularity gap between e-layer and o-layer. Since the each LP is with a fixed or discrete series of bandwidth, which is deemed with coarse granularity, while data flows or data packets at the e-layer are with an arbitrary and much less bandwidth. A smart framing means that the data ports are capable of aggregating flows of various bandwidths without causing problems like contention or interleaving. Grooming indicates an efficient multiplexing is employed², and possibly reduces the electronic processing of e-layer (for most cases, the add/drop operations). The detailed physical implementation is not discussed here. However, in a computational view, this entity needs such information as connections and usage of the connections (e.g. ratio of spare to used bandwidth). Such information is fetched from electronic control counterpart across the UNI.

As is learnt from MPLS framework, connection or lightpath setup can be either data-driven or control-driven⁹. By selecting different routing and signaling in the control plane across UNI and NNI, we can manage to realize both of them. Details of the selections are for future topic.

4. PROBLEM FORMULATION

By adopting the concept of dynamic virtual topology, we can re-use some formulations previously used in joint planning^{4,5}. These formulations are useful in designing control algorithm in the control plane and in establishing analytical models. We present these formulations according to the model illustrated in last section. We mention e-layer and o-layer to match the layered model in the data plane.

In this section, the following are defined:

- N Number of nodes, a node is an oxc (o-switch) overlaid by one or a group of e-switches.
- N_{sd} Number of source-destination node pairs, $N_{sd} = N*(N-1)/2$. For simplicity, we assume all connections bi-directional and symmetric.
- $\mathbf{D} = \{D_n\}$ Number of data ports on node n , where $n = 1, 2, \dots, N$
We assume a uniform capacity for all data ports and take it as 1 unit. So D_n also represents the maximum capacity for node n .
- $\mathbf{d} = \{d_s\}$ Number of data links over node pair s , also the total capacity for connections over node pair s , where $s=1,2, \dots, N_{sd}$.
The value of 0 means no connectivity.
- $\mathbf{t} = \{t_s\}$ Aggregated traffic over node pair s in terms of requested bandwidth, where $s=1,2, \dots, N_{sd}$
- $\mathbf{R} = \{r\}$ Set of routes r , where r is a concatenation of node pairs, over each of which there is at least one data link.
- $\mathbf{a} = \{a_r\}$ Bandwidth allocated to route r . $r \in \mathbf{R}$
- $\mathbf{A} = \{A_{s,r}\}$ Traffic routes matrix in which $A_{s,r}$ takes the value of 1 if route r belongs to s-d pair s , 0 otherwise.
- $\mathbf{B} = \{B_{s,r}\}$ Traffic routing matrix in which $B_{s,r}$ takes the value of 1 if route r goes through a DL over node pair s , 0 otherwise.

First of all, the allocated bandwidth for all the routes added up should meet the bandwidth demand. We have

$$\sum_{r \in \mathbf{R}} A_{s,r} \cdot \mathbf{a}_r \geq t_s, \quad \forall s \in [1, N_{sd}] \quad (1)$$

The internet traffic has been characterized as bursty and fractal in nature. In (1) we use the sign of inequality instead of equality to spare room for sudden change of traffic demand. The term bandwidth works as a common word for mean traffic bitrate, peak bitrate, or equivalent bitrate, depending on which metric is of concern.

At the e-layer, some traffic shaping mechanisms may be employed to utilize multiplexing gain and increase bandwidth efficiency. Buffers, for example, can be placed at the source and destination nodes to smooth a bursty traffic. An equivalent bitrate for a peak counterpart is determined by the buffer space without violating such QoS constraints as a given packet loss ratio, delay, jitter, etc. Details of traffic shaping, however, are out of the topic of this paper.

Secondly, over each s-d pair, the aggregated bandwidth should not exceed the total capacity of the data links, i.e.

$$\sum_{r \in \mathbf{R}} B_{s,r} \cdot \mathbf{a}_r \leq d_s, \quad \forall s \in [1, N_{sd}] \quad (2)$$

Expression (1) and (2) regulate the determinations of routes \mathbf{R} and allocated bandwidth \mathbf{a} . We define **routing** as find or computation of the routes \mathbf{R} , and **grooming** as allocation of bandwidth \mathbf{a} for these routes. The idea of separate definitions

for bandwidth and routes is not novel but borrowed from “VP” in ATM. To support grooming, the data ports must be capable of smart framing and bandwidth management.

Expression (1) relates routing and grooming (RAG) with traffic matrix \mathbf{t} , while (2) connects them with data link matrix \mathbf{d} . Matrix \mathbf{d} could be considered the demand matrix of light paths for o-layer. These relations indicate that RAG works as a “**bridge and cushion**” between traffic demand of e-layer and provision ability of o-layer. By properly altering \mathbf{R} and \mathbf{a} , we could accommodate some traffic changes without affecting o-layer configurations. When o-layer reconfiguration is unavoidable due to bigger traffic variations, a smart RAG could also minimize such reconfiguration or maximize resource efficiency.

There is a special group of routes, each of which passes over only one data link. They are also called one-hop routes. These routes are important since traffic taking on them do not incur any electrical forwarding, which is a key factor affecting the network performance. In fact, if there are enough resources for all traffic to be carried on one-hop routes, no routing and grooming is needed, traffic are transported on the fly. However, such situation could hardly happen because of the obvious scalability problem and limitations of both optical resources like wavelength and electrical resources like data ports or transceivers.

One-hop routes correspond to node pairs with at least one data link. We assume there is a potential data link and hence a one-hop route over every node pair. We denote the allocated bandwidth for one-hop routes as $\mathbf{a}^{(1)}$. (If there is no data link for some node pair s at a certain network state, the allocated bandwidth $\mathbf{a}_s^{(1)}$ is 0.) When one-hop route is not available or bandwidth along with it is congested, a detouring multi-hop (more than one hops) route is chosen for demanded traffic. Detoured traffic is very common in today’s e-layer networks. Typically a minimum hop or a shortest path routing algorithm is running. If load balancing or traffic engineering is leveraged, several edge-disjoint routes may be chosen for traffic detouring. The total allocated bandwidth for multi-hop routes per node pair is denoted by \mathbf{a}^m . Thus, the anticipated traffic could be carried by two parts, one-hop routes and multi-hop routes, i.e.

$$\mathbf{a}_s^{(1)} + \mathbf{a}_s^m \geq \mathbf{t}_s, \quad \forall s \in [1, N_{sd}] \quad (3)$$

For data links per node pair, the bandwidth constraint still holds. (2) could be rewritten as

$$\mathbf{a}_s^{(1)} + \sum_{s' \in [1, N_{sd}], s' \neq s} C_{s,s'} \mathbf{a}_{s'}^m \leq \mathbf{d}_s, \quad \forall s \in [1, N_{sd}] \quad (4)$$

In expression (4), a multi-hop grooming matrix is denoted by $\mathbf{C} = \{C_{s,s'}\}$. Here the value of $C_{s,s'}$ indicates the allocated bandwidth on data links over node pair s for multi-hop traffic of node pair s' . If more than one multi-hop routes are chosen and bifurcation of traffic is allowed (an implicit assumption in this paper), the value of $C_{s,s'}$ can be a fraction other than 1 or 0. Note that $C_{s,s} = 0$, since \mathbf{C} refers only to bandwidth distribution of multi-hop traffic.

Now we can turn (3), (4) into matrix forms:

$$\mathbf{E} \cdot \mathbf{a}^{(1)} + \mathbf{E} \cdot \mathbf{a}^m \geq \mathbf{t} \quad (5)$$

$$\mathbf{E} \cdot \mathbf{a}^{(1)} + \mathbf{C} \cdot \mathbf{a}^m \leq \mathbf{d} \quad (6)$$

Here \mathbf{E} denotes an N_{sd} -by- N_{sd} identity matrix. By reversing the sign of inequality in (5), we can merge (5) and (6) into a more concise expression, i.e.

$$\begin{pmatrix} -\mathbf{E} & -\mathbf{E} \\ \mathbf{E} & \mathbf{C} \end{pmatrix} \begin{pmatrix} \mathbf{a}^{(1)} \\ \mathbf{a}^m \end{pmatrix} \leq \begin{pmatrix} -\mathbf{t} \\ \mathbf{d} \end{pmatrix} \quad (7)$$

$\mathbf{a}^{(1)}$, \mathbf{a}^m , \mathbf{t} and \mathbf{d} are all N_{sd} -by-1 column vectors. By eliminating $\mathbf{a}^{(1)}$ in (5) and (6), we have,

$$(\mathbf{C} - \mathbf{E}) \cdot \mathbf{a}^m \leq (\mathbf{d} - \mathbf{t}) \quad (8)$$

Since each value in \mathbf{C} is non-negative, multiplexing \mathbf{C} to both sides of (5) does not change the sign. By eliminating \mathbf{a}^m , we have

$$(\mathbf{C} - \mathbf{E}) \cdot \mathbf{a}^{(1)} \geq (\mathbf{C} \cdot \mathbf{t} - \mathbf{d}) \quad (9)$$

From (8) and (9), we can see how $\mathbf{a}^{(1)}$, \mathbf{a}^m , \mathbf{C} , \mathbf{t} and \mathbf{d} are coupled together.

In order to have a closer look at the RAG issue, let’s define some derived variables:

$$\Delta = \mathbf{d} - \mathbf{t} \quad (10)$$

Δ refer to the difference between provisioned bandwidth and the demanded bandwidth over each node pair;

$$\mathbf{S} = \mathbf{d} - \mathbf{a}^{(1)} \geq 0 \quad (11)$$

\mathbf{S} refer to the spare capacity left for grooming of multi-hop traffic;

$$\mathbf{R} = \mathbf{t} - \mathbf{a}^{(1)} \geq 0 \quad (12)$$

\mathbf{R} refer to the residue traffic other than one-hop traffic, these traffic must be multi-hop routed. The nonnegativeness of \mathbf{R} and \mathbf{S} sets an upper bound for one-hop traffic $\mathbf{a}^{(1)}$. Finally we define

$$\mathbf{G} = \mathbf{C} \cdot \mathbf{a}^m \quad (13)$$

\mathbf{G} refer to the bandwidth groomed over each node pair.

From the meaning of \mathbf{D} , \mathbf{S} , \mathbf{R} and \mathbf{G} , we also have

$$\Delta = \mathbf{S} - \mathbf{R} \quad (14)$$

$$\mathbf{R} \geq \mathbf{a}^m \quad (15)$$

$$\mathbf{G} = \mathbf{C} \cdot \mathbf{a}^m \leq \mathbf{S} \quad (16)$$

From these equations we can determine three distinguished states of connections over each node pair, as shown in the following table. These states are determined by bandwidth difference \mathbf{D} and above equations.

State	I	II	III
Bandwidth difference	$\mathbf{D} \gg 0$	$\mathbf{D} \approx 0$	$\mathbf{D} \ll 0$
One-hop traffic carried	$\mathbf{a}^{(1)} > t$	$\mathbf{a}^{(1)} = d - S$	$\mathbf{a}^{(1)} = d$
Multi-hop traffic groomed	$\mathbf{a}^m = 0$	$\mathbf{a}^m > R$	$\mathbf{a}^m > R$
Residue traffic for multi-hop routed	$R = 0$	$R = S - \mathbf{D}$	$R = -\mathbf{D}$
Spare space for traffic grooming	$S = \mathbf{D}$	$S > 0$	$S = 0$

Table 1 Bandwidth usage states for connections over one node pair

In case we could find the an grooming matrix \mathbf{C} satisfying \mathbf{S} , the network is in a stable state where each node pair remains in one of the three states, and there is no need to initiate the reconfiguration at o-layer or re-routing at e-layer. Otherwise, at least one node pair is departed from the stable states. By changing R or S (adjusting the one hop traffic bandwidth) for each node pair, we can expect a new \mathbf{C} generated. When it does not success, a VT reconfiguration is initiated. Usually, grooming adjusting is again evoked after a VT change. Therefore special care should be taken to avoid a circular initiation of grooming adjusting and VT change. And that's why we put grooming and lightpath control entities in one domain (optical domain) in our integration model shown in figure 3.

5. ROUTING AND SIGNALING

The prevailing routing protocols over Internet are OSPF, BGP, RIP, IS-IS, etc. They have common traits. They all carry one or more metric or cost value as network information to be exchanged among network nodes. Routing entities within each node then decides routes and stores network topological information based on these values. Such cost value can be such simple additive metric as hop count, distance, network reach ability, or resource related metrics such as bandwidth, spare resources, etc.¹²

In our model, cost is an important function, which may be used in routing and signaling within the control plane. Chiefly there are two usages: one is to determine the time to initiate VT change or grooming adjusting as stated in last section, the other is to determine routes and lightpath allocation (RWA problem¹). The second usage can reuse the mature routing protocols, which are extended into the wavelength domain. For the second usage, there are three sources for defining the cost function:

1. Static or administrative: distance, hop, propagation delay, or topology dependent metrics, this is quite common in today's Internet
2. Resource related, bandwidth dependent, or shared resources, for example, the wavelength converters¹³, etc.
3. Allocation scheme related, for example for wavelength assignment we have PACK, SPREAD scheme¹⁴, or in such order: first fit, random, or longest path first, these schemes could also be represented by a cost function.

Finally, a shortest path algorithm based on these cost functions could be run to simulate a routing algorithm. We will select several combinations of these three categories of cost functions and test them in a simulated environment in our future work.

6. CONCLUSION

In this paper, we study the joint operation approach in integration of IP over WDM networks. Two proposed frameworks MPLS and ASON are analyzed and compared. We propose a network model conforming to both of the frameworks. This model is established on a mesh-connected optical (WDM) core network with electronic switches/routers attached to it. A separation of control plane and data plane is defined. The data plane resembles a layered model, and dynamic virtual topology works fine in this model. We then put virtual topology into formulations and define the grooming and routing in mathematical expressions. Three stable states of network connections are identified through these formulations. We finally

talk about the routing and signaling implementation within the control plane. General rules for defining cost functions are proposed. And the hence proposed algorithm need further test and simulation.

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