

End-to-End Service Provisioning in Multi-granularity Multi-domain Optical Networks

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Abstract—In this paper, we propose a multi-segment optical network framework as a tool to solve a generalized category of problems related to end-to-end provisioning over interconnected optical networks. This network model is referred to as multi-segment network model, where the notion of networking segments refers to any portion of an optical network that requires particular consideration for control, e.g., sub-networks characterized by logical segments of the optical control plane that can refer to different levels of traffic aggregation, different administrative areas, or different transport layer technologies. Based on the multi-segment framework, we developed routing schemes for the multi-granularity multi-domain optical networks. For examples of regional all-optical networks interconnected over an all-optical WDM backbone under a variety of traffic conditions, we present and compare numerical results. The performance results demonstrated the ability of our schemes to handle various network conditions under different control plane architectures.

I. INTRODUCTION

The need to deliver global services with QoS guarantees to end-users combined with advances in IP-over-optical networking technologies motivates the consideration of *End-to-End Wavelength Service Provisioning*. In this visionary scenario, wavelength services carrying data originating from higher-layer applications are provisioned from residential or business end-customers in the access networks, over interconnected metro and backbone networks. Assumed is the non-manual provisioning that enables timely configuration of the network infrastructure supported by the advanced solutions for the distributed control plane architectures. We also envision that future wavelength services with little or no reliance on the electronic layer, e.g. SONET/SDH. Significant work has recently been carried out to generate the tools required for end-to-end service provisioning. Among them, the definition of standard control plane architectures for network control and user-to-network and network-to-network interfaces (UNI and NNI, respectively) for inter-domain communication have enabled the development of major building blocks [1,2].

The control of interconnected networks can be generally characterized by three basic parameters: a) properties of each network, b) properties of traffic granularities within the network and on gateways interconnecting them, and c) properties of traffic locality, *i.e.*, whether the traffic is local or global. The complexity associated with provisioning end-to-end optical services depends on three basic dimensions: locality (metro/backbone, single/multi-domain), granularity (single/multi-granularity) and ownership (single/multi-carrier). By varying their combination and significance, various

networking scenarios can be identified. Consider an example of the multi-granularity, multi-domain network scenario shown in Figure 1. Each network domain (here 3) is first characterized by its topology, routing policy, or transport layer properties (e.g. conversion/no conversion). In addition, each domain can be characterized by different traffic granularities. The notion of “multi-granularity” is referred to as the case where the service goes through networks with “multi-layer” transport planes (e.g., STS-1 within a wavelength) [3], which, in addition, can have different granularities of wavelength connections (e.g. 2.5Gb/s, 10Gb/s). While multi-granularity is thus a more general concept than what is usually referred to as “multi-layer”, for practical reasons we will use these two terms interchangeably. For example, the STS-1 granularity of traffic can be accommodated within OC-12 in the metro segments, while higher granularities, e.g. within OC-192 or a wavelength can be defined for the backbone networks. Finally, the traffic is characterized by its locality, *i.e.*, local or global, which means that some traffic is only carried within the metro network, while some other cross the backbone on the way from source to destination. Furthermore, an end-to-end path can be within a single granularity or across multiple granularities.

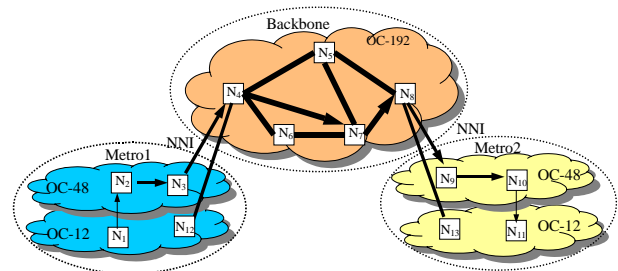


Figure 1. Multi-granularity multi-domain network

For end-to-end service provisioning in this and similar scenarios, detailed routing information may not be available outside the local sub-network. For example, sub-networks from different carriers do not exchange full information, or in a multi-granularity network, resources in one granularity (layer) may be transparent to the other. In addition, local and global traffic may be required to be routed differently. Typically, local traffic could be accommodated regardless of the status of other networks. In contrast, global traffic must be accommodated with the collaboration among multiple networks since the source and destination of global traffic belong to different networks. Therefore, the solutions to the control planes that has to handle different granularities, types of traffic and transport layer properties has to be general

enough to handle the emerging scenarios, such as multi-vendor or multi-carrier scenarios.

In this paper, we propose a multi-segment optical network framework as a tool to solve this generalized category of problems related to the control plane architecture required for end-to-end provisioning over interconnected optical networks. This control plane model is referred to as *multi-segment* network model, where the notion of networking segments refers to any portion of the control plane that will require particular consideration for end-to-end provisioning. For example, segmented control plane can refer to different levels of traffic aggregation (“multi-granular”), different administrative areas (“multi-carrier”), or different transport layer technologies (“multi-vendor”).

Based on the multi-segment framework, we developed in this paper routing schemes for the multi-granularity multi-domain optical networks as the example scenario of the applicability of the general framework. Recently, a number of works addressed the multi-layer/multi-granularity issue. Ho *et.al.*, solve the RWA problem with multi-granularity traffic [4]. Zhu *et.al.*, perform traffic engineering in multi-granularity optical networks using dynamic traffic grooming [5]. However, in contrast to the recent works in this area, which all focus on transport plane issues and assume single administrative domain where full information of all layers/granularities is available, the solution presented here is more general and capable of performing multi-granularity routing under various control plane scenarios.

The rest of this paper is organized as follows. Section II presents the multi-segment framework as a tool to solve a generalized category of problems described before. Section III develops the end-to-end provisioning schemes for the multi-granularity multi-domain networks. Section IV presents the performance study and numerical results. We conclude the paper and discuss future work in Section V.

II. MULTI-SEGMENT OPTICAL NETWORK MODEL

The multi-segment network model presented next includes three key components: 1) a single segment model with segment specific properties, 2) segment interconnections through gateways, and 3) traffic.

A. Networking segments

Networking segment represents any portion of an optical network that requires particular consideration for control of end-to-end provisioning. It is therefore a general concept and can model vendor specific networks, carrier-specific networks or sub-networks with different traffic granularity. Each segment is characterized by following parameters.

Segment topology (G): The topology of each segment is a connected graph $G=(V,E)$, where the set of vertices V , and set of unidirectional edges E represent nodes and links in the segment respectively. We further divide the nodes into internal

nodes (V_I) and border nodes (V_B). Nodes that only have segment internal links are internal nodes and nodes that have links to outside the segment are border nodes.

Weight function (w): Associated with each edge $e \in E$, there is a non-negative weight $w(e)$, representing the cost to route the connection through this edge. As we will see in the next section, weights can be assigned to reflect specific applications and optimization goals.

Segment specific properties (P): Associated with each segment are some segment specific properties in the transport layer. Among all segment specific properties, we are particular interested in traffic granularity (TG) which represent the set of units of bandwidth that can be carried on each transport link.

B. Gateways

The multi-segment network is composed of a number of segments $S = \{s_i\}$, $i=1,2,\dots,Q$ and a set of gateways GW . Each network node can be addressed as (s_i, u) , $s_i \in S, u \in V_{(i)}$. Neighboring segments are interconnected through gateways. Each gateway $gw \in GW$ contains two border nodes from different segments connected by one *bridge link*. We characterize a gateway as $gw=(id, s_i, u, s_j, v)$, where id denotes the index of the gateway (for numbering multiple gateways connecting the same pair of segments), s_i and s_j are starting and ending segment interconnected through the gateway respectively and $u \in V_{B(i)}, v \in V_{B(j)}$ are the starting and ending vertexes (border nodes) of the bridge link respectively. Figure 2 shows an example of a multi-segment network composed of 4 segments interconnected through 4 gateways, in which the gateway connecting segment s_i and s_j is (id, s_i, v_2, s_j, v_1) . Each gateway $gw \in GW$ also has a non-negative weight $w(gw)$, representing the cost to carry the connection through this gateway.

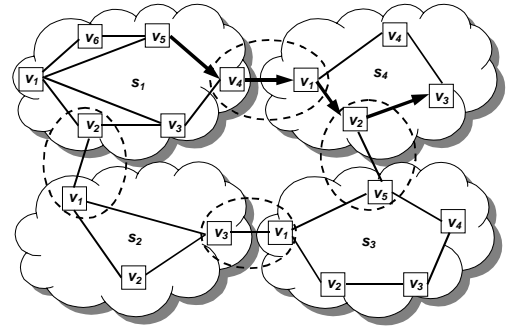


Figure 2. Multi-segment network, gateway are circled using dash lines.

Associated with each gateway $gw \in GW$ are various adaptation functions $A(gw)$, which enable to interconnect multiple segments for end-to-end provisioning. Examples of gateway adaptation functions in the transport layer include: wavelength conversion, wavelength merging, or traffic granularity adaptation. Since our focus in this paper is multi-granularity wavelength routing from the point of view of the control plane (*i.e.*, the data from the transport plane are given), we will only consider adaptation on traffic granularities. The

granularity adaptation here is used to represent the control of mux/de-mux nodes in networks with various levels of traffic granularities which are often referred to as multi-layer networks or networks with traffic grooming.

C. Traffic locality

In the multi-segment model, traffic is represented as $(tid, s_s, v_s, s_D, v_D, P_t)$, where tid is index of the traffic, node $n_{s=(s_s, v_s)}$ and $n_{D=(s_D, v_D)}$ are the source and destination of the traffic respectively and P_t is the properties of the traffic such as bandwidth requirement (b), service level agreement (SLA).

In multiple segments interconnected by gateways, the traffic may originate from and be destined to any segment. We refer to the traffic whose source and destination are within the same segment as local traffic, i.e., $s_s = s_D$. Traffic whose source and destination belong to different segments is called global traffic, i.e., $s_s \neq s_D$. Global traffic will travel a number of segments and the gateways connecting them. This paper focuses on end-to-end service provisioning for global traffic and we assume that the local traffic is accommodated with segment internal mechanisms, which do not impact the global routing strategies. For example in Figure 2, the end-to-end path for global traffic from node (s_1, v_5) to (s_4, v_3) is $(s_1, v_5) \rightarrow (s_1, v_4) \rightarrow (s_4, v_1) \rightarrow (s_4, v_2) \rightarrow (s_4, v_3)$, where $(s_1, v_5) \rightarrow (s_1, v_4)$ and $(s_4, v_1) \rightarrow (s_4, v_2) \rightarrow (s_4, v_3)$ are segment internal paths of s_1 and s_4 respectively and $(s_1, v_4) \rightarrow (s_4, v_1)$ is the gateway connecting them.

III. MULTI-GRANULARITY MULTI-DOMAIN SERVICE PROVISIONING

In this section, we will illustrate the applicability of the multi-segment model by using the example of end-to-end provisioning in multi-granularity multi-domain networks. Specifically, we will first illustrate how the problem can be described and mapped to the multi-segment model. Based on that, we will then provide heuristics that can enable end-to-end provisioning. These heuristics will be the basis for the related numerical results shown in the next section.

The input of the multi-granularity wavelength routing problem is the multi-granularity network topology used in the control plane that will enable to find a path, available wavelengths, and traffic granularity channels along that path to achieve certain optimization objectives such as maximum bandwidth utilization, minimum use of mux/de-mux nodes or minimum number of hops. Note that what will be next represented as a *graph*, is the basis for a variety of different control plane architectures. For example, a control plane architecture can assume that all graphs are known centrally. On the other hand, each graph can be known to separate control planes, which then have to interact with other control planes in order to assess the reachability information. In the rest of this subsection, we will present a 5-step heuristic method to solve the above end-to-end provisioning problem based on the multi-segment model.

We first consider a single domain multi-granularity network. Given a single-vendor network topology $G=(V, E)$

with associated traffic granularity function TG , and the set of mux/de-mux nodes, the start point of multi-granularity routing is to accommodate the connection request $c=(source, dest, b)$ where b is the requested bandwidth.

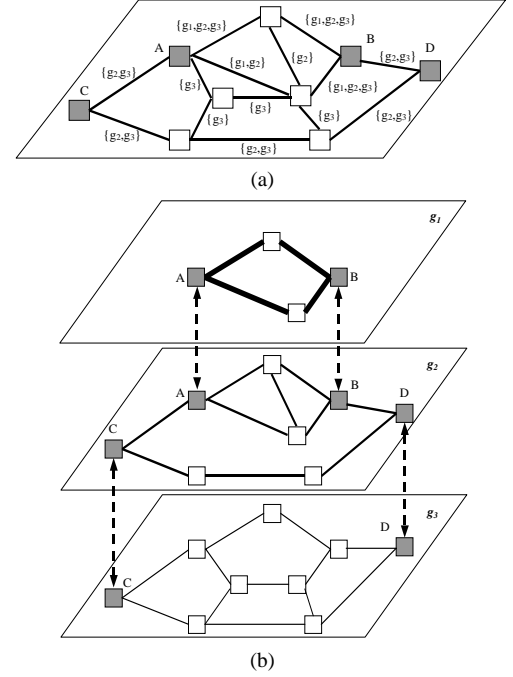


Figure 3. (a) Network with multiple traffic granularity (b) its corresponding multi-granularity graph.

Step 1: Multi-granularity graph transformation

In the network with heterogeneous traffic granularities, traffic can only aggregate and split at multiplexing/de-multiplexing nodes. In the most general case, locations of mux/demux nodes can be anywhere in the network and different traffic granularity can exist at anywhere in the network. The network is first transformed into multi-granularity graph as follows:

- For each $g_i \in TG(G)$, create a separate sub-graph (granularity graph) $G_i^L = (V_i^L, E_i^L)$, which is initially empty.
- For each vertex $v \in V$, add a new vertex in the corresponding granularity graph to each of the granularities in the set $TG(v)$.
- For each edge $e \in E$, add an edge link in the corresponding granularity graph to each of the granularities in $TG(e)$.
- For each mux/de-mux node $v \in V$, add a bi-directional mux/de-mux link between corresponding nodes in the corresponding granularity graphs.

Figure3(a) gives an example of a network supporting 3 traffic granularities: $TG(G) = \{g_1, g_2, g_3\}$, and the traffic granularity set $TG(e)$ is marked besides each edge $e \in E$.

Mux/de-mux nodes are marked in gray in the figure. The corresponding multi-granularity graph is shown in Figure 3(b).

Step 2: Multi-segment network representation

In the multi-granularity graph, although the whole network is connected, each individual granularity graph itself is not always connected. If we directly use single segment to model the each of them, then there will be the case that the local traffic needs to be accommodated by resources outside the segment (“leased resources”). This can be illustrated as Figure 4(a), where connection request from node A to D need to be routed though granularity g_2 although the source and destination (A & D) belong to the same granularity g_1 graph. To solve this problem, we divide each granularity graph further into a number of self-connected sub-graphs. Each of these sub-graphs is represented by a separate segment. Figure 4(b) shows an example of the 3-segment network corresponding to the 2-granularity network.

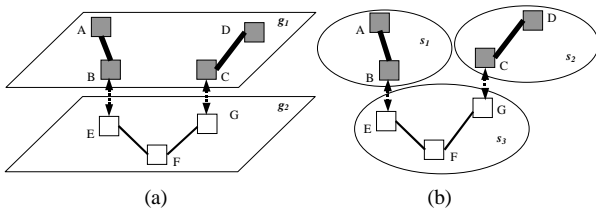


Figure 4. Example of “leased resources” from the higher granularity traffic.

The detailed transformation is showed as follows:

- For each granularity graph $G_i^L = (V_i^L, E_i^L)$, calculate its connected components $(V_{i1}^L, V_{i2}^L, \dots)$.
- For each V_{ij}^L , induce a sub-graph
- Create one segment s_{ij}^L for each sub-graph $G_{ij}^L = (V_{ij}^L, E_{ij}^L)$
- Create one gateway between corresponding segments for each mux/de-mux link in the multi-granularity graph.
- The traffic granularity function is: $TG(G_{ij}^L) = \{g_i\}$, for any segment and is homogenous for all edges within the segment.

At the end of this step, the original connection request $c=(source, dest, b)$ is mapped into multi-segment connection request $c=(tid, s_s, v_s, s_D, v_D, b)$ where (s_s, v_s) and (s_D, v_D) are source and destination addresses in the multi-segment network respectively.

Step 3: Weight assignment

In the multi-segment network generated above, weights within in each segment are uniform distributed and depends on the traffic granularity it carries, i.e.,

$$w(e) = w(G_{ij}^L) = w(g_i) \text{ for each } e \in E_{ij}^L$$

We have the following heuristic weight assignment schemes:

- Finest granularity first (FINE)

For segment internal link, $e \in E_{ij}^L$, $w(e) = w(G_{ij}^L) = w(g_i) = \alpha \cdot g_i$. For gateway bridge link e_{GW} , connecting segments with granularity g_i and g_j , $w(e_{GW}) = \beta \cdot \text{Min}(g_i, g_k)$, $\alpha, \beta > 0$ and $\alpha \gg \beta$

- Minimize number of mux/de-mux nodes (*MinMux*)

For segment internal link, $e \in E_{ij}^L$, $w(e) = w(G_{ij}^L) = w(g_i) = \alpha$. For all gateway bridge link e_{GW} , $w(e_{GW}) = \beta$, $\alpha, \beta > 0$ and $\alpha \ll \beta$

- Minimize hop counts (*MinHop*)

For segment internal link, $e \in E_{ij}^L$, $w(e) = w(G_{ij}^L) = w(g_i) = \alpha$. For gateway link e_{GW} , $w(e_{GW}) = 0$

Step 4: Path selection

We have developed three generic multi-segment wavelength routing algorithms: E2E, CSR and HIR in [6]. After the weight assignment, these multi-segment routing algorithms can be applied to select the path. E2E routing can be used in the multi-vendor network with unified control plane where full network information is available. It selects the end-to-end path using global shortest path algorithm. However, E2E routing cannot work for networks with vendor specific integrated control plane where different vendors cannot exchange detailed routing information. Instead, CSR and HIR routing can be used here to find the end-to-end path. In CSR routing, each segment decides the route and allocates wavelengths only based on local information. Gateways, on the other hand, make the decision regarding to the next segment towards the destination based on the segment interconnection information. HIR routing is between E2E and CSR in the sense that all nodes maintain local information and some inter-segment connectivity information such that they can directly choose the right gateway towards the next segment to the destination.

Step 5: Resource allocation

After path selection, channel/wavelength assignments are performed along the end-to-end path. If there is no enough resource available, the call is blocked.

The above 5-step scheme can be extended to multi-carrier or multi-vendor multi-granularity network, where the network is composed of sub-networks from different administrative domains and each domain has multiple granularities (layers). In this scenario, we first apply the step 1-3 to each administrative domain with multiple granularities to generate connected sub-graphs in each layer of each carrier/vendor network. The multi-segment representation of the multi-granularity multi-domain network is determined by it control plane scenarios, which could be either vendor-specific or unified. For example, in the multi-layer vendor specific control plane scenario (MLS), each vendor specific part of the optical network is mapped into a segment and all interfaces between these vendor-specific networks are mapped into gateways. In the single layer vendor specific control plane scenario (SLS), each segment represents a single layer within

each vendor network and gateway represents the both SNP interfaces between different layers [1] and interfaces between different vendor networks [1, 2]. In the single layer unified control plane scenario (SLU), each segment represents a single layer across all vendor networks and gateway represents the SNP interfaces between different layers. In the example of a 3-domain multi-granularity network shown in Figure 1, if each granularity graph is connected, then the number of segments in the corresponding multi-segment network will be 3 for MLS control plane, 5 for both SLS and SLU control plane. In this paper, we assume the given control plane and focus on the routing schemes. The analysis and comparison of various control planes is beyond the scope of this paper.

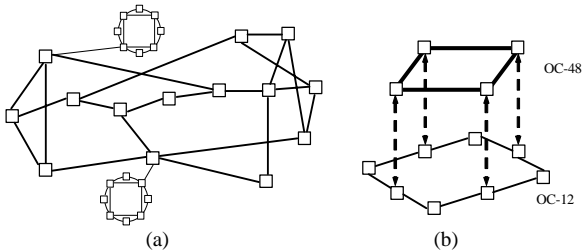


Figure 5. (a) 14-node NSFNET backbone, each backbone node is attached to a replicated metro network (only shown 2 here) (b) 2-layer metro topology.

IV. PERFORMANCE STUDY AND NUMERICAL RESULTS

In this section, we will show the numerical results related to the proposed end-to-end provisioning schemes for multi-granularity multi-domain networks and particularly focus on metro-backbone interconnection scenarios where the backbone and metro networks have their own, i.e. vendor-specific properties. The backbone network topology used in our experiments is a 14-node single layer (OC-192) NSFNET topology (shown in Figure 5(a)). A replicated metro network is attached to each backbone node. All metro networks have 2 granularities (OC-12 and OC-48). OC-12 layer is an 8 node bi-directional ring with 8 channels, and OC-48 layer is a 4-node bi-directional ring with 8 channels (Figure 5(b)). All nodes in OC-48 layers are capable of muxing/de-muxing to OC-12 layer (shown as dashed vertical links in Figure 5(b)). Metro networks are connected to the backbone at both OC-12 and OC-48 layers. In all the experiments, the connection requests arrive according to a Poisson process with call holding time being exponentially distributed and the bandwidth requirement uniformly distributed from OC-1 to OC-12 (discretely). Although the multi-segment model is capable of handling various transport plane scenarios (full wavelength conversion, partial wavelength conversion, wavelength merging) [6, 7], our focus here is how to perform end-to-end provisioning under given control plane architectures. Therefore, we only show the scenario that all nodes are capable of full wavelength conversion (i.e., OEO in all nodes) for illustration. To focus on the end-to-end provisioning, we also assume all traffic are global. The backbone does not generate any traffic and only carries global traffic generated between metro networks. Metro traffic distribution is uniform, i.e., all global calls are equally likely to arrive at any node at any layer, and are equally likely to be destined to any nodes at any layer in any other metro network. Each result is obtained with 95% of confidence level.

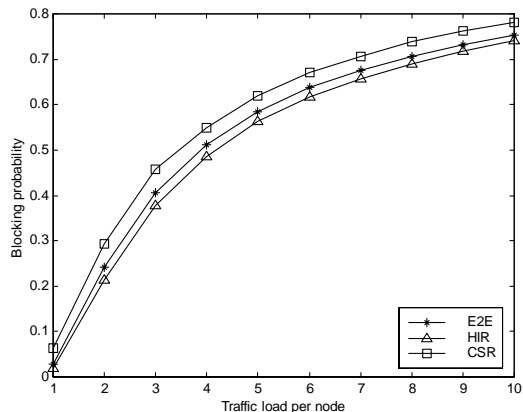


Figure 6. Blocking performance for SLS control plane.

The first experiment compares the blocking performance different multi-segment routing algorithms [6]. Assuming the network has the single layer vendor specific control plane (SLS), the whole network is represented as a 29-segment network where each segment represents a separate control plane for a single layer within a single vendor network. The weight assignment scheme is MinHop. The result in Figure 6 shows that CSR routing has the highest blocking probability since only local information is available for the routing algorithm, which is consistent with our previous study on the single granularity networks [6]. However, HIR routing has lower blocking probability than the E2E, this is caused by the special topology rather than a general conclusion. We represent 2 layers in each metro as two separate segments. Since HIR routing uses the segment level shortest paths, the traffic load will be distributed on both layers under uniformly distributed traffic. In contrast, E2E routing selects the path based on global shortest path, it always routes the traffic on the OC-48 layer (since it gives shorter routes than the OC-12 layer as shown in Figure 5(b)). Therefore, the traffic is concentrated on OC-48 layers, which results in higher blocking.

To further compare the performance of end-to-end provisioning in terms of blocking probability, average path length and bandwidth utilization, in the rest of our experiments we will focus on multi-layer vendor specific control plane scenario (MLS), where each segment represents a control plane for all layers within a vendor network (either backbone or metro). Therefore, the total number segment is 15 now. The parameters for various weight assignment schemes are chosen as follows: $\alpha = 1, \beta = 0.1$ in FINE scheme, $\alpha = 1, \beta = 500$ in MinMux scheme and $\alpha = 1$ in MinHop scheme.

The blocking probability results in Figure 7 show that different weight assignment schemes have different blocking performance. This is because they have different optimization objectives. For example, the FINE scheme chooses the finest granularity first and has the highest blocking probability, since all the metro traffic is concentrated on the finest granularity channels (OC-12). Because of the special topology we are using, traffic of MinHop scheme concentrates on OC-48 channels (since they provide shorter path than the OC-12 channels), therefore, it also has higher blocking than the

MinMux scheme which distribute the traffic load on both OC-12 and OC-48 layers.

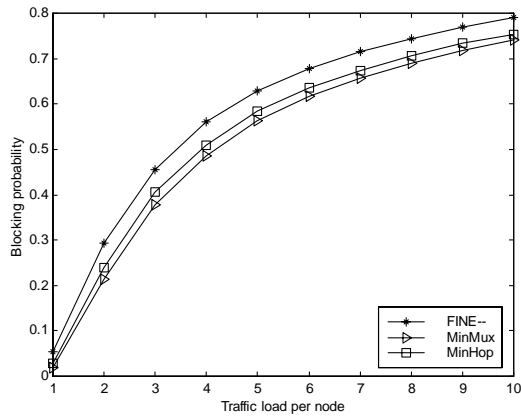


Figure 7. Blocking performance v.s. traffic load

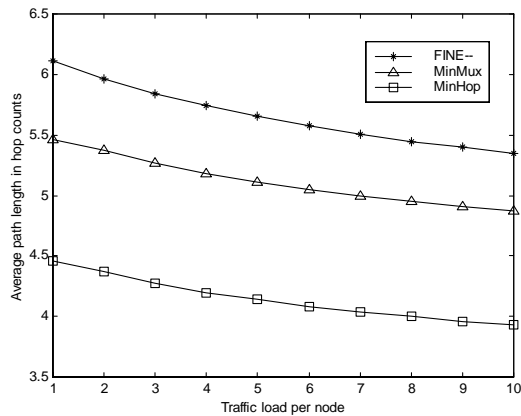


Figure 8. Average path length v.s. traffic load

Shorter end-to-end path means lower the end-to-end call setup delay. Therefore, average path length is another important performance parameter for end-to-end provisioning. Figure 8 shows that MinHop scheme successfully achieves the lowest average path length. FINE scheme, however, has the longest average path length since it goes through longer routes for the finest possible channels.

For the same multi-granularity multi-domain network and control plane architectures, we also compared the metro bandwidth utilization of each scheme. The bandwidth utilization for a channel is defined as the ratio of utilized bandwidth to the available bandwidth (granularity). Table II shows the average bandwidth utilization of all channels across all metro networks under low, medium and high traffic loads (corresponding traffic load per node are 1, 5 and 10). The results here indicate that FINE scheme achieves the much higher bandwidth utilizations than the other two schemes. This is because the FINE scheme always selects the finest possible granularities so less bandwidth is wasted per channel. The MinHop scheme and MinMux schemes on the other hand are aimed to improve other performances and do not differentiate among different granularities. Therefore, they cannot achieve the same bandwidth utilization as the FINE scheme.

TABLE I. METRO NETWORK BANDWIDTH UTILIZATION

Traffic load	Low	Medium	High
FINE	56.2%	55.6%	53.8%
MinMux	40.4%	43.9%	41.7%
MinHop	24.3%	25.6%	27.8%

The above experiments indicate that there are tradeoffs among different end-to-end provisioning schemes. For example, FINE scheme achieves the best bandwidth utilization with the tradeoff of longer end-to-end paths and higher blocking probability. MinHop scheme can reduce the end-to-end setup delay by minimize the end-to-end path length. But it has low bandwidth utilization. These numerical results also demonstrate the ability of the proposed multi-segment framework for end-to-end provisioning in multi-granularity multi-domain optical networks under different control plane architectures.

V. CONCLUSIONS

In this paper, we proposed a multi-segment optical network framework as a tool to solve a generalized category of problems related to end-to-end provisioning over interconnected optical networks. This network model is referred to as *multi-segment* network model, where the notion of networking segments refers to any portion of an optical network that requires particular consideration for end-to-end provisioning, *e.g.*, sub-networks characterized by different levels of traffic aggregation, different administrative domains, or logical segments of the optical control plane. Based on the multi-segment framework, we developed routing schemes for the multi-granularity multi-domain optical networks. The performance results demonstrated the ability of our schemes to handling various network conditions under different control plane scenarios. We will next focus on the issues of service recovery and efficient routing information exchange for practically relevant examples of interconnected optical networks.

REFERENCES

- [1] ITU-T Rec. G.8080/Y.1304, Architecture for the Automatic Switched Optical Network (ASON).
- [2] IETF draft- Generalized Multi-Protocol Label Switching Architecture, draft-ietf-ccamp-gmpls-architecture-07.txt
- [3] IETF draft, "Optical Inter Domain Routing Considerations," draft-ietf-ipo-optical-inter-domain-02.txt.
- [4] P. Ho and H. T. Mouftah, "Routing and Wavelength Assignment With Multigranularity Traffic in Optical Networks," Journal of Lightwave Technology, pp.1292-1303, vol.20, no.8, 2002.
- [5] K. Zhu, H. Zhu and B. Mukherjee, "Traffic Engineering in Multigranularity Heterogeneous Optical WDM Mesh Networks through Dynamic Traffic Grooming," IEEE Network, pp.8-15, March/April 2003.
- [6] Y. Zhu, A. Jukan and M. Ammar, "Multi-segment Wavelength Routing in Large-scale Optical Networks," ICC2003.
- [7] Y. Zhu, A. Jukan and M. Ammar, "Performance analysis of multi-segment wavelength routing", IEEE/LEOS Summer Topical Meetings, 2002, Quebec, Canada.