PAPER

# Performance Evaluation of Dynamic Multi-Layer Routing Schemes in Optical IP Networks

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**SUMMARY** This paper presents two dynamic multi-layer routing policies for optical IP Networks. Both policies first try to allocate a newly requested electrical path to an existing optical path that directly connects the source and destination nodes. If such a path is not available, the two policies employ different procedures. Policy 1, which has been published already, tries to find available existing optical paths with two or more hops that connect the source and destination nodes. Policy 2, which is proposed in this paper, tries to establish a new one-hop optical path between source and destination nodes. The performances of the two routing policies are evaluated. Simulation results suggest that policy 2 outperforms policy 1 if $p$ is large, where $p$ is the number of packet-switching-capable ports; the reverse is true only if $p$ is small. We observe that $p$ is the key factor in choosing the most appropriate routing policy.

***key words:*** *dynamic routing, optical network, IP network, traffic grooming*

## 1. Introduction

The explosion of Internet traffic has led to a greater need for high-speed backbone networks. The rate of growth in Internet-protocol (IP) traffic exceeds that of IP packet processing capability. Therefore, the next-generation backbone networks should consist of IP routers with IP-packet switching capability and optical cross-connects (OXC); wavelength-path switching will be used to reduce the IP-packet switching loads.

A photonic MPLS router has been developed by NTT [1]. It offers both IP/Multi-Protocol Label Switch (MPLS) packet switching and wavelength-path switching. Wavelength paths, called lambda label switched paths (lambda LSPs) are set and released in a distributed manner based on the generalized multi-protocol label switch (GMPLS). Since the photonic MPLS router has both types of switching capabilities and can handle GMPLS, it enables us to create, in a distributed manner, the optimum network configuration considering IP and optical network resources. Multi-layer traffic engineering, which yields the dynamic cooperation of IP/MPLS and optical layers, is required to provide IP services cost-effectively [2].

The bandwidth granularity of the photonic layer is coarse and equal to wavelength bandwidth, $\lambda$, i.e. 2.5 Gbit/s or 10 Gbit/s. On the other hand, the granularity of the IP/MPLS layer is flexible and well engineered. Consider the case in which source and destination IP routers request packet label switch paths (packet LSPs) with specified bandwidths. Packet LSPs are routed on the optical network that consists of lambda LSPs. When the specified packet LSP bandwidths are much smaller than the lambda LSP bandwidth, the one-hop lambda LSP between the source-destination IP routers is not fully utilized. In order to utilize network resources, low-speed packet LSPs should be efficiently merged at some transit nodes into high-speed lambda LSPs. This agglomeration is called *traffic grooming* [3]. There are two main options for routing a packet LSP over the optical network: single hop routes or multiple hop routes. Whether low-speed traffic streams should be groomed or not depends on the network resource availability such as the wavelengths available and the number of available ports in the packet-switching fabric.

The traffic-grooming problems have been extensively studied [3]–[7]. Note that these papers dealt with the traffic-grooming problem for two different layers of the SONET and optical WDM layers. When the photonic-MPLS-router network is considered, the essential traffic-grooming problem for MPLS and optical WDM layers is the same as that for the SONET and optical ones. In this paper, we consider the IP/MPLS and optical layers and use the terms of packet LSP and lambda LSP to refer to electrical and optical paths, respectively.

The papers in [3], [4] addressed a traffic-grooming off-line approach, where traffic demands are given and the optimization problem is formulated and solved. On the other hand, the papers in [5]–[7] considered an on-line approach in which connection requests with different bandwidths arrive randomly; the routes must be established in a real-time manner with given network resources. Since it is difficult to predict traffic demands precisely, the on-line approach is realistic and useful in utilizing the network resources more fully and maximizing the revenue from the given resources.

Based on the on-line approach, Zhu et al. in [6] presented two grooming algorithms: two-layered route-computation algorithms (TLRC) and a single-layered route-computation algorithm (SLRC). TLRC computes routes separately over the two layers, while SLRC computes routes over the single layer that is generated as a new graph by combining the layers. While SLRC outperforms TLRC under some conditions, the reverse is true in others. From the computation-time-complexity point of view, the TLRC algorithm is attractive, because its computation-time complexity is less than that of SLRC. It is $O(N^2)$, where $N$ is the

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number of nodes [5]. Given the above argument, we focus on TLRC-based routing policies.

In [5] and [6], the following TLRC-based routing scheme was proposed. The proposed routing policy tries to find a packet LSP route with one hop or multiple hops by using existing lambda LSPs as much as possible. Only if it is not able to find a route on the exiting lambda LSP network, does it try to establish a new lambda LSP. However, from the viewpoint of effective network utilization, it may be more preferable to establish a new lambda LSP before a multiple hop route is assigned on the exiting lambda LSP network even if TLRC is adopted. This is because using the existing lambda LSP network may waste the network's resources.

This paper presents two dynamic multi-layer routing policies for optical IP networks. When a new packet LSP is requested with specified bandwidth, both policies first try to allocate the new requested packet LSP to an existing lambda LSP that directly connects the source and destination nodes. If such a lambda LSP (existing) is not available, the two policies adopt different procedures. Policy 1, which was presented in [5], [6], tries to find a series of available existing lambda LSPs with two or more hops that connect source and destination nodes. On the other hand, policy 2, introduced in this paper, tries to setup a new one hop lambda LSP between source and destination nodes. The performance of the two routing policies are evaluated. Numerical results suggest that policy 1 outperforms policy 2 when the number of packet-switching-capable ports in the photonic MPLS router is large, while policy 2 outperforms policy 1 when the number of PSC ports is small.

The remainder of this paper is organized as follows. Section 2 describes GMPLS-based multi-layer traffic engineering with the photonic MPLS router. Section 3 describes two dynamic multi-layer routing policies. Section 4 describes multi-layer signaling schemes for each policy. Section 5 compares the performances of the two policies. Section 6 summarizes the key points.

## 2. Multi-Layer Traffic Engineering with Photonic MPLS Router

The structure of the photonic MPLS router is shown in Figure 1 [11], [12]. It consists of a packet-switching fabric, lambda-switching fabric, and photonic-MPLS-router manager. In the photonic-MPLS-router manager, the GMPLS controller distributes own IP and photonic link states, and collects link states of other photonic MPLS routers with the routing protocol of Open Shortest Path First (OSPF) extensions. A multi-layer topology routing engine processes the collected IP and optical link states.

Figure 2 shows a node model of the photonic MPLS router. The packet-switching and lambda-switching fabrics are connected by internal links. The number of internal links, i.e. the number of packet-switching-capable (PSC) ports, is denoted as $p$. The parameter $p$ represents how many lambda LSPs the node can terminate. $w$ is denoted as the number of wavelengths accommodated in a fiber × the number of fibers connected to the same adjacent photonic MPLS routers. Note that the interface of the lambda-switching fabric has both PSC and lambda switching capable (LSC) ports. When a lambda LSP is terminated at the packet-switching fabric through the lambda-switching fabric, the interface that the lambda LSP uses is considered as PSC. On the other hand, when a lambda LSP goes through the lambda-switching fabric to another node without termination, the interface that the lambda LSP uses is considered as LSC. Therefore, if we focus on the interfaces of the lambda-switching fabric, there are at most $p$ PSC interfaces and $w$ LSC interfaces.

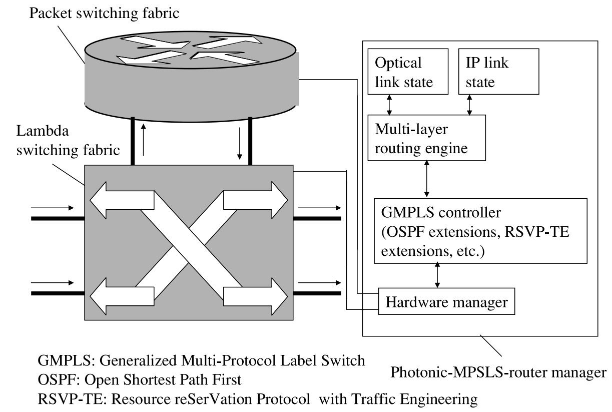
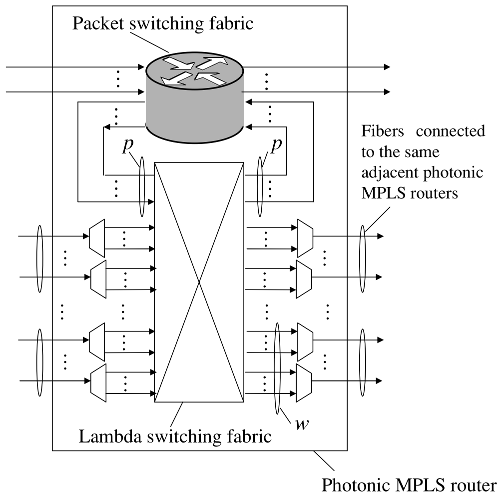


**Fig. 1** Structure of photonic MPLS router with multi-layer traffic engineering.



$p$: Number of packet-switching capable (PSC) ports
$w$: Number of wavelengths per fiber

**Fig. 2** Node model of photonic MPLS router.

These values of $p$ and $w$ impose network resource constraints on multi-layer routing [13]. Since $p$ is limited, not all lambda LSPs are terminated at the photonic MPLS router. Some lambda LSPs cut though the photonic MPLS router. How lambda LSPs are established so that packet LSPs are effectively routed over the optical network is a key

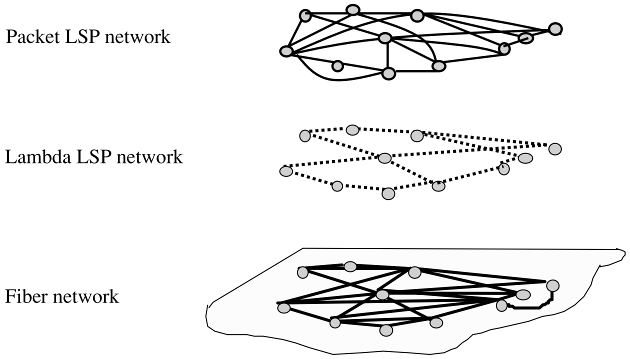


**Fig. 3** Multi-layer routing problem.

to the traffic-grooming problem.

GMPLS introduces the concept of forwarding adjacency (FA). In the multi-layer network, lower-layer LSPs are used to forward the upper-layer LSPs. An example of the multi-layer network is shown in Fig. 3. Once an lower-layer LSP is established, it is advertised by OSPF extensions as "FA-LSP" so it can be used for forwarding an upper-layer LSP. In this way, the setup and tear-down of LSPs trigger changes in the virtual topology of the upper-layer LSP network.

FA-LSP enables us to implement a multi-layer LSP network control mechanism in a distributed manner [13]. In multi-layer LSP networks, the lower-layer LSPs form the virtual topology for the upper-layer LSPs. The upper-layer LSPs are routed over the virtual topology. Figure 3 shows that the multi-layer path network consists of fiber, lambda LSPs, and packet LSP layers. Lambda LSPs are routed on the fiber topology. Packet LSPs are routed over the lambda LSP topology.

The photonic MPLS router uses the RSVP-TE signaling protocol (resource reservation protocol with traffic engineering) extensions [8], [9] to establish packet and lambda LSPs in the multi-layer networks. An upper-layer LSP setup request can trigger lower-layer LSP setup if needed. If there is no lower-layer LSP between adjacent nodes (adjacent from the upper-layer perspective), a lower-layer LSP is set up before the upper-layer LSP.

## 3. Multi-Layer Routing

When the setup of a new packet LSP with specified bandwidth is requested, lambda LSPs are invoked as needed to support the packet LSP. This section describes dynamic multi-layer routing, which involves packet LSP and lambda LSP establishment driven by packet LSP setup requests. Figure 4 shows the framework of dynamic multi-layer routing. If a new lambda LSP must be setup to support packet LSP routing, a lambda LSP setup request is invoked and lambda LSP routing is performed. The lambda LSP-routing result is returned to the packet LSP routing procedure for confirmation of its acceptability. The process will be terminated when the packet LSP is accepted or rejected, and the latter case may not be the desired result. If successful, the multi-layer routing procedure notifies its acceptance the packet LSP setup request.

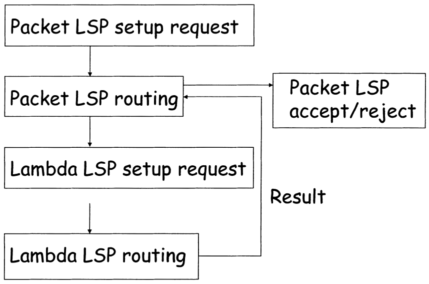


**Fig. 4** Framework for dynamic multi-layer routing.

In dynamic multi-layer routing, there are two possible routing policies as described in Sect. 2. Both policies first try to allocate the newly requested packet LSP to an existing lambda LSP that directly connects the source and destination nodes. If such existing lambda LSP is not available, policy 1 tries to find a series of available existing lambda LSPs that use two or more hops to connect source and destination nodes; while policy 2 tries to setup a new 1-hop lambda LSP that connects source and destination nodes.

Details of the two routing policies are given below.

**Policy 1**

- Step 1: Check if there is any available existing lambda LSP that directly connects source and destination nodes that can accept the newly requested packet LSP. If yes, go to Step 4[†]. Otherwise, go to Step 2.
- Step 2: Find available existing lambda LSPs that connect source and destination nodes with two or more hops; the maximum hop number is $H$, and the preference is for the minimum number of hops. If candidates exist, go to Step 4. Otherwise go to Step 3.
- Step 3: Check if a new lambda LSP can be setup. If yes, go to Step 4. Otherwise go to Step 5.
- Step 4: Accept the packet LSP request and terminate this process.
- Step 5: Reject the packet LSP request.

**Policy 2**

- Step 1: Check if there is any available existing lambda LSP that directly connects source and destination nodes and can support the new packet LSP. If yes, go to Step 4. Otherwise, go to Step 2.
- Step 2: Check if a new lambda LSP can be setup. If yes, go to Step 4. Otherwise go to Step 3.
- Step 3: Check if there is any series of available existing lambda LSPs that connect source and destination nodes using two or more hops; the maximum hop number is $H$, and the preference is the minimum number of hops. If yes, go to Step 4. Otherwise go to Step 5.

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[†] If there are several candidates, select one based on an appropriate selection policy. Such policies include least-loaded and most-loaded policies. This paper uses the least-loaded policy unless specifically stated otherwise.

- Step 4: Accept the packet LSP request and terminate this process.
- Step 5: Reject the packet LSP request.

Note that the major difference between policies 1 and 2 is the order of Steps 2 and 3.

## 4. Multi-Layer Signaling

GMPLS realizes the concept of layered signaling [8]–[10]. Figures 5 and 6 show examples of RSVP signaling message sequence in policy 1 and policy 2, respectively. We assume that lambda LSPs 1 and 2 are already established between node 1 and node 2 and between node 2 and node 4, respectively. We assume that a new packet LSP is requested to be set up between node 1 and node 4. In policy 1, since there is no lambda LSP between node 1 and node 4, node 1 tries to use the available existing lambda LSPs, LSP 1 and 2. In Fig. 5, by using already established lambda LSPs 1 and 2, the packet LSP is routed over nodes 1, 2, and 4. A PATH message in the packet LSP is transmitted from node 1 to node 4, and a RESV message is returned from node 4 to node 1. This establishes the new packet LSP. In policy 2, since there is no lambda LSP between node 1 and node 4, node 1 tries to establish a new lambda LSP that directly connects node 1 with node 4 and then sets up a new packet LSP over the new lambda LSP. As shown in Fig. 6, node 1 first sends a PATH message to set up a lambda LSP. After node 1 receives the RESV message for the lambda LSP, node 1 sends a PATH message to set up a packet LSP. The reception of a RESV message of the packet LSP, indicates the establishment of the packet LSP.

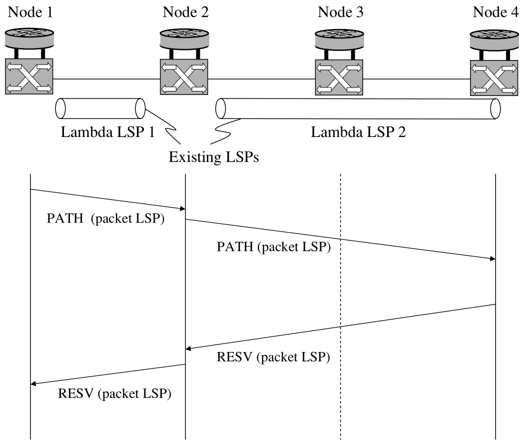

**Fig. 5** Example of RSVP signaling in policy 1.

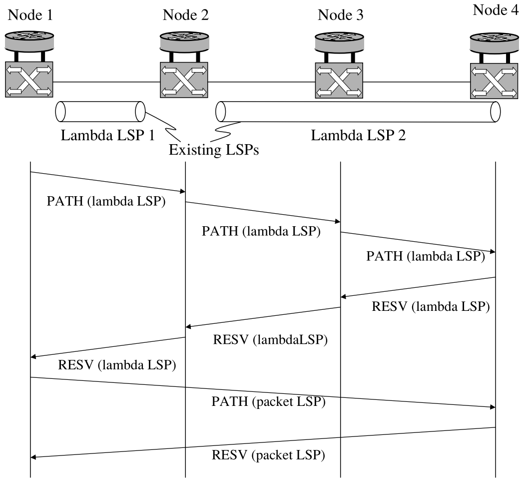

**Fig. 6** Example of RSVP signaling in policy 2.

## 5. Performance of Multi-Layer Routing Policies

We evaluated the two multi-layer routing policies by simulating the 14-node NSFNET model [16], as shown in Fig. 7. NSFNET consists of 14 nodes and 21 physical links. Each adjacent node pair is connected through a bi-directional physical link that consists of two fibers, where each fiber is assumed to have the same number of wavelengths. Therefore, $w$ is the same for all links. The transmission speed of each wavelength is set to 10 Gbit/s. The number of PSC ports $p$ is assumed to be the same in each node. The simulations assume that traffic demands between all source and destination nodes are the same. Requests for packet LSP setup follow a Poisson distribution. The packet LSP holding time of each source and destination node pair is considered to follow an exponential distribution. The required packet LSP bandwidth is set to 500 Mbit/s unless specifically stated otherwise. When an existing lambda LSP does not accommodate any packet LSPs, the lambda LSP is disconnected. The packet LSP hop limit $H$ is set to 2. $H$ impacts the blocking probability of packet LSP setup. In this evaluation, we chose the best of several $H$ values so as to minimize the blocking probability for both policies. Setting $H$ very large may waste network resources. Therefore, an appropriate value of $H$ should be used. This generally increases with network size.

Figure 8 compares admissible traffic volumes between each source-destination node pair. The admissible traffic volume is defined as the maximum admissible traffic volume under the condition that the blocking probability of packet LSP setup requests is less than 0.01. Policy 1 outperforms policy 2 when $p < 10$, while policy 2 outperforms policy 1 with $p \geq 10$.

To get the admissible traffic volume, blocking proba-

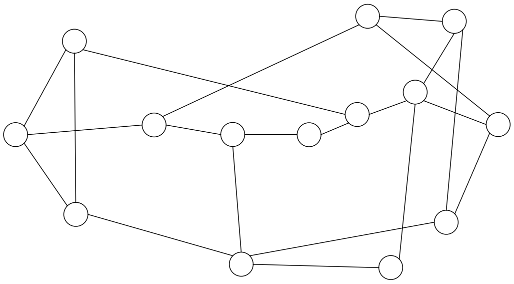

**Fig. 7** NSFNET model.

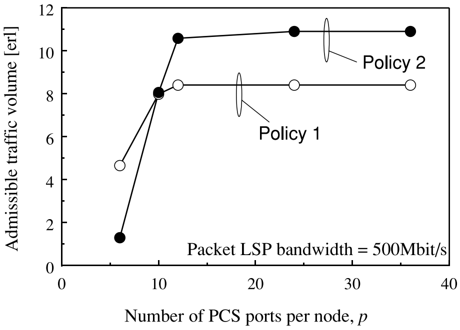

**Fig. 8** Comparison of two multi-layer routing policies ($w$ = 8).

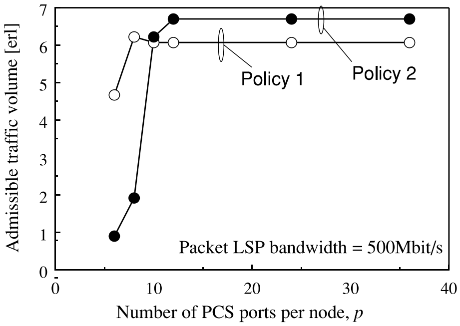

**Fig. 9** Comparison of two multi-layer routing policies ($w$ = 6).

bilities for given traffic conditions were obtained by simulation. $10^6$ LSP setup requests were generated to obtain a blocking probability. The simulation time was about 30 minutes to get one plot in Fig. 8 using Linux-based PC with 3.0GHz. The average wavelength utilization, which is defined as the average ratio of the number of utilized wavelengths per link to the number of wavelengths per link, was in the range of 50% and 60% when the number of PSC ports is enough large ($p$ > 12) in Fig. 8. As the number of PSC ports decreases, the average wavelength utilization decreases accordingly.

The results shown in Fig. 8 are explained as follows. When $p$ is small, blocking is mainly due to too-few available PSC ports rather than too-few available wavelengths. In this case, existing lambda LSPs should accommodate as many new packet LSPs as possible even though this wastes wavelength resources. On the other hand, when $p$ is large, blocking is mainly due to too-few available wavelengths. In this case, wavelength resources utilization should be emphasized at the expense of PSC-port resource utilization efficiency. Since policy 2 tries to use a lambda LSP that directly connects source and destination nodes while minimizing packet LSP de-routing, wavelength resources are utilized effectively. Therefore, policy 2 outperforms policy 1 when $p$ is large.

Note that multi-layer routing using photonic MPLS routers that have multiple switching capabilities is attractive when $p < d \times w$, where $d$ is the node degree. $d$ is the number of adjacent nodes that are connected by fiber links. In this case, at a transit node, some lambda LSPs are switched by the lambda switching fabric without using the packet switching fabric. This reduces the processing load of the packet switching fabric. Since the maximum node degree $d_{max}$ in Fig. 7 is four, multi-layer routing using photonic MPLS routers is practically effective when $p$ is less than 32 (=4 × 8). Although we used the same value of $p$ for all the photonic MPLS routers, how $p$ is designed for each photonic MPLS router to utilize network resouces is for further study.

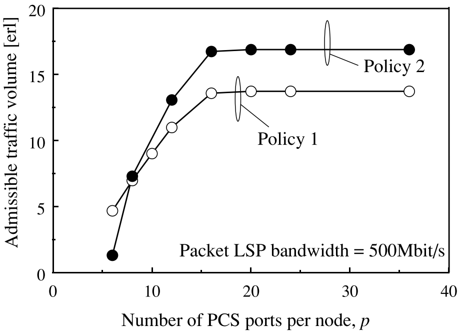

**Fig. 10** Comparison of two multi-layer routing policies ($w$ = 12).

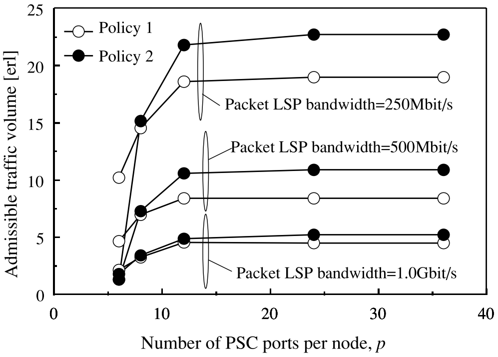

**Fig. 11** Dependency of different packet LSP bandwidths ($w$ = 8).

We basically confirmed the above observation using $w$ = 6 and $w$ = 12, as shown in Figs. 9 and 10, respectively; there was, however, a slight difference noted. We found that as $w$ increases, the value of $p$ at which the admissible traffic volume saturates for both policies increases.

Figure 11 shows the impact of using different packet LSP bandwidths: 250 Mbit/s, 500 Mbit/s, and 1.0 Gbit/s. Here again, the same basic tendency, policy 2 outperforms policy 1 at large $p$ values, was observed. However, as packet LSP bandwidth increases, the performance difference between policy 1 and policy 2 becomes small. When packet LSP bandwidth approaches lambda LSP bandwidth, more packet LSP setup requests trigger a new lambda LSP setup request. The performance of policy 1 approaches that of policy 2 as packet LSP bandwidth increase. On the other hand, when packet LSP bandwidth is small relative to the lambda LSP bandwidth, the performance difference is significant. Therefore, if packet LSP bandwidth is small, network operators should carefully choose an appropriate routing policy considering the constraints of the number of PSC ports.

## 6. Conclusions

This paper presented two dynamic multi-layer routing policies for optical IP Networks. Both policies first try to allocate a newly requested packet LSP to an existing lambda LSP that directly connects source and destination nodes. If such an existing lambda LSP is not available, the two policies take different approaches. Policy 1, which was previously proposed in the literature, tries to find a series of available existing lambda LSPs, that use two or more hops to connect source and destination nodes, while policy 2, which was introduced in this paper, tries to setup a new lambda LSP between source and destination nodes to create a one-hop packet LSP. The performances of the two routing policies were evaluated. We observed via simulation that policy 1 outperforms policy 2 only when $p$ is small, where $p$ is the number of PSC ports. The impact of the packet LSP bandwidth was also investigated using various numbers of PSC ports. When packet LSP bandwidth is small relative to lambda LSP bandwidth, the performance difference between the two policies is significant. Our numerical results suggested that the number of PSC ports is a key factor in choosing the appropriate policy.

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