Dynamic Multilayer Routing Schemes in GMPLS-Based IP+Optical Networks

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ABSTRACT

This article presents two dynamic multilayer routing policies implemented in the photonic MPLS router developed by NTT for IP+optical generalized MPLS networks. According to IP traffic requests, wavelength paths called lambda label switched paths are set up and released in a distributed manner based on GMPLS routing and signaling protocols. Both dynamic routing 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 tries to find available existing optical paths with two or more hops that connect the source and destination nodes. Policy 2 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. We also describe items that need to be standardized in the IETF to effectively achieve multilayer traffic engineering.

INTRODUCTION

The explosion of Internet traffic has strengthened the 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 (OXCs); wavelength path switching will be used to reduce IP packet switching loads.

Generalized multiprotocol label switching (GMPLS) is being developed in the Internet Engineering Task Force (IETF) [1]. It is an extended version of MPLS. While MPLS was originally developed to control packet-based networks, GMPLS controls several layers, such as IP packet, time-division multiplexing (TDM), wavelength, and optical fiber layers. The GMPLS suite of protocols is expected to support new capabilities and functionalities for an automatically switched optical network (ASON) as defined by the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) [2]. ASON provides dynamic setup of optical connections, and fast and efficient restoration mechanisms and solutions for automatic topology discovery and network inventory.

NTT has developed a photonic MPLS router that offers both IP/MPLS packet switching and wavelength path switching [3]. Wavelength paths, called lambda label switched paths (LSPs), are set up and released in a distributed manner based on 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 with regard to IP and optical network resources. Multilayer traffic engineering, which yields the dynamic cooperation of IP/MPLS and optical layers, is required to provide IP services cost effectively.

The bandwidth granularity of the photonic layer is coarse and equal to wavelength bandwidth (i.e., 2.5 or 10 Gb/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 packet LSPs with specified bandwidths. Packet LSPs are routed on the optical network as lambda LSPs. If the specified packet LSP bandwidth is much smaller than the lambda LSP bandwidth, the one-hop lambda LSP between the source and destination IP routers is not fully utilized. In order to better 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* [4]. There are two main options for routing a packet LSP over the optical network: single-hop or multihop routes. Whether

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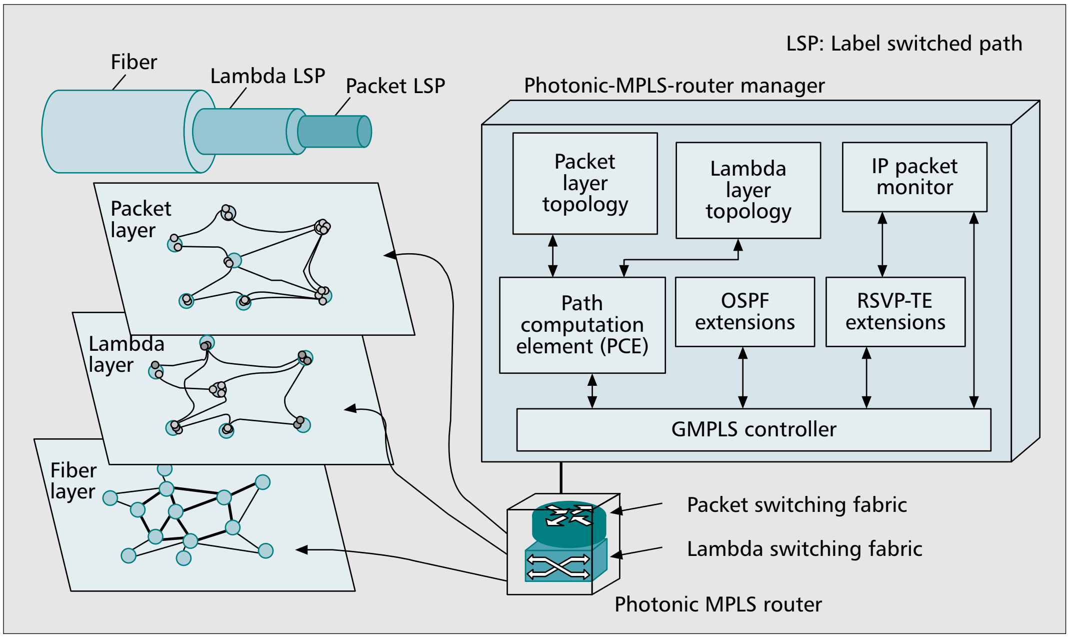


Figure 1. *The structure of a photonic MPLS router with multilayer traffic engineering.*

Since it is difficult to predict traffic demands precisely, the online approach is realistic and useful in utilizing the network resources more fully and maximizing the revenue from the given resources.

low-speed traffic streams should be groomed or not depends on network resource availability such as the wavelengths available and the number of available ports in the packet switching fabric.

Traffic grooming problems have been extensively studied. Some important studies were presented in [4–6]. Note that these papers dealt with the traffic grooming problem in two different layers: synchronous optical network (SONET) and optical wavelength-division multiplexing (WDM). 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 layers. In this article we consider the IP/MPLS and optical layers, and use the terms packet LSP and lambda LSP to refer to electrical and optical paths, respectively.

Reference [4] addressed the offline traffic grooming approach, where traffic demands are given, and the optimization problem is formulated and solved. On the other hand, the research in [5, 6] considered an online approach in which connection requests with different bandwidths arrive randomly; the routes must be established in a real-time manner within the limits of the network resources. Since it is difficult to predict traffic demands precisely, the online approach is realistic and useful in utilizing network resources more fully and maximizing revenue from the given resources.

Based on the online approach, Zhu *et al.* [5] presented two grooming algorithms: a two-layered route computation algorithm (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. The SLRC approach detailed in [6] employs a generic graph model. While SLRC outperforms TLRC under some conditions, the reverse is true in others. From the computation time complexity point of view, the TLRC approach is attractive, because its computation time complexity is less than that of SLRC. In addition, it is not easy to set parameters in the SLRC approach such that network utilization can be maximized. Given the above argument, we focus on TLRC-based routing policies.

In [5] 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. The policy tries to establish a new lambda LSP only when it is impossible to find a route on the existing lambda LSP network. However, from the viewpoint of effective network utilization, it may be better to establish a new lambda LSP before a multihop route is assigned on the existing lambda LSP network even if TLRC is adopted. This is because using the existing lambda LSP network may cause more LSP hops and waste the network's resources.

This article introduces two dynamic multilayer routing policies for optical IP networks. Both place the traffic dynamic multilayer routing functions in the photonic MPLS router. When a new packet LSP is requested with specified bandwidth, both policies first try to allocate it to an existing lambda LSP that directly connects the source and destination nodes. If such an existing lambda LSP is not available, the two policies adopt different procedures. Policy 1 tries to find a series of available existing lambda LSPs with two or more hops that connect source and destination nodes. Policy 2 tries to set up a new one-hop lambda LSP between source and destination nodes. The performances of the two routing policies are evaluated. Note that although other policies were introduced in [6], we focus on the two presented policies as other policies can be roughly categorized as one of the two. Numerical results suggest that policy 1 outperforms poli-

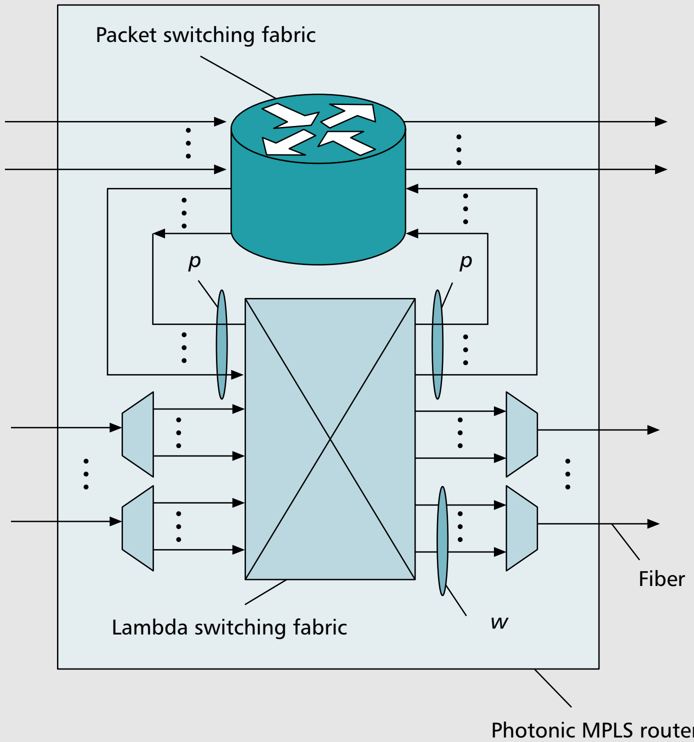


Figure 2. *A node model of a photonic MPLS router.*

cy 2 when the number of packet-switching-capable (PSC) ports in the photonic MPLS router is large, while policy 2 outperforms policy 1 when the number of PSC ports is small.

We clarify the relationship of dynamic multilayer routing policies and the required GMPLS suite of protocols. We present our developed photonic MPLS router with multilayer traffic engineering functions. Some GMPLS protocols are being standardized in the IETF, but there are still additional items that need to be standardized to effectively achieve traffic engineering. We use simulations to elucidate which items of the GMPLS protocols need to be extended. We discuss issues on the path computation element (PCE), which provides functions of multilayer traffic engineering in GMPLS networks.

Multilayer Traffic Engineering with a Photonic MPLS Router

Multilayer traffic engineering is performed in a distributed manner based on GMPLS techniques. We consider three layers: fiber, lambda, and packet. Packet LSPs are accommodated in lambda LSPs, Lambda LSPs are accommodated in fibers. The structure of the photonic MPLS router is shown in Fig. 1 [3]. 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 its own IP and photonic link states, and collects the link states of other photonic MPLS routers with the routing protocol of Open Shortest Path First (OSPF) extensions. Based on link-state information, PCE finds an appropriate multilayer route, and the signaling protocol of the Resource Reservation Protocol with traffic engineering (RSVP-TE) extensions module sets up each layer's LSPs. PCE provides the functions of traffic engineering, including LSP routes and optimal virtual network topology reconfiguration control, and judges whether a new lambda LSP should be established or not when a packet LSP is requested.

Figure 2 shows a node model of the photonic MPLS router. The packet and lambda switching fabrics are connected by internal links. The number of internal links (i.e., the number of PSC ports) is denoted p. p represents how many lambda LSPs the node can terminate. The number of wavelengths accommodated in a fiber is w. Note that the interface of the lambda switching fabric has both PSC and lambda switching capability (LSC). When a lambda LSP is terminated at the packet switching fabric through the lambda switching fabric, the interface the lambda LSP uses is treated as PSC. On the other hand, when a lambda LSP goes through the lambda switching fabric to another node without termination, the interface the lambda LSP uses is treated 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.

The values of p and w impose network resource constraints on multilayer routing. Since p is limited, not all lambda LSPs are terminated at the photonic MPLS router; some go through only the lambda switching fabric, but do not use the packet switching fabric. How lambda LSPs are established so that packet LSPs are effectively routed over the optical network is important in solving the traffic grooming problem.

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

FA-LSP enables us to implement a multilayer LSP network control mechanism in a distributed manner. In multilayer 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. The multilayer path network consists of fiber, lambda LSPs, and packet LSP layers, as shown in Fig. 1. Lambda LSPs are routed on the fiber topology. Packet LSPs are routed on the lambda LSP topology.

The photonic MPLS router uses the RSVP-TE signaling protocol (resource reservation protocol with traffic engineering) extensions to establish packet and lambda LSPs in 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.

Multilayer Routing

When the setup of a new packet LSP with the specified bandwidth is requested, lambda LSPs are invoked as needed to support the packet LSP. This section describes dynamic multilayer routing, which involves packet LSP and lambda LSP establishment driven by packet LSP setup requests. Figure 3 shows the framework of dynamic multilayer routing. If a new lambda LSP must be set up 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. This process is iterated until the desired result is obtained. If successful, the multilayer routing procedure notifies its acceptance of the packet LSP setup request.

In dynamic multilayer routing, there are two possible routing policies. 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 an 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. Policy 2, on the other hand, tries to set up a new one-hop lambda LSP that connects source and destination nodes.

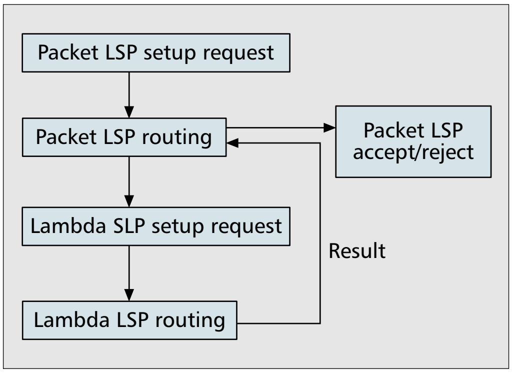
Details of the two routing policies are given below.

Policy 1

Step 1: Check if there is any available existing lambda LSP that directly connects source and destination nodes, and can accept the newly requested packet LSP. If yes, go to step 4.[1] 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 set up. If yes, go to step 4. Otherwise, go to step 5.



■ **Figure 3.** *A framework for dynamic multilayer routing.*

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 set up. 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 for the minimum number of hops. If yes, go to step 4. Otherwise, go to step 5.

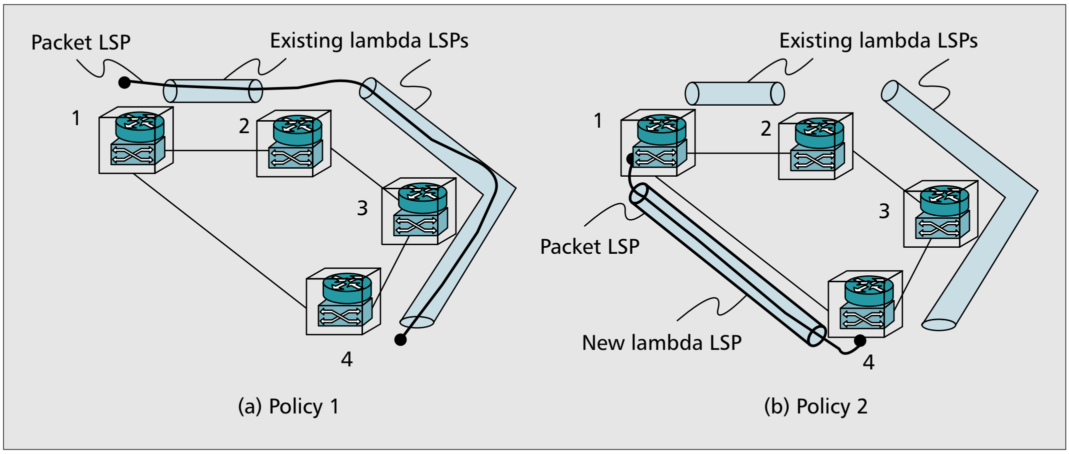
Step 4: Accept the packet LSP request and terminate this process.

Step 5: Reject the packet LSP request.

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

Figure 4 illustrates examples of the two policies. Let us consider that a packet LSP is requested to be set up between nodes 1 and 4. Two LSPs already exist: one between nodes 1 and 2, and one between nodes 2 and 4. There is no direct lambda LSP between nodes 1 and 4. In this situation, policy 1 uses two existing lambda LSPs to set up a packet LSP between nodes 1 and 4. Policy 2 creates a new direct lambda LSP with one hop.

In dynamic multilayer routing, there are two possible routing policies. Both policies first try to allocate the newly requested packet LSP to an existing lambda LSP that directly connects the source and destination nodes.



■ **Figure 4.** *Examples of the two policies.*

[1] *If there are several candidates, select one based on an appropriate selection policy. Such policies include least-loaded and most-loaded policies. The least-loaded policy is used hereafter unless specifically stated otherwise.*

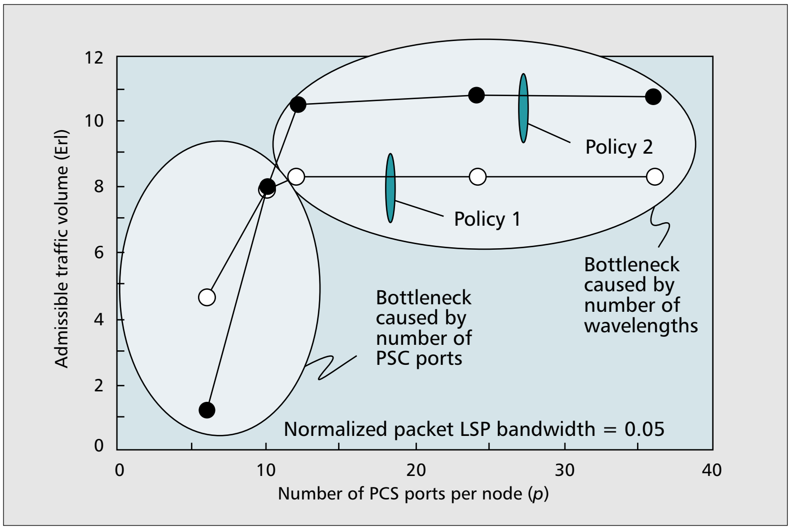


Figure 5. *A comparison of two multilayer routing policies (*w = *8).*

Performance of Multilayer Routing Policies

We evaluated the two multilayer routing policies by simulating the NSFNET model, which consists of 14 nodes and 21 physical links [8]. Each adjacent node pair is connected through a bidirectional physical link that consists of two fibers; each fiber is assumed to have the same number of wavelengths, w. 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 normalized by wavelength bandwidth is set to 0.05 unless specifically stated otherwise. An existing lambda LSP is disconnected if it does not accommodate any packet LSPs. The packet LSP hop limit, H, is set to 2.

Figure 5 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 $p \geq 10$.

The results shown in Fig. 5 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 resource 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 derouting, wavelength resources are utilized effectively. On the other hand, policy 1 tends to use multiple lambda LSPs. This makes policy 1 use the wavelength resources less efficiently. Note that due to the coarse granularity of the wavelength channel bandwidth compared to the packet LSP bandwidth, one could expect that setting up a direct lambda LSP would waste more resources. However, the residual bandwidth may be useful for succeeding packet LSP requests. When p is large, the impact of using multiple packet LSP derouting on the wavelength resource utilization efficiency is stronger than that of residual bandwidth caused by direct lambda LSPs. Therefore, policy 2 outperforms policy 1 when p is large.

We confirmed that the above observation was true at various w values; there was, however, an interesting discovery. We found that as w increases, the value of p at which the admissible traffic volume saturates for both policies increases.

Figure 6 shows the impact of using different packet LSP bandwidths normalized by wavelength bandwidth: 0.025, 0.05, and 0.10. Here again, the same basic tendency was observed (i.e., policy 2 outperforms policy 1 at large p values). 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 increases. 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 providers should carefully choose their routing policy considering the constraint imposed by the number of PSC ports.

We used simple assumptions in establishing the performance study. In realistic network environments, traffic and network models will be more complex. The numerical results will depend on the model used. It is true that the crossing points between two policies may change according to the model used, but our objective as the first step is to investigate the impacts of the number of PSC ports and normalized packet LSP bandwidth on network utilization for each policy. We observe that the number of PSC ports in GMPLS networks and packet LSP bandwidth are key factors in choosing the appropriate policy. The appropriate policy choice is critical because it impacts the revenue of network providers. This indicates that network providers should explore effective multilayer traffic engineering policies that consider available network resources.

IETF Standardization for Multilayer GMPLS networks

Routing Extensions

GMPLS protocols are mainly standardized in the common control and measurement plane (CCAMP) working group (WG) of IFTF. GMPLS networks have the potential to achieve multilayer traffic engineering, but GMPLS protocols being standardized in the IETF focus on single-layer networks. As the next step, GMPLS protocols for multilayer networks will begin to be discussed. Some of the drafts driving the standardization process of multilayer GMPLS networks are [8, 9]. These drafts analyze the GMPLS signaling and routing aspects when considering network environments consisting of multiple switching data layers. Draft [9] suggests that the information on p should also be advertised using the routing protocol of GMPLS OSPF extensions to effectively achieve multilayer traffic engineering. This suggestion is consistent with our observation in the previous section.

PCE IMPLEMENTATION

The PCE, as shown in Fig. 1, provides the functions of traffic engineering in GMPLS networks. Traffic engineering policies such as the multilayer routing policy selections introduced in this article, may differ among network providers. PCE performance affects the revenue of network providers. Network providers want to have their own PCE, because they want to choose the most appropriate algorithms, which depend on their policies. From the vendors' perspective, it is not desirable to implement PCE that supports all requirements of all network providers. A complicated PCE may also degrade the node's processing capability.

From the above considerations, it is desirable to functionally separate PCE from a GMPLS node. Draft [10] discusses several issues on required protocol extensions related to PCE when PCE is separately functionally implemented in a GMPLS node. Draft [10] also discusses several requirements, such as lambda LSP setup triggered by a packet LSP, to achieve dynamic multilayer routing. Some protocol extensions between PCE and a GMPLS node are required.

CONCLUSIONS

This article presents two dynamic multilayer routing policies for GMPLS-based 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 no such LSP is available, the two policies take different approaches. Policy 1 tries to find a series of available existing lambda LSPs that use two or more hops to connect source and destination nodes. Policy 2 tries to set up a new lambda LSP between source and destination nodes to create a one-hop packet LSP. The performances of the two routing policies are 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 packet LSP bandwidth was also investigated for 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 suggest that the number of PSC ports is a key factor in choosing the appropriate policy. The multilayer routing functions are implemented in the photonic MPLS router. We confirmed that these traffic engineering functions work successfully.

This article describes multilayer routing policies for unprotected path cases. Protected path cases should also be addressed to consider more realistic situations. For example, a study on routing of protected paths in GMPLS networks [11] can be combined with the work presented in this article.

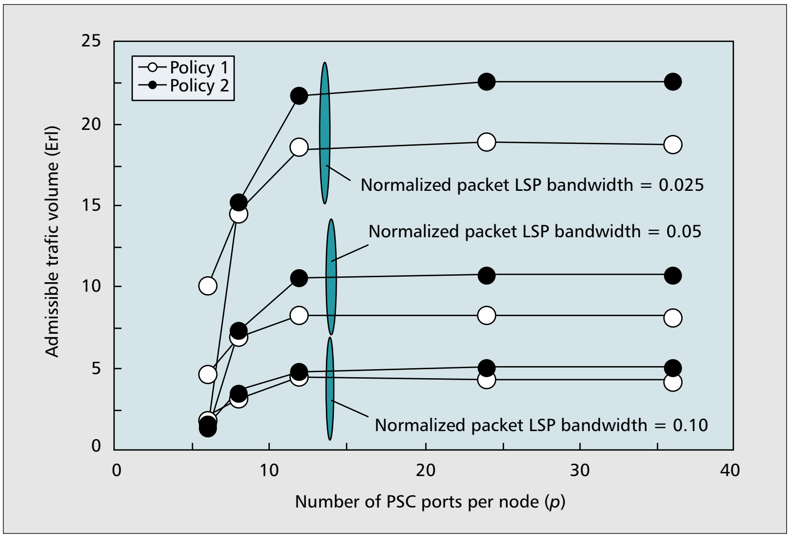


Figure 6. *The impact of packet LSP bandwidth* (w = *8*).

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BIOGRAPHIES

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(NTT's) Communication Switching Laboratories, Tokyo. He has been researching multimedia-communication network architectures based on ATM techniques, traffic control methods, and high-speed switching systems. From 2000 to 2001 he was a visiting scholar at Polytechnic University, Brooklyn, New York, where he was involved in designing terabit switch/router systems. He is now engaged in researching and developing high-speed optical IP backbone networks as a senior research engineer with NTT Network Service Systems Laboratories. He was the recipient of the 1998 Switching System Research Award and the 1999 Excellent Paper Award presented by IEICE, and the 2001 Asia-Pacific Outstanding Young Researcher Award presented by IEEE Communications Society for his contribution to broadband network, ATM, and optical IP technologies. He co-authored a book, *Broadband Packet Switching Technologies* (Wiley, 2001). He is a member of the IEICE.

KOHEI SHIOMOTO [M] is a senior research engineer, supervisor, at NTT Network Service Systems Laboratories, Japan. He joined NT), Tokyo, in April 1989, where he was engaged in research and development of ATM traffic control and ATM switching system architecture design. From August 1996 to September 1997 he was engaged in research on high-speed networking as a visiting scholar at Washington University, St. Louis, Missouri. From September 1997 to June 2001 he directed architecture design for high-speed IP/MPLS label switch router research project at NTT Network Service Systems Laboratories, Tokyo. Since July 2001 he has been engaged in the research fields of photonic IP router design, routing algorithms, and GMPLS routing and signaling standardization at NTT Network Innovation Laboratories. He received his B.E., M.E., and Ph.D. from Osaka University, Japan, in 1987, 1989, and 1998. He is a member of IEICE and ACM. He is Secretary of International Affairs of the Communications Society of IEICE. He is Vice Chair of Information Service of the IEEE ComSoc Asia Pacific Board. He has been engaged in organizing several international conferences, including HPSR 2002, WTC 2002, HPSR 2004, and WTC 2004. He received the Young Engineer Award from the IEICE in 1995.

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YOSHIHIRO TAKIGAWA received B.S. and M.S. degrees from Waseda University, Tokyo, Japan, in 1980 and 1982, respectively. He has been with NTT from 1982. He was in charge of research and development of ISDN subscriber systems and ATM subscriber systems. He was an active contributor to the ATM Forum. He was engaged in the NTT Multimedia Joint Trial and the Asia Multimedia Forum. From 2000 he has been responsible for research on photonic MPLS routers and an optical cross-connect system.