

On the integration of IP routing and wavelength routing in IP over WDM networks

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ABSTRACT

One approach for accommodating IP traffic on the WDM (Wavelength Division Multiplexing) network is to construct a logical topology by establishing a set of lightpaths between nodes. The lightpath carries IP traffic and does not require any electronic processing at intermediate nodes, which reduce the load of packet processing at those nodes. However, if IP and WDM networks have its own routing functions, the lightpaths configured in WDM network may not be fully utilized by IP unless the route of IP packets can be explicitly determined. Therefore, the integration of routing mechanisms is necessary to provide efficient resource utilization and flexible adaptation against traffic changes. In this paper, we propose an integrated routing mechanism for IP over WDM networks. The key idea is to prepare a set of *virtual-links* based on a resource utilization of the WDM network, and then calculate the minimum cost route on the IP network. Our simulation results show that the performance of our method outperforms those of optimally designed logical topologies when traffic patterns change. Fluid flow network simulation is conducted for simulating IP traffic flow on WDM networks.

Keywords: Wavelength Division Multiplexing, IP over WDM, Routing, Link Cost Metrics, Integrated Routing Algorithm

1. INTRODUCTION

Wavelength Division Multiplexing (WDM) technology, which carries multiple wavelengths on a single fiber, is expected to cope with the explosion of the traffic demand for the current and future Internet. Since the majority of Internet traffic is IP, much researches have been devoted to an IP over WDM network where IP packets are directly carried over the WDM network [1–6]. One approach for accommodating IP traffic on the WDM network is to establish a set of lightpaths (i.e., logical links) between nodes. The lightpath carries IP traffic and does not require any electronic processing at intermediate nodes, which reduces the load of packet processing at those nodes.

In the IP over WDM network, there are three different network models; peer, augmented, and overlay model [7]. One of the most important difference among these models is what type of information is shared between IP layer and optical layer. In the peer model, the topology and other network information (e.g., routing information and link state information) are shared between both layers, and then the unified routing mechanism controls the whole network. On the other hand, in the overlay model, no information is shared between the two layers, and each layer is controlled dependently by its own routing mechanism. The augmented model is the hybrid of the peer model and the overlay model. That is, the augmented model shares some part of information, such as reachability information, between two layers according to a certain agreement, and two layers are managed dependently as like the overlay model.

For the overlay model, a logical topology is first constructed by setting lightpaths between nodes in the WDM network, and then existing routing protocols for IP packets are performed on that logical topology (see Ref. [8] and references there in). In this case, the IP protocols need not change. However, since both IP and WDM networks have its own routing functions, the lightpaths configured in WDM network may not be fully utilized by IP. That is, the routes of IP packets are decided by IP routing mechanism, and IP does not necessarily use lightpaths provided by the WDM network. Therefore, the integration of routing mechanisms is necessary such that efficient resource utilization and flexible adaptation against traffic changes are provided.

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The integrated routing method for the peer model is proposed in Refs. [5, 6]. In these papers, IP/MPLS over WDM network where the route of IP packets can be explicitly determined by MPLS's LSP is investigated. In Ref. [5], MIRA (Minimum Interference Routing Algorithm) is proposed as an integrated routing algorithm for calculating route of LSPs and the lightpaths. The IP/MPLS network has a unified routing entity that collects all of the topology information and link state information of both IP/MPLS and WDM networks. For incrementally arriving traffic flows, MIRA calculates routes of the traffic flow where required bandwidth is explicitly specified. MIRA pays attention to residual bandwidth that will be used by future LSP requests, and therefore tries to maximize the residual bandwidth. When there is no appropriate route, LSP requests are blocked. Reference [6] shows that the blocking probability of LSP requests improves by using topology information of the GMPLS network.

In the peer model, efficient route controls can be performed since all of the network information is available. However, collecting the information requires the advertisement of the information of both IP layer and WDM layer. This leads to excessive update overhead, and therefore lack of scalability. On the other hand, in the overlay model, only the information of each layer need to be advertised, and thus scales well comparing to the peer model. However, since the availability of information is limited, it is difficult to perform efficient routing as we will show the results in Section 3 by comparing the algorithm in [9]. In this paper, we therefore use the augmented model that shares some part of information (more specifically, the information of lightpaths that can be established in the WDM layer and their cost) between IP and WDM layers.

In this paper, we integrate IP routing and wavelength routing on the IP over WDM network, and propose the routing method where IP packets are surely forwarded on the lightpath configured by the wavelength routing. For this purpose, we introduce a concept of *virtual-links* that are configured between IP routers. The virtual-link is a logical link which is not configured as a lightpath, but can be activated as a lightpath by reserving the wavelength resource according to the request. In the IP network, our routing method first calculates routes on the topology including these virtual-links. If a virtual-link is selected as a route of IP packets, a lightpath corresponding to the virtual link is established. By this way, we can calculate the route of IP packets and the route of lightpaths simultaneously. In this paper, we give the cost function to virtual-links aiming at reducing the load of nodes, and the results of computer simulations show the effectiveness of our proposal method in terms of the average end-to-end delay and throughput.

Unlike the previous works that investigate blocking probability of LSP requests, we intend to reveal the packet-level behavior in the IP directly over WDM networks. However, by the WDM technology, the traffic that can be accommodated in the network increases, which makes computer simulations be difficult since there are huge number of IP packets on WDM networks. In this paper, we develop the computer simulation technique based on the fluid flow model that greatly reduces the number of packets during the computer simulations. We compare the results of flow-level simulation based on the fluid flow model with the results by the packet-level simulation, and reveal that end-to-end packet delay shows almost the same.

The rest of the paper is organized as follows. In Section 2, we describe the network model and the concept of virtual-links that is the key idea of our routing method. We evaluate the performance of our routing method in Section 3. Finally, we conclude this paper and present future works in Section 4.

2. INTEGRATED ROUTING WITH VIRTUAL-LINKS

In this section, we introduce our network model and the concept of virtual-links, which is the key idea of our routing method. Then, we elaborate on our routing algorithm and discuss our choice of cost metrics.

2.1. Network Model and the Concept of Virtual-Links

We consider the network that consists of optical fiber links having W wavelengths, and nodes that consist of both IP routers with WDM interfaces and optical cross-connects (OXCs). In Figure 1, we illustrate the node architecture used in this paper. The upper part of this figure shows IP router and the lower part shows OXC. The IP router is connected to the OXC via a WDM interface which converts optical (electronic) signal to electronic (optical) signal. The control plane in the WDM layer manages the topology database with wavelength availability information. The control plane in the WDM layer calculates the cost of lightpath that can be established, and provides this information to the IP router. The IP router has route managers which have three main blocks: the routing controller, the topology database, and OSPF-TE.

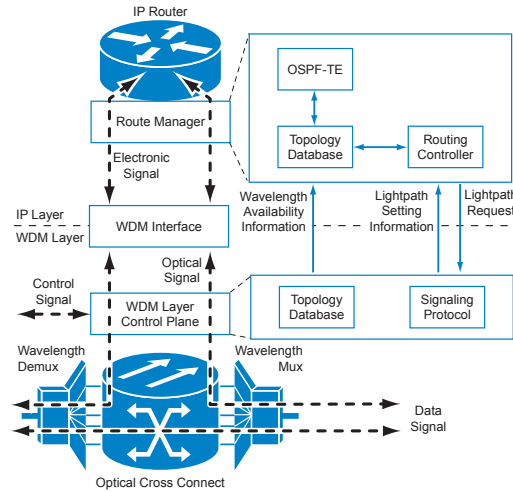


Figure 1. A node architecture

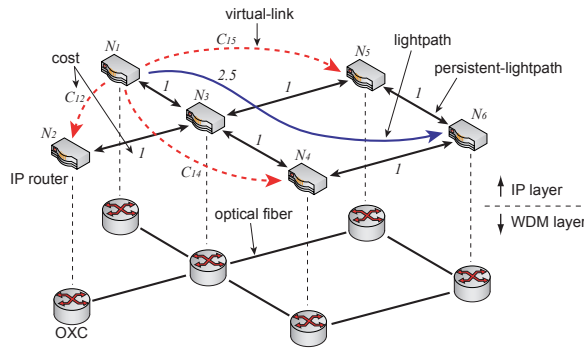


Figure 2. An example of a network with virtual-links

A lightpath is statically set up between all adjacent nodes using one wavelength to ensure the end-to-end reachability. We refer to this lightpath as *persistent-lightpath*. The other wavelength resources are used for non-persistent lightpaths that are dynamically set up according to traffic changes.

To integrate IP routing and WDM routing, we propose a concept of virtual-links. A virtual-link is a logical link which has not yet been configured as a lightpath, but can be activated if necessary. An example of a network with virtual-links is illustrated in Fig. 2. In this figure, one lightpath has already configured from router R_1 to router R_6 , and three virtual-links are placed from router R_1 to routers R_2 , R_4 , and R_5 . Each link and virtual link has a cost value that is used by the IP routing. Note that in our proposal method, the cost of virtual link gives much impact on the performance. We discuss about the cost functions for the virtual-links in section 2.3, and show the evaluation result in section 3.

2.2. Routing Algorithm

2.2.1. Topology database

OSPF-TE in the IP router advertise the link state information, and each IP router collects all the link state information. In addition to this, the control place in the WDM layer tells the existence of virtual-links and its cost to the IP router. Then, the IP router generates following topology database, which include the virtual-links and its cost.

Step 1: Remove all physical links having no available wavelength resource from physical topology.

Step 2: Determine the route of virtual-links. Find minimum hop routes on the topology.

- Step 3: Set virtual-links from the source node to all destination nodes if there is no lightpath configured.
- Step 4: When a lightpath cannot be set since there is no available wavelength resource, the virtual-link is not set.
- Step 5: Assign link cost values to each virtual-link, as well as update link cost values of existing lightpaths (virtual-links).

2.2.2. Route selection

Based on the topology database obtained from the above procedures, the routing algorithm calculates routes of IP packets, and if virtual-link is selected, corresponding lightpath is dynamically configured on WDM networks.

- Step 1: Calculate the minimum cost routes on the logical topology including virtual-links and existing lightpaths via the IP routing algorithm.
- Step 2: If the resulting routes contain one or more virtual-links, activate the virtual-links as lightpaths by reserving wavelength resources [10].
- Step 3: Release lightpaths which are not used as a the route of IP packets.

The routing in IP layer and WDM layer is integrated by searching for the minimum cost routes from a logical topology where virtual-links are included. In this case, IP traffic is surely forwarded on the virtual-links (i.e, lightpaths) since lightpaths are selected using IP routing metrics.

2.3. Cost Metrics

In our approach, a fundamental problem is to select the cost function of virtual-links. The main objective of the cost function of virtual-links is to minimize the end-to-end delay. In order to minimize this, reducing the load of IP routers is important. However, setting lightpaths (virtual-links) may cause an unnecessary increase to the load of nodes. This is because more traffic may come to destination nodes of virtual links. We show an simple example in Figure 3. In Figure 3(a), two flows, f_1 and f_2 , are forwarded through route $N_1 \rightarrow N_3 \rightarrow N_5$ and $N_2 \rightarrow N_4 \rightarrow N_6 \rightarrow N_5$, respectively. Figure 3(b) illustrates the network after one lightpath is configured from node N_2 to N_3 . Since the lightpath is newly set, the route of flow f_2 is changed to $N_2 \rightarrow N_3 \rightarrow N_5$. In this case, traffic of f_2 that was pass through node N_4 and node N_6 is then pass through the node N_3 . Consequently, the load of N_3 increases. We therefore use the load of the destination node of the virtual-link as a parameter of our cost function of virtual-links to prevent from concentrating traffic on the destination node of the lightpath.

The cost function of virtual-link between nodes i and j , C_{ij} , is given by,

$$C_{ij} = \alpha v_j^2 + \beta, \quad (1)$$

where v_j is the load of node j , α is coefficient of the cost function, and β is offset. In this paper α is set to 1.0, and β is set to 0.5. As noted above, our primal purpose is to reduce the end-to-end delay, and therefore balances the load of nodes by using the cost function. We therefore use the convex cost function against the load of node v_j , which is expected to prevent the increase of the delay of node j .

3. SIMULATION EXPERIMENTS

In this section, we evaluate the performance of the proposed algorithm through computer simulations. Before we present the performance of our integrated routing algorithm, let us describe the flow-level simulation method based on the fluid flow model.

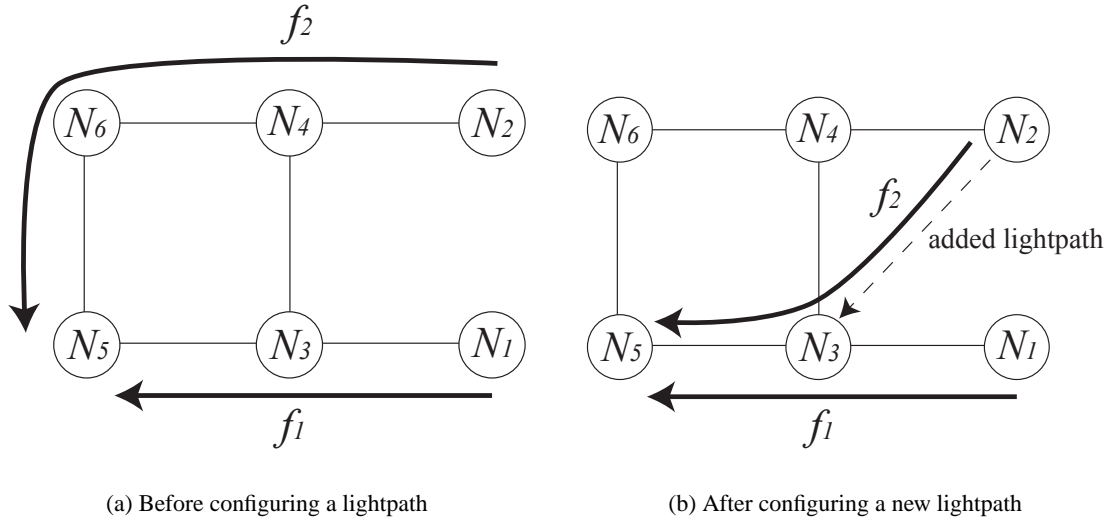


Figure 3. An example of the cause of congestion

3.1. Flow-Level Simulation

Discrete event network simulators use events in order to simulate the movement of packets in the network. This requires computers to process a lot of events to simulate large and high bandwidth networks, such as WDM networks. In this paper, we evaluate our integrated routing mechanism by a fluid flow approximation that enables much smaller number of packets to be processed in the computer simulations. We call the simulation method based on fluid flow model as flow-level simulation, and the conventional simulation method that processes every packet as packet-level simulation.

We define following terminologies to explain the flow-level simulation.

- t_n : n th time when arrival or departure of flows occur.
- $L(t_n)$: Number of packets in the node at time t_n .
- $a(t_n)$: Packet arrival rate to the node at time t_n .
- a_i : Packet arrival rate in each flow i .
- μ : Service rate of the node.
- $W(t_n)$: Delay in the node at time t_n .

Here, we assume that the arrival process of packets in each flow follows Poisson with average rate a_i , and the average rate is not change.

Figure 4 illustrates the outline of the computational method of the packet arrival rate at the node. The figure illustrates three flows (flow₁, flow₂, flow₃) that arrive at the node. The flow₁, flow₂, and flow₃ arrive (depart) at time t_1 , t_2 , and t_3 (t_6 , t_4 , and t_5), respectively. Each flow has a parameter, a_i which is an arrival rate of packets in the flow _{i} . In other word, the interval of packet arrival for flow _{i} is $1/a_i$. The packet arrival rate for this node (denote $a(t_n)$) is the sum of the packet arrival rate a_i of each flow, and thus $a(t_n)$ changes according to the arrival/departure process of flows, as shown in the upper part of Fig. 4.

The increase of the number of packets in the node between time t_{n-1} and t_n can be represented by $\{a(t_n) - \mu\} \times (t_n - t_{n-1})$. Here, $a(t_n) \times (t_n - t_{n-1})$ means the number of packets which arrived at the node between time t_{n-1} and t_n , and $\mu \times (t_n - t_{n-1})$ means the number of packets which departed from the node. Note that, if $\{a(t_n) - \mu\} \times (t_n - t_{n-1}) < 0$, the number of packets

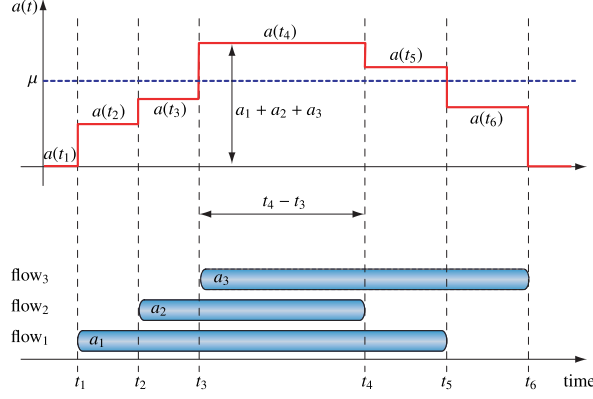


Figure 4. Calculation of the number of packets at a node

in the node decreases. Using the number of packets at time t_{n-1} (i.e., $L(t_{n-1})$), the total number of packets in the node at the time t_n can be expressed by,

$$L(t_n) = \{a(t_n) - \mu\} \times (t_n - t_{n-1}) + L(t_{n-1}).$$

Here, $L(t_n)$ is non-negative number, and therefore $L(t_n) = 0$ if $L(t_n) < 0$. Then, the delay experienced at a node can be calculated as $W(t_n) = L(t_n)/a(t_n)$ by applying Little's theorem.

In the flow-level simulation, only head and tail packets of flows are processed to update parameters, $a(t_n)$, $L(t_n)$, and $W(t_n)$, while in the packet-level simulation every packets in the flow have to be processed. That is, packet-level simulation updates $a(t_n)$, $L(t_n)$, and $W(t_n)$ whenever the packet arrives at the node.

To show the validity of the fluid flow model approximation, we compare the results of flow-level simulation with those of the packet-level simulation. Figure 5 shows the average end-to-end delay when we use these two simulation techniques on NSFNET topology. The number of wavelength of each link is eight, and wavelength converters are not used in this simulation. The bandwidth of one wavelength is assumed to be 10 Gbps. The processing capacity of the router is set to 1 Gbps to perform the packet-level simulation. The flow length is exponentially distributed with a mean value of 12 Mbyte, and flows between each node-pair ij arrive according to Poisson process with average rate $\gamma \times d_{ij}$, where $D = \{d_{ij}\}$ is traffic demand matrix and γ is scale factor of the traffic demand matrix. We use the traffic demand matrix shown in the reference [11]. Figure 5 shows the average end-to-end delay dependent on the total amount of traffic by changing the scale factor γ . From this figure, we observe that the average end-to-end delay obtained by flow-level simulation shows the similar tendency to the delay by packet-level simulation. Although the difference appears at a high load (greater than 3.5 Gbps) because of fluid flow model approximation, the saturation point is almost the same. Thus, the computer simulations based on the fluid flow model can be used to evaluate our routing method.

3.2. Performance Evaluation

We evaluate the performance of the proposed routing algorithm through flow-level simulation on the NSFNET (shown in Figure 6(a)) that has 14 nodes and 21 bidirectional links, and the EON (European Optical Network) (shown in Figure 6(b)) that has 19 nodes and 39 bidirectional links. A bidirectional link has an unidirectional optical fiber in each direction, and the transmission capacity of each wavelength is set to 10 Gbps. In this section, the processing capacity of IP router is set to 10 Gbps, and flow length is exponentially distributed with a mean value of 75 Mbyte. Under these parameters settings, the bottleneck of the network is processing capacity of routers. The traffic we use in our simulation is generated according to a traffic demand matrix given in [11] for NSFNET topology. For EON topology, we randomly generate a traffic matrix.

For comparison purpose, we use two logical topologies designed by SHLDA [9] (Shortest-Hop Logical topology Design Algorithm) and MLDA (Minimum delay Logical topology Design Algorithm) [11]. MLDA use the performance metric d_{ij} for node-pair ij , where d_{ij} is the traffic demand from node i to node j , in order to construct a logical topology. First of all, it places a lightpath between two nodes if a fiber directly connecting these nodes exists. Then, it constructs a logical topology by configuring lightpaths in an descending order of traffic demand d_{ij} . Finally, if non-utilized wavelengths

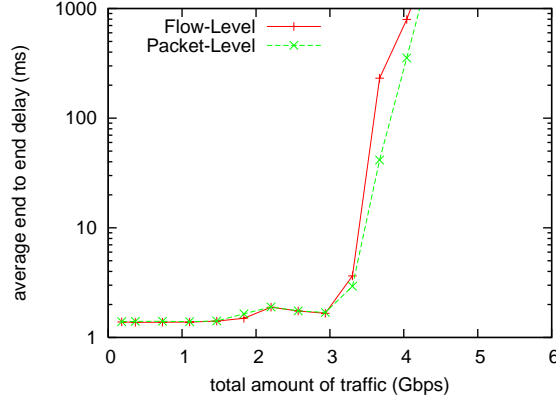


Figure 5. The results of flow-level simulation and packet-level simulation

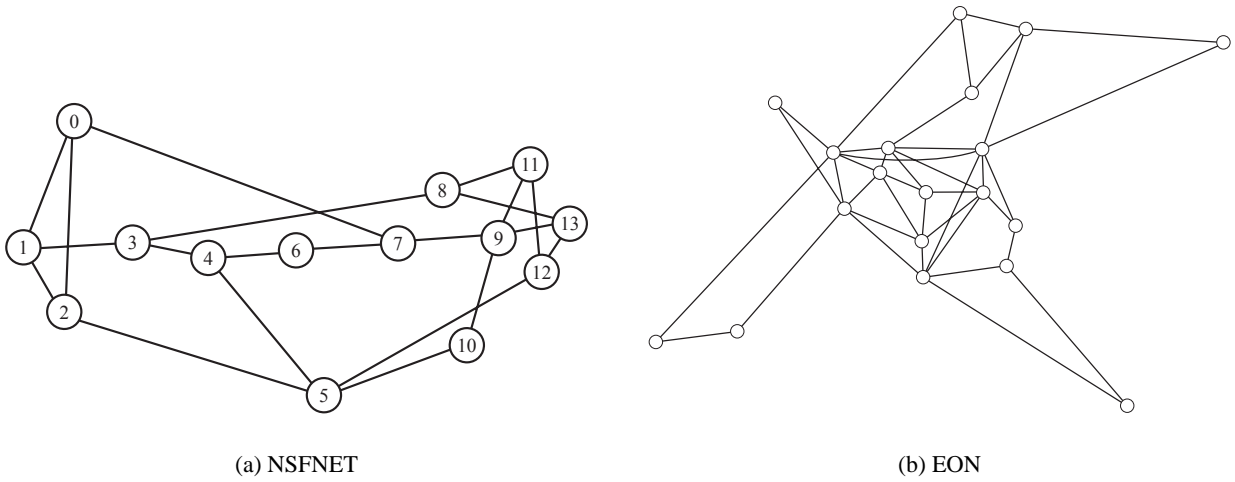


Figure 6. Network topology used in simulation experiments

still exist, lightpaths are placed randomly by using those wavelengths. On the contrary, SHLDA use the performance metric F_{ij} , which is determined by $F_{ij} = d_{ij} \times h_{ij}$, where h_{ij} is the hop-count of the minimum hop route for node-pair ij on the physical topology. Here, the hop-count of the lightpath refers to the number of physical links that the lightpath traverses. SHLDA configures lightpaths in the descending order of F_{ij} , and other steps are the same as MLDA. For the IP packet routing, we use minimum hop routing on the logical topology.

Figure 7 shows the average end-to-end delay on NSFNET. The horizontal axis shows the total traffic volume in the network. Figure 7(a) shows the result when the traffic matrix in Ref. [11] is used. In the figure, the average end-to-end delay by our routing method and by logical topologies obtained from MLDA/SHLDA shows almost the same performance. This is because the logical topology is designed optimally for the given traffic demand. In Figure 7(b), we show the result when traffic change occurs. Here, we change traffic matrix by regenerating traffic demand matrix randomly every 200 seconds while keeping the sum of the matrix to be a constant value (i.e., x -axis value in the figure). As expected, changing traffic patterns degrades the performance of SHLDA and MLDA dramatically. For our algorithm case, however, we observe little increase in the average end-to-end delay, and our proposed method shows almost the same performance as Figure 7(a) even when traffic demand matrix changes. This means that our integrated routing mechanism efficiently utilizes wavelength resources. To see this more clearly, we show the average load of each node in Fig. 8. In obtaining this figure, we set the total traffic demand when the average end-to-end delay begins to increase by referring Fig. 7. We set the total traffic volume

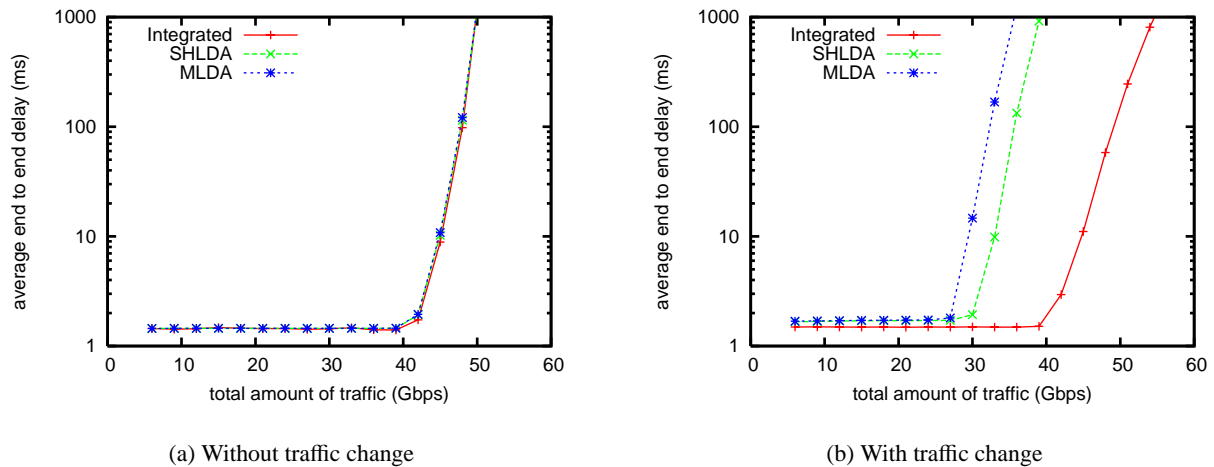


Figure 7. Average end-to-end delay (NSFNET)

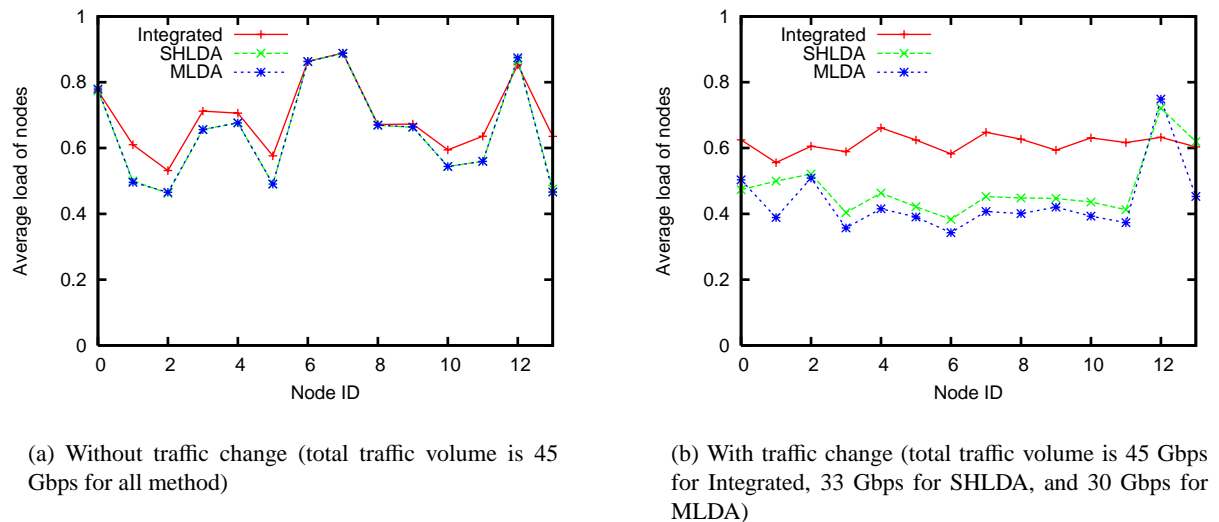
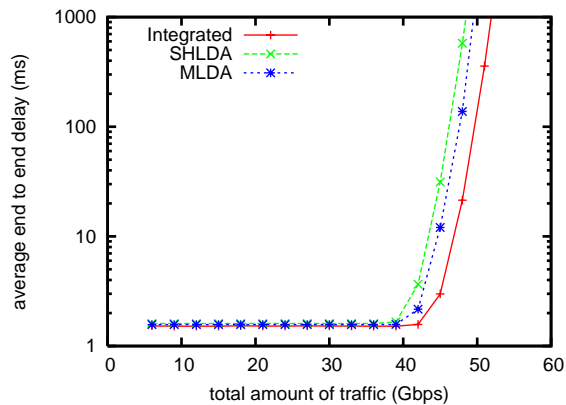


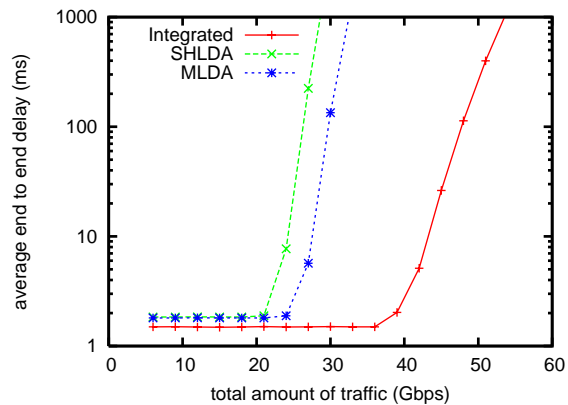
Figure 8. Load of nodes (NSFNET)

in the network to 45 Gbps for all method in the case of the static traffic pattern. In the case of dynamic traffic patterns, we select 45 Gbps for our method, 33 Gbps for SHLDA, and 30 Gbps for MLDA. Figure 8(b) shows that our algorithm can balance the load of nodes around 0.6 when slight congestion occurs in the network. On the contrary, in SHLDA and MLDA, the node 12 is being saturated while other nodes remains under-utilized.

We next evaluate the proposal method on NSFNET topology using the random traffic matrix. Figure 9 shows the average end-to-end delay on NSFNET topology dependent on the total amount of traffic. From this figure, we observe that our routing method outperforms conventional logical topology design methods. Moreover, the average end-to-end delay by our method keeps constant against the traffic change, while the delay of SHLDA or MLDA much depends on the traffic demand matrices. Figure 10 depicts the results of our routing mechanism by applying to the EON topology, which show the similar tendency that we have observed on the NSFNET topology.

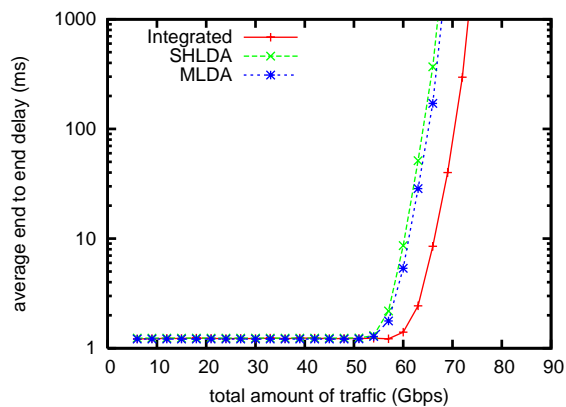


(a) Without traffic change

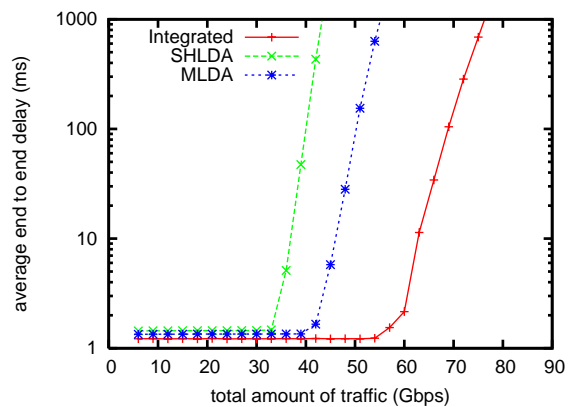


(b) With traffic change

Figure 9. Average end-to-end delay with random traffic demand matrix (NSFNET)



(a) Without traffic change



(b) With traffic change

Figure 10. Average end-to-end delay with random traffic demand matrix (EON)

4. CONCLUSION

In this paper, we proposed a new integrated routing algorithm that uses the virtual-link concept for selecting routes of IP packets and find the necessity of dynamic lightpath configuration in IP over WDM networks. The main objective of our algorithm is to reduce the load of IP routers. Through simulation, we showed that our algorithm outperforms the design method for logical topologies especially when traffic demand changes.

In this paper, we have assumed that the minimum hop path is used for virtual-links. For our next step, we will consider other routing strategies for virtual-links, and evaluate how the end-to-end delay improves by our integrated routing algorithm. Moreover, we plan to use the wavelength usage information as one of parameters for the cost function and changes cost values depending on the wavelength usage information.

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REFERENCES

1. J. Li, G. Mohan, E. C. Tien, and K. C. Chua, "Dynamic routing with inaccurate link state information in integrated IP over WDM networks," *Computer Networks* **46**, pp. 829–851, Dec. 2004.
2. T. Ye, Q. Zeng, Y. Su, L. Leng, W. Wei, Z. Zhang, W. Guo, and Y. Jin, "On-line integrated routing in dynamic multifiber IP/WDM networks," *IEEE Journal on Selected Areas in Communications* **22**, pp. 1681–1691, Nov. 2004.
3. S. Arakawa, M. Murata, and H. Miyahara, "Functional partitioning for multi-layer survivability in IP over WDM networks," *IEICE Transactions on Communications* **E83-B**, pp. 2224–2233, Oct. 2000.
4. N. Ghani, S. Dixit, and T.-S. Wang, "On IP-over-WDM integration," *IEEE Communications Magazine* **38**, pp. 72–84, Mar. 2000.
5. M. Kodialam and T. V. Lakshman, "Integrated dynamic IP and wavelength routing in IP over WDM networks," in *Proceeding of IEEE INFOCOM*, pp. 358–366, Apr. 2001.
6. J. Comellas, R. Martinez, J. Prat, V. Sales, and G. Junyent, "Integrated IP/WDM routing in GMPLS-based optical networks," *IEEE Network Magazine* **17**, pp. 22–27, March/April 2003.
7. S. Koo, G. Sahin, and S. Subramaniam, "Dynamic LSP provisioning in overlay, augmented, and peer architectures for IP/MPLS over WDM networks," in *Proceeding of IEEE INFOCOM*, Mar. 2004.
8. R. Dutta and G. N. Rouskas, "A survey of virtual topology design algorithms for wavelength routed optical networks," *Optical Network Magazine* **1**, pp. 73–89, Jan. 2000.
9. J. Katou, S. Arakawa, and M. Murata, "A design method for logical topologies with stable packet routing in IP over WDM networks," *IEICE Transactions on Communications* **E86-B**, pp. 2350–2357, Aug. 2003.
10. K. Lu, J. P. Jue, G. Xiao, I. Chlamtac, and T. Ozugur, "A distributed signaling scheme for provisioning dynamic traffic in wavelength-routed networks," in *Proceeding of SPIE Opticomm*, pp. 151–162, Oct. 2003.
11. R. Ramaswami and K. N. Sivarajan, "Design of logical topologies for wavelength-routed optical networks," *IEEE Journal on Selected Areas in Communications* **14**, pp. 840–851, June 1996.