PAPER *Special Issue on Photonic IP Network Technologies for Next Generation Broadband Access*

A Design Method for Logical Topologies with Stable Packet Routing in IP over WDM Network

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SUMMARY An IP (Internet Protocol) over WDM network is expected to be an infrastructure for the next–generation Internet by directly carrying IP packets on the WDM–based network. Among several architectures for IP over WDM networks, one promising way is to overlay a logical topology consisting of lightpaths over the physical WDM network so that IP packets are carried on the lightpaths. The conventional methods for designing the logical topology have been focusing on maximizing throughput of the traffic. However, when the WDM network is applied to IP, the end-to-end path provided by the logical topology of the WDM network is not suitable to IP since IP has its own metrics for route selection. In this paper, we propose a new heuristic algorithm to design a logical topology by considering the delay between nodes as an objective metric. This algorithm uses a non-bifurcated flow deviation to obtain a set of routes that IP packets are expected to traverse. Our proposal is then compared with conventional methods in terms of the average packet delays and throughput. It is shown that our method becomes effective when the number of wavelengths is a limited resource.

key words: *Photonic Network, IP over WDM, logical topology, flow deviation, route stability*

1. Introduction

An IP (Internet Protocol) over a WDM (Wavelength Division Multiplexing) network, in which IP packets are directly carried over the WDM network, is expected to offer an infrastructure for the next generation Internet. A lot of products for IP over WDM networks only provides large bandwidth on point-to-point links. That is, each wavelength on the fiber is treated as a physical link between conventional IP routers. The link capacity is certainly increased by the number of wavelengths multiplexed on the fiber. However, it is insufficient to resolve the network bottleneck against an explosion of traffic demands since it only results in that the bottleneck is shifted to an electronic router.

One promising way to alleviate the bottleneck is to configure the wavelength paths over the WDM physical network and to carry IP packets. Here, the physical network means an actual network consisting of optical nodes and optical–fiber links connecting nodes. Each node has optical switches directly connecting an input wavelength to an output wavelength with no electronic processing at the node. A wavelength path can be set up directly between two nodes via one or more optical switches. Hereafter, the wavelength path directly connecting two nodes is referred to as a *lightpath*.

By consisting of lightpaths over the physical topology, the logical topology of WDM networks is embedded, and the logical topology is viewed as underlying network by the IP. If the lightpaths are placed between every two end nodes, no electronic processing is necessary within the network. However, many wavelengths are necessary to establish such a network [1]. By limiting the number of lightpaths, on the other hand, we need less wavelength, though a routing capability should be provided at nodes (see the next section for more detail). In this approach, lightpaths are first established by using the available wavelengths as much as possible. If a direct lightpath cannot be set up between two nodes, two or more lightpaths are used so packets that reach their destination.

Many researchers have developed design methods for the logical topology [2–4]. For example, the authors in [3] formulate a method for designing logical topology as an optimization problem, and show that the problem is NP-hard. In [4], the authors consider the logical topology design problem together with packet routing problem so as to maximize the network throughput. Since the combined problem is computationally hard to solve, it is split it into two subproblems, and solve those two subproblems independently. The routing problem is formulated as a linear-programming problem by imposing a delay constraint on each node pair. Several heuristics are also proposed to relax the computational burden.

We should note here that MPLS (Multi-Protocol Label Switching) is developed by IETF [5–8], and is being applied to IP over WDM networks [9], called as MPL (ambda) S or λ–MPLS. Its general extension to fibers and wavelengths, called GMPLS (Generalized MPLS), is also being discussed [10]. Among several options of MPLS, the route that the lightpath traverse may be determined explicitly (explicit routing). In such a network, the lightpath should be prepared among every end node pairs within the MPLS domain, which requires too many wavelengths as described in the above. To alleviate the problem, we split the lightpath within the network. In this approach, it may take two or more lightpaths within the IP over WDM network for the packets to be forwarded. The IP routing capability within the network thus becomes necessary.

In our network, a packet route is determined by the

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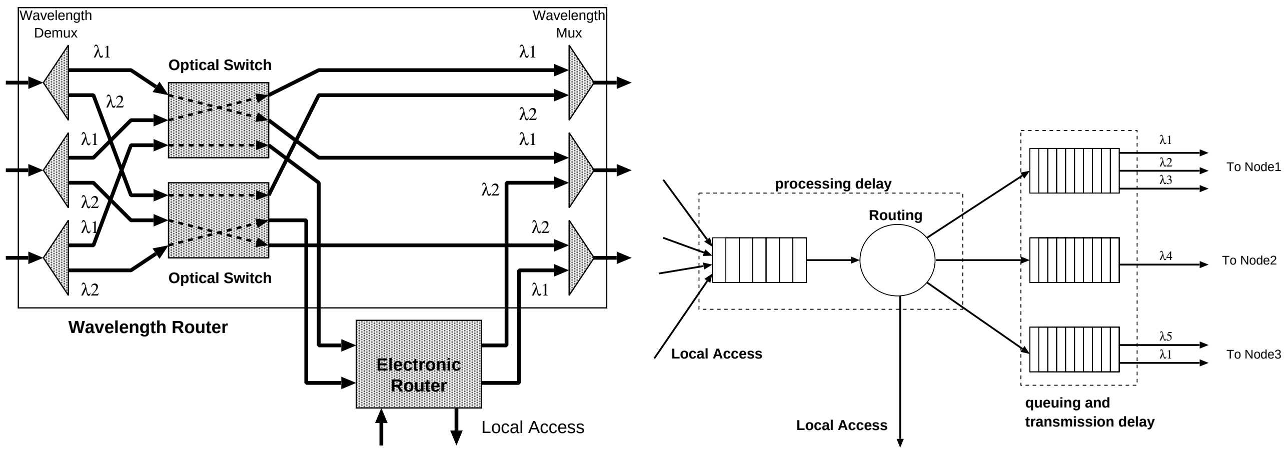

(a) Node Architecture

(b) Model of Electronic Router

Fig. 1 Node Architectural Model

routing protocol provided by the IP layer, and underlying WDM network only provides (logical) paths between nodes. Then, in designing the logical topology, the routes of the lightpaths should be determined by considering the nature of the IP routing protocol. That is, we place lightpaths such that the IP packet experiences smaller delays on its end-to-end path. For this purpose, we try to reduce the number of electronic nodes, in addition to small propagation delays between two end nodes.

The routing stability of IP is another important issue in designing IP over WDM networks. Most conventional researches assume the amount of traffic between nodes is given and fixed. In building IP networks, however, the issue on routing stability should also be considered. In this paper, we compare the delays of first and second shortest end-to-end paths, and if packet delays experienced by those two paths are much different, we conclude that the logical topology is "robust" against traffic fluctuation. Actually, we will show through numerical examples that our proposed method is robust against routing instability.

The paper is organized as follows. In Section 2, we describe our architecture model of optical node. In Section 3, we propose the logical topology design method considering the routing stability. A flow deviation method, one of methods for flow assignments on a logical topology, is introduced in Section 4. In Section 5, we compare and evaluate our proposed algorithm with the conventional algorithm. Finally, Section 6 concludes our paper.

2. Architectural Model of Nodes

Fig. 1 shows our architectural model of an optical node. Every optical node is equipped with an optical switch and an electronic router. The optical switch consists of three main blocks: input section, non-blocking switch, and output section. At the input section, optical signals are demultiplexed into W fixed wavelengths, $\lambda_1, \ldots, \lambda_W$. Each wavelength is switched into an appropriate output port of a non-blocking switch without wavelength changes. The output section again multiplexes the output wavelengths of non-blocking switches into the fiber, and the optical signals goes to the next node. Note that a lightpath is set between two nodes by configuring non-blocking switches along the path so that packets on a particular wavelength from the input port to the output port are forwarded with no electronic processing.

As described in the previous section, since the number of wavelengths necessary can be reduced, one-hop lightpaths are not always provided for all end-node pairs. If the lightpath is terminated at the node within the network, IP packets on that lightpath are converted to electronic signals and forwarded to the electronic router. The electronic router processes packet forwarding, just the same as conventional routers. If the packet should be further forwarded to other nodes, the electronic router puts it on the appropriate lightpath.

A model of electronic router is shown in Fig. 1(b). IP packets, which come from an optical switch or local access, are first buffered, and then these packets are processed on a FIFO (First In First Out) basis. When the packets are forwarded to the network, they are queued on the appropriate output-port buffer. In this paper, we assume that multiple lightpaths between an adjacent node pair share the same buffer. We last note that the other structures of optical nodes can also be considered, but the above–mentioned node architecture is preferable since there is no need to modify the IP routing mechanism.

3. Design Algorithm for Logical Topology

A heuristic algorithm called MLDA (Minimum delay Logical topology Design Algorithm) to establish a logical topology has already been developed [11]. MLDA works as follows. First, it places the lightpath between two nodes if a fiber directly connecting these nodes exists. Then, attempts are made to place lightpaths between nodes in the order of descending traffic demand. Finally, if non-utilized wavelengths still exist, lightpaths are placed randomly by utilizing those wavelengths as much as possible. A lot of conventional methods including MLDA focuses mainly on maximizing throughput of traffic, but they are not adequate for designing a logical topology suitable for carrying IP traffic since the IP routing protocol selects a route that has smaller delays on its end-to-end path.

We therefore developed a new logical topology design algorithm called SHLDA (Shortest-Hop Logical topology Design Algorithm). As described before, we assume that a routing function is performed only on the IP layer. Thus, the logical topology should be designed by incorporating the nature of route selection used in the IP routing protocol. It is natural that a shorter path would be selected by the IP routing protocol for forwarding packets. Note here that *a short path* means that the number of lightpaths between two nodes is small. Actually, queueing and propagation delays also affect route selection. Therefore, hop counts of lightpaths (i.e., the number of lightpaths that the packet traverses) should be reduced as much as possible; that is the primary objective of the developed algorithm.

Once the lightpath is allowed to be split between two end-node pairs, a series of lightpaths is necessary to reach the destination, and the processing delay at the electronic router must be considered. To incorporate the delays at electronic routers into the final determination of packet routes, we apply flow deviation methods [12], which will be described in the next section.

MLDA uses traffic demand between node pairs to set up the next lightpath in the algorithm. On the contrary, we use the performance metric F_{ij} for node pair ij, which is determined by the following equation,

$$F_{ij} = \gamma_{ij} \times h_{ij}, \qquad (1)$$

where γ_{ij} is the traffic demand from node i to j, and 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. Note that F_{ij} is equal to γ_{ij} in MLDA, i.e., MLDA does not consider the hop–count of the lightpath, and only uses the propagation delay in determining the shortest route for the lightpath. On the other hand, SHLDA first uses the hop–count as a metric in calculating the order of lightpath configuration. The propagation delay and the hop–count are then taken into account in determining the route for the lightpath. In determining the route of the lightpath from node i to j, metric R_{ij} is given by the following equation,

$$R_{ij} = D_{ij} \times h_{ij}, \qquad (2)$$

where D_{ij} is the total propagation delay of the route from node i to j. SHLDA selects the route with the smallest R_{ij} shortest route between nodes i and j. It enables us to establish a lightpath that cut through a large number of electronic routers. The SHLDA algorithm consists of the following steps.

- Step 1: Calculate metric F_{ij} for each node pair ij from traffic matrix $Q = q_{ij}$. In initially determining F_{ij}, h_{ij} is simply set as the hop–count of the shortest physical path.
- Step 2: Place the lightpath between two nodes if there exists a fiber.
- Step 3: Select the node pair $i'j'$, where i' and j' are indices giving $\max_{ij} F_{ij}$. If $F_{i'j'} = 0$, go to Step 5. Otherwise, go to Step 4.
- Step 4: Find **the shortest route** for node pair $i'j'$, and check the availability of wavelengths in order to configure the lightpath. If a wavelength is available, use the wavelength with the lowest index to establish the lightpath. Then set $F_{i'j'} = 0$ and go back to Step 3. If there is no available wavelength, set $F_{i'j'} = 0$ and go back to Step 3.
- Step 5: If non-utilized wavelengths still exist, lightpaths are configured randomly using those wavelengths as in MLDA.

4. Applying Flow Deviation Method

4.1 Description of Flow Deviation Method

In this subsection, we summarize the flow deviation method [12]. It works as follows. It incrementally changes the flow assignment along the feasible and descent direction. Given an objective function T, the flow deviation method sets l_{ij} as a partial derivative with respect to λ_{ij}, where λ_{ij} is the flow rate of lightpath(s) between nodes i and j. Then, the new flow assignment is solved by using the shortest path algorithm in terms of l_{ij}. By incrementally changing from the old flow assignment to the new one, the optimal flow assignment is determined. The flow deviation consists of following steps.

- Step 1: Prepare a feasible starting flow assignment f^0. Let $n = 0$.
- Step 2: Set $g \leftarrow f^n$. Assume that flow assignment f^n is represented as $\{x_{11}, \ldots, x_{pq}, \ldots, x_{NN}\}$.
- Step 3: Calculate $l_{ij} = \frac{\partial T}{\partial \lambda_{ij}}$. Then, set the new flow assignment $R(g)$ to $\{x'_{11}, \ldots, x'_{pq}, \ldots, x'_{NN}\}$ by solving the shortest path algorithm using the metric l_{ij}.
- Step 4: For each node pair ij, perform the following steps.
  - Step 4.1: Let v be the flow assignment by deviating the flow between nodes i and j from g toward $R(g)$. That is, the resulting flow assignment, v, is set to $\{x_{11}, \ldots, x'_{ij}, \ldots, x_{NN}\}$.
  - Step 4.2: Check whether v is feasible. In our case, feasible v means that the processing capability of IP routers and/or the capacity of a lightpath do not exceed its limits. If the v is not feasible, then the deviation at Step 4.1 is

rejected, and go back to Step 4.

Step 4.3: Check whether v is decreasing. If $T(v) < T(g)$, g is allowed to be deviated toward v. Then, $g \leftarrow v$. And go back to Step 4. If $T(g) \leq T(v)$, the deviation from g toward $R(g)$ is rejected, and go back to Step 4.

Step 5: If $g = f^n$, stop iteration. Note that $g = f^n$ means there is no improvement of performance by deviating the flow. Otherwise, set $n \leftarrow n+1$, and go back to Step 2.

4.2 Derivation of Metric l_{ij}

We next determine metric l_{ij} of the flow deviation. The following notations are used.

- N: number of nodes in the network
- P_{ij}: propagation delay of a lightpath ij
- C: transmission capacity of each wavelength
- μ: processing capability of an electronic router. Assumed to be identical among all routers for simplicity.

The following variables are also introduced.

- a_{ij}^{sd}: when the packets are routed from node s to node d via the direct lightpath ij, the value is set to be 1. Otherwise, 0.
- δ_i: the sum of all traffic switched by the IP electronic router at node i, except the traffic flow originating at node i.

Objective function T is given as the average T_{sd} (delay between node s and d), i.e.,

$$T = \frac{1}{N(N-1)} \sum_{s=1}^{N} \sum_{d=1}^{N} T_{sd} \tag{3}$$

As shown in Fig. 1, the delay incurred at a node consists of processing delay and transmission delay. Henceforth, the delay between nodes s and d consists of propagation delay, processing delay, and transmission delay. It thus follows that

$$\begin{aligned} T_{sd} = & \left[\textstyle\sum_{ij} a_{ij}^{sd} P_{ij}\right] + \left[\textstyle\sum_{ij} a_{ij}^{sd} Q_{ij}\right] \\ & + \left[\textstyle\sum_{ij} (a_{ij}^{sd} R_i) + R_d\right], \end{aligned}$$

where Q_{ij} is the transmission delay of the packets on lightpath ij, and R_i is the processing delay in the electronic router for node i. In this paper, Q_{ij} is determined by a $M/M/k_{ij}$ (where k_{ij} shows the number of lightpaths between node pair ij) queuing system, and R_i by a $M/M/1$ queueing system. A multiple number of lightpaths between the node pair is allowed , and those lightpaths share the same buffer (see Section 2). Q_{ij} and R_i are then determined as follows.

$$Q_{ij} = \frac{X_l}{l \cdot C - \lambda_{ij}} + \frac{1}{C} \tag{4}$$

$$R_i = \frac{1}{\mu - (\lambda_{ij} + \delta_i)} \tag{5}$$

where

$$X_l = \frac{p_0 \, (l\rho)^l}{(1-\rho) \, l!}$$

$$\rho = \frac{\lambda_{ij}}{k_{ij} \cdot C}$$

$$p_0 = \left\{ \sum_{x=0}^{k_{ij}-1} \frac{(k_{ij}\rho)^x}{x!} + \frac{(k_{ij}\rho)^{k_{ij}}}{k_{ij}!(k_{ij} - \rho)} \right\}^{-1}$$

Three kinds of packets arrive at the electronic router of node i: packets destined for node i, packets arriving at node i from local access, and packets changing the lightpath at node i. Thus, δ_i is given by the following equation.

$$\delta_i = \left[\sum_j \gamma_{ji} + \sum_j \gamma_{ij} + \sum_j a_{ij}^{sd} \gamma_{sd} \right] - \lambda_{ij}$$

Note that λ_{ij} is the flow rate of lightpath(s) between nodes i and j. That is,

$$\lambda_{ij} = \sum_{sd} a_{ij}^{sd} \gamma_{sd}.$$

Equations (4) and (5) give l_{ij} as

$$l_{ij} = \frac{\partial T}{\partial \lambda_{ij}} = \frac{1}{N\,(N-1)} \sum_{s=1}^{N} \sum_{d=1}^{N} a_{ij}^{sd} \alpha_{sd},$$

where

$$\alpha_{sd} = \frac{X_{k_{ij}}}{(l \cdot C - \lambda_{ij})^2} + \frac{1}{(\mu - (\lambda_{ij} + \delta_i))^2}.$$

5. Numerical Evaluation and Discussions

5.1 Network Model

As a network model, a 14–node NSFNET is considered (F Fig. 2). A traffic matrix given in [4] is used in the numerical evaluation. Since the traffic matrix is given by a relative value, we introduce *traffic scale* α, and actual traffic

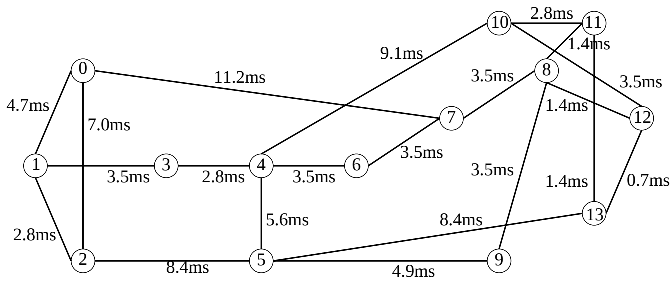

Fig. 2 NSFNET

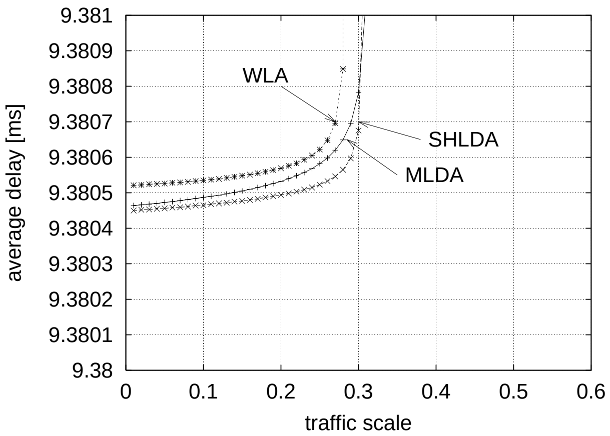

Fig. 3 Average delay of end-to-end paths : W = 8, μ = 40 Mpps

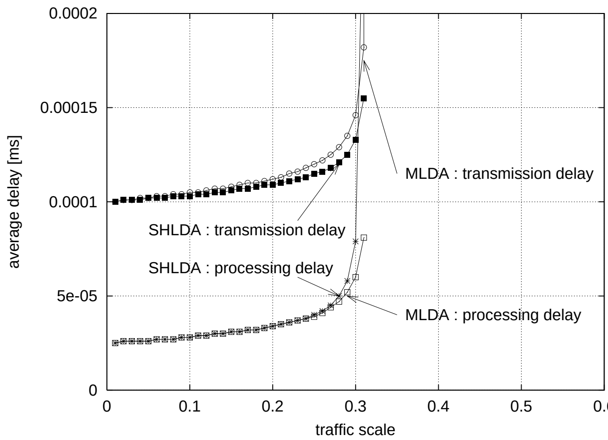

Fig. 5 Average of packet processing and transmission delays at electronic routers : W = 8, μ = 40 Mpps

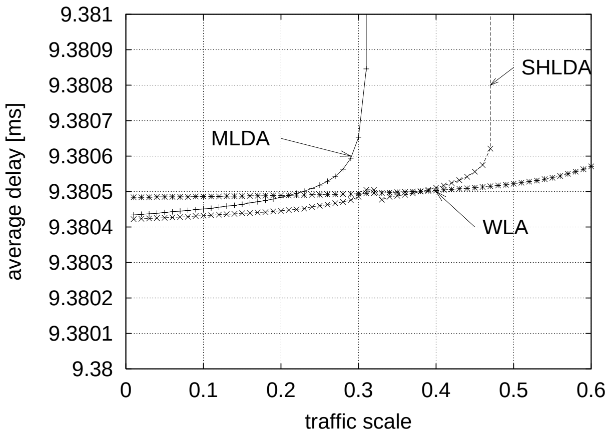

Fig. 4 Average delay of end-to-end paths : W = 8, μ = 100 Mpps

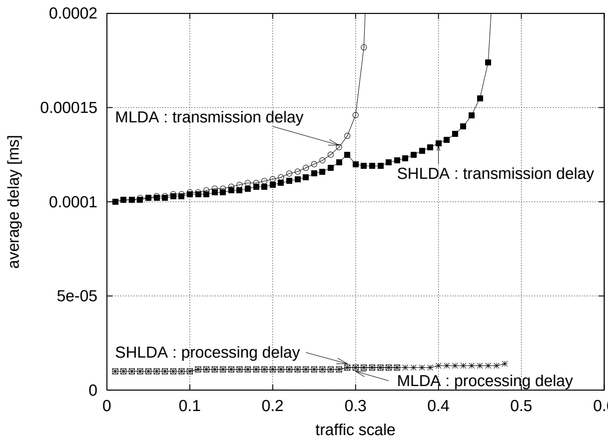

Fig. 6 Average of packet processing and transmission delays at electronic routers: W = 8, μ = 100 Mpps

demands between nodes are given by the traffic matrix multiplied by α. It is also assumed that the value of the given traffic matrix is represented in gigabits per second. And the transmission capacity of each wavelength is set to 10 Gbps. The packet processing capability of the electronic router, μ, is represented in pps (packet per second) under the assumption that the mean packet size is 1,000 bits long.

5.2 Numerical Results and Discussions

We evaluate our SHLDA by comparing with MLDA. In addition to MLDA, we also consider WLA (WDM Link Approach), where a WDM technology is only utilized for point-to-point links between adjacent IP routers. Fig. 3 compares the average delays obtained by the three algorithms, SHLDA, MLDA and WLA. The horizontal axis shows the traffic scale α. The number of W is set to eight and the packet processing capacity of the IP router, μ, is set to 40 Mpps. In the figure, when α is small, no significant difference between the three algorithms can be seen. In the case of all three algorithms, the delays suddenly increase as α becomes large. It is notable that our SHLDA has the same performance as MLDA in terms of the maximum throughput, i.e., the saturation point of the delays.

Fig. 4 shows the effect of increasing the packet forwarding capability of IP routers by changing μ from 40 Mpps to 100 Mpps. The other parameters are the same as those in Fig. 3. Comparing these two figures shows that the maximum throughput values by SHLDA is increased. On the other hand, an increased in the maximum throughput cannot be seen when we apply MLDA. To explain this result, the nodal delays were studied in more detail. Figs. 5 and 6 show the dependency of processing and transmission delays on α. As expected, the processing delay at the electronic router decreases both SHLDA and MLDA when the capability of the IP routers changes from 40 Mpps to 100 Mpps. Since the processing delay is reduced as the capacity of the IP router increases, the transmission delay becomes the bottleneck of the network. In that case, SHLDA becomes superior to MLDA.

Next, we set the number of wavelengths W to twelve and μ to 40 Mpps. The average delay is plotted in Fig. 7. By

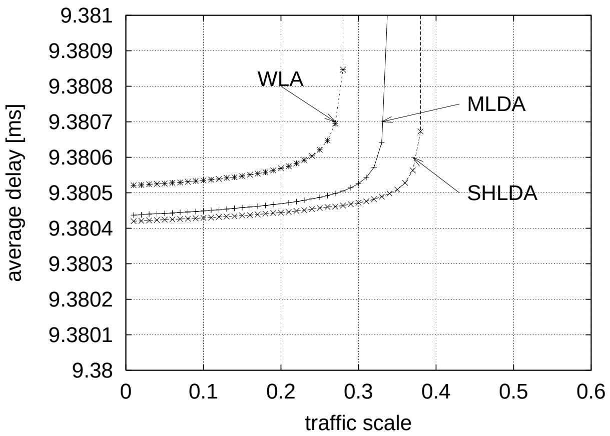

Fig. 7 Average delay of end-to-end paths: W = 12, μ = 40 Mpps

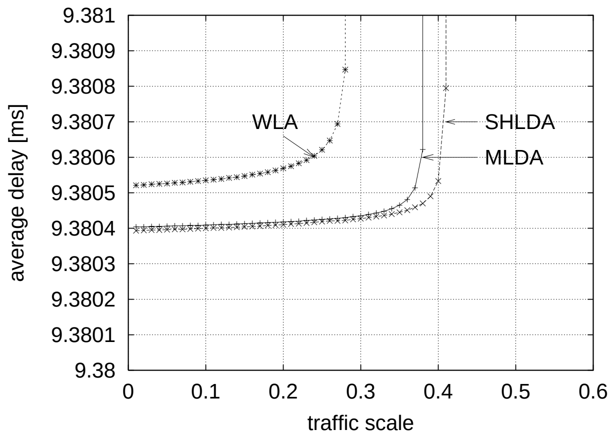

Fig. 9 Average delay of end-to-end paths: W = 20, μ = 40 Mpps

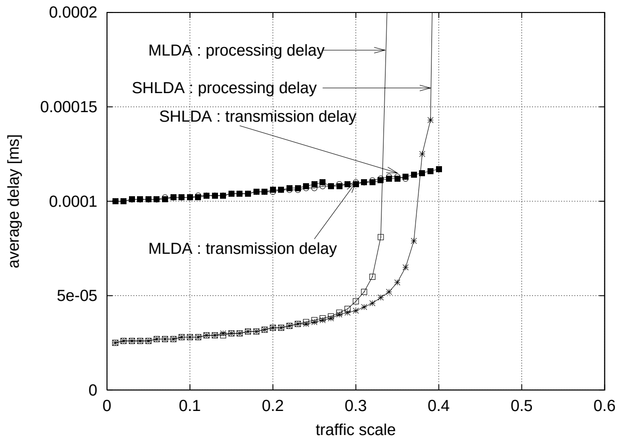

Fig. 8 Average of packet processing and transmission delays at electronic routers: W = 12, μ = 40 Mpps

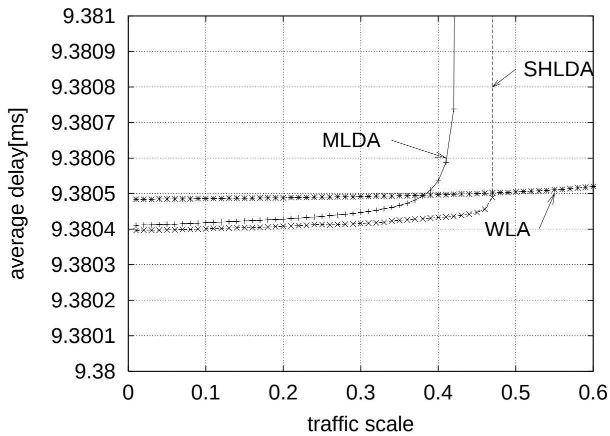

Fig. 10 Average delay of end-to-end paths: W = 12, μ = 100 Mpps

comparing Figs. 3 and 7, it is apparent that SHLDA exhibits the largest increase in maximum throughput. To see this more clearly, Fig. 8 presents components of delays shown in Fig. 7.

According to Figs. 5 and 8, the transmission delay by MLDA is decreased more than that by SHLDA. Its reason can be explained as follows. SHLDA places lightpaths in a descending order of the product of the hop–count and traffic demand. As a result, a lightpath placed by SHLDA tends to utilize more links than the one by MLDA. Thus, MLDA can find more lightpaths than SHLDA as the number of available wavelengths increases. This leads to decreasing the transmission delay in the case of MLDA. Comparing the processing delay in Figs. 5 and 8 shows that, when the traffic scale is from 0.27 to 0.37, the processing delay at the IP router is decreased as the number of available wavelengths increases. Its effect is larger in the case of SHLDA. As mentioned before, the lightpaths placed by SHLDA tend to utilize more physical links. This results in more reduction of electric processing in SHLDA than that in MLDA.

The average delay determined by SHLDA by increasing the number of wavelengths is explained in the following. Fig. 9, where W is 20 and μ is 40 Mpps, plots average delay against traffic scale. In this figure, SHLDA still attains a higher throughput than MLDA, but the difference is comparatively smaller than that in Fig. 7. The reason for this is that by increasing the number of wavelengths, the logical topologies obtained by SHLDA or MLDA become close to a fully meshed network. The advantage of SHLDA thus becomes small since it tries to reduce the traffic load on the IP router. We also show the case that μ is 100 Mpps. The result is plotted in Fig. 10 where we set $W = 12$. Comparing Figs. 7 and 10 also shows the effectiveness of SHLDA.

Lastly, we summarize the characteristics of WLA by observing Figs. 3, 4, 7 and 10. Figs. 3 and 7 indicate that the increase in the maximum throughput by WLA is very limited. This is because the processing delay at the electronic router is the primary bottleneck of the network; thus, the effect of increasing the number of wavelengths cannot be observed. As one can easily imagine, the results regarding for WLA are greatly improved as the capability of the IP router becomes large (compare Figs. 3, 4 and 10). Only in such a large capability, WLA is not a bad choice for IP over

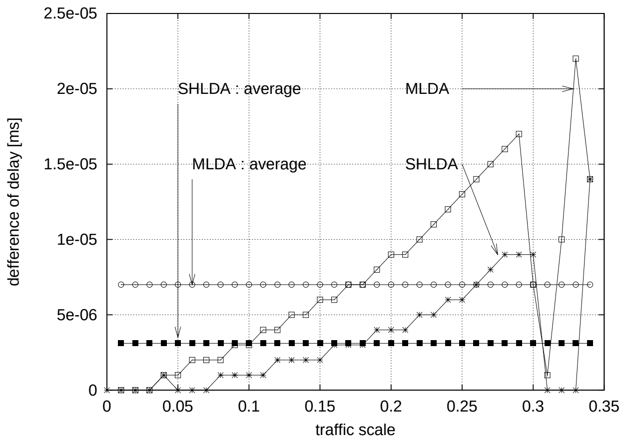

Fig. 11 Route stability: Delay difference between the first and sencond shortest path (W = 8, μ = 40 Mpps)

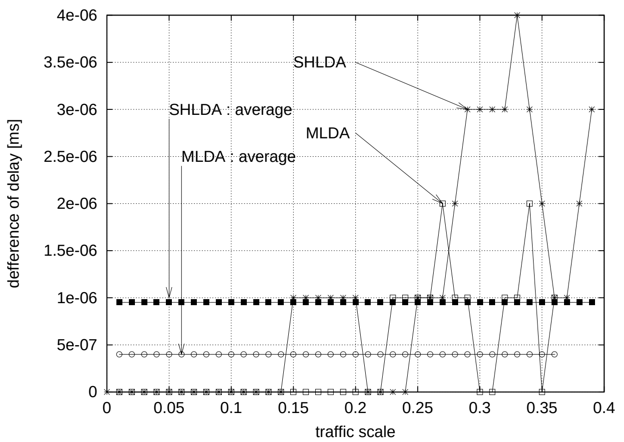

Fig. 12 Route stability: Delay difference between the first and sencond shortest path (W = 12, μ = 40 Mpps)

WDM networks.

5.3 Investigation on Routing Stability

We finally discuss the new logical topology design algorithm from the viewpoint of the stability of IP routing. In IP networks, it is necessary to avoid or at least to reduce unnecessary changes of the routes, which are caused by dynamically changing traffic demand. To evaluate routing stability, we show the packet delays of the first and second shortest end-to-end paths (lightpaths) determined by SHLDA . If these two values are close, the route of the IP packets may frequently change with traffic fluctuation.

Metric d_{sd}, which defines the difference of delays of the first and second shortest routes between node pair sd, is introduced here. From all possible combinations of source and destination node pairs, the smallest one was chosen as d_{min}, i.e., $d_{min} = min_{sd}\{d_{sd}\}$. We consider here that the design algorithm that provide the larger d_{min} gives a higher routing stability. Figs. 11 and 12 plot d_{min} obtained from SHLDA and MLDA as a function of α, where the number of wavelengths W is set to eight and twelve, respectively. The processing capacity of the IP router, μ, is identically set to 40 Mpps in both figures. The average value of d_{min} is also shown in the figures. It is clear that when W is 8 (Fig. 11), SHLDA is not very good especially when the traffic scale is large. However, it gives higher stability than MLDA when the number of wavelength is twelve (Fig. 12).

The problem with both of MLDA and SHLDA is that at several values of α, d_{min} takes very small values. This is mainly because SHLDA as well as MLDA is a “one–way algorithm”. That is, there are no step-back operation in the algorithms; in other words, if the nodal delay is high, it is likely that the delay of the first shortest route becomes close to the delay of the second shortest one, since the nodal delay becomes dominat in such a region. We believe the situation can be avoided by reassembling the lightpaths to reduce the nodal delay, but this issue is one of our future research topics.

6. Conclusion

We have proposed a new heuristic algorithm, SHLDA, for designing a logical topology by considering the delay between nodes as an objective metric. The proposed algorithm was compared with conventional methods in terms of the average packet delay and throughput. The results show that SHLDA becomes effective when the number of wavelengths is low and the processing capacity of a IP router is large. Furthermore, SHLDA was evaluated from a viewpoint of routing stability. It was found that SHLDA improves the maximum throughput, compared with a conventional algorithm, without sacrificing routing stability.

However, at certain traffic scales, it was also found that SHLDA selects routes that can cause more routing instability than that for MLDA. To solve this problem, in our future work, lightpaths must be reconfigured to increase the routing stability.

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