Design of Logical Topology with Effective Waveband Usage in IP over WDM Networks

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We deal with the problem of designing the logical topology in IP over WDM network. Many conventional methods for designing the logical topology assume that a constant number of wavelengths be available on each fiber. But it is not necessary to utilize all wavelengths on each fiber in building an effective logical topology on a WDM network. Instead, several wave–bands may be considered for introduction by deploying optical fiber amplifiers when additional wavelengths are actually required. In this case, the number of wavelengths available on the respective fibers depends on the number of optical fiber amplifiers deployed on each fiber. In this paper, we propose a heuristic algorithm for the design of a logical topology with as few optical fiber amplifiers as possible. Our results indicate that our algorithm reduces the number of optical fiber amplifiers with the slight increase of average packet delays.

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1. Introduction

WDM technology, in which multiplexed wavelength channels are carried on a single fiber, is expected to provide the infrastructure of the next generation Internet. Since the majority of Internet traffic is 'packets' on IP, much recent research has been devoted to an IP over WDM network where IP packets are directly carried over the WDM network. Among several architectures for IP over WDM networks, one promising approach is to create a logical topology that is made up of lightpaths as an overlay upon the physical WDM network, each of which carries IP traffic between edge nodes [1]. Such a lightpath is a wavelength–channel that does not require any electronic processing at intermediate nodes. This reduces the load of packet processing at the intermediate nodes.

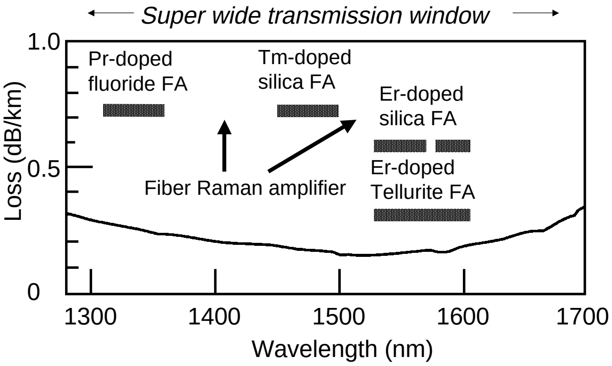


Fig. 1. Loss spectrum of typical low-loss optical fiber [2]

The number of wavelengths available on a single fiber is an important parameter in the design of the logical topology. Having more wavelengths multiplexed on each fiber allows the network to accommodate more lightpaths. Using a spectral range of 1290–1690 nm leads to multiplexing 1,000 wavelengths on the fiber. As has been discussed in earlier work [2, 3], deploying additional optical fiber amplifiers makes high loss regions (e.g., 1530–1610 nm) available. That is, we will require several kinds of optical fiber amplifiers to utilize 1,000 wavelengths. Figure 1 shows the amplifiers required across the spectral to realize 1,000 wavelengths. Since preparing several amplifiers for the entire spectral range is costly, we want to reduce the number of optical amplifiers (and the number of wavelengths) on the fiber. We can actually realize this because 1,000 wavelengths are not necessary at all links. For this purpose, however, we need a new way of designing the logical topology such that it minimizes the number of optical amplifiers while meeting the demands imposed by traffic. This is the main subject of our current paper.

A lot of work has dealt with methods for the design of the logical topology [4, 5, 6, 7]. For example, one approach is to minimize the number of wavelengths required within the WDM network [5, 6]. Much other work has been based on the assumption that a constant number of wavelengths is available on each fiber [7]. However, the number of multiplexed wavelengths is determined by the number of the wave–bands available, thus the number of the optical fiber amplifiers deployed on the fiber. Therefore, in a cost–effective design of the logical topology, we need to introduce fiber amplifiers only on fiber which would otherwise lack the required bandwidth (i.e., number of wavelengths). Many existing design algorithms are only intended for use with a rather small number of wavelengths. The resulting optimization problem is to try to completely utilize the wavelengths on the fiber in accommodating the traffic. In this paper, we propose a new algorithm called MALDA (Minimum number of fiber Amplifiers Logical topology Design Algorithm). This algorithm is in contrast to earlier approaches in that it minimizes the deployment of optical fiber amplifiers on the fiber, rather than minimizing the number of wavelengths required to accommodate the traffic demand.

The paper is organized as follows. In Section 2, we extend the conventional method for designing the logical topology to set lightpaths based on the actual traffic demand. We next propose a logical topology design method that has, as its objective function, the minimization of the number of fiber amplifiers. This is in Section 3. Section 4 is a comparative evaluation of our proposed algorithms and the conventional algorithm. We finally conclude our paper in Section 5.

2. Design of Logical topology based on the requested traffic volume

In this section, we extend MLDA (Minimum–delay Logical topology Design Algorithm), a conventional method for designing the logical topology proposed in [8]. Since the MLDA targets the network with a small number of wavelengths multiplexed, the logical topology designed by the MLDA may not accommodate the traffic demand when a large number of wavelengths are multiplexed in the network. On the other hand, we want to accommodate the given traffic demand, the unit of which has a particular value in, e.g., Gbps, on the network with a lot of wavelengths multiplexed. Then, our new algorithm sets up lightpaths enough to accommodate the volume of required traffic. We call our new algorithm the e-MLDA (extended MLDA). We need this extension to deal with our main objective of minimizing the number of optical fiber amplifiers. This objective is covered in the next section. Note that in this section we extend the conventional approach assuming that the number of wavelengths on the fiber is fixed. In the next section, we will also cover the case where the number of wavelengths is a design variable that is dependent on some number of costly optical amplifiers.

Before describing our algorithm, we depict the node–architecture model in Fig. 2. Every node is equipped with an optical switch and an electronic router. The optical switch consists of three main blocks; input section, a non–blocking switch, and output section. In the input section, the optical signals are demultiplexed into W fixed wavelengths, $\lambda_1, \cdots, \lambda_W$. Each wavelength is then switched into an appropriate output port, without wavelength conversion, by a non–blocking switch. Finally, the wavelengths are again multiplexed on the fiber, that go to the respective next nodes. Note that a lightpath is configured by the non–blocking switches along the paths, so that the traffic on a particular wavelength is forwarded from the input port to the required output port without any electronic processing.

At the terminal node of a lightpath, IP packets in the lightpath are converted to electronic signals and forwarded to the electronic router. The electronic router processes the packet forwarding, in the same way as in a conventional router. If the packet requires further forwarding to other nodes, it is put on the appropriate lightpath. IP packets, whether they come through the optical switch or are received via local access, are first buffered for processing. The packets are then processed on a FIFO (first–in first–out) basis. Packets that are to be forwarded within the network are queued in the appropriate output port buffer.

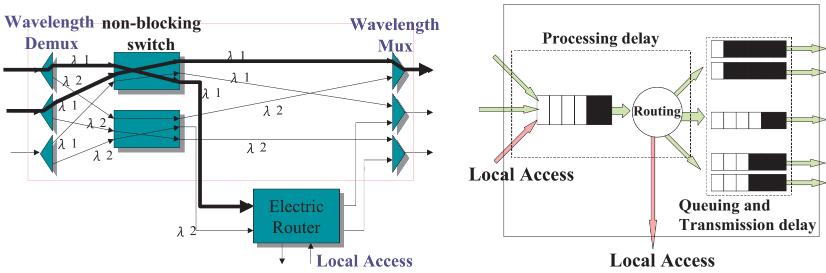
The design problem of logical topology is traditionally called RWA (Routing and Wavelength Assignment) problem. In RWA problem, given (1) physical network, (2) traffic matrix that expresses the static traffic demand in the physical network, and (3) constraints (e.g., the number of wavelengths multiplexed on a fiber), which can be an objective function in other case, we must determine (1) the route and (2) the wavelength to be assigned to the lightpath of each traffic demand so that an objective function (e.g., throughput, the number of wavelengths utilized) is optimized.

Now we show our e-MLDA algorithm. Note again that the extension of the MLDA to the e-MLDA is the first step to propose the design method of logical topology whose objective function is to minimize the number of optical fiber amplifiers. The objective of the e-MLDA is to ensure the accommodation of the traffic demand with the consideration of the route for IP packet to flow. We introduce the following notations to represent the physical network.

N: The number of nodes in the WDM network.

P_{ij}: Represents the elements of the physical network. If there is a fiber that connects node i and node j, then $P_{ij} = 1$, otherwise $P_{ij} = 0$.

Q: A traffic distribution matrix. The value of an element (i, j) represents the traffic demand between nodes i and j.



(a) Node architecture

(b) Model of electronic router

Fig. 2. Node architecture model

C: Bandwidth of each wavelength.

W: The number of wavelengths multiplexed on a single fiber.

Given these parameters, the e-MLDA designs the logical topology by setting up multi-hop lightpaths that are sufficient to accommodate the requested traffic volume between nodes. The reason we set up multi-hop lightpaths is to avoid the lack of wavelengths. If we set up single-hop lightpaths from source node to destination one, we can only set up fewer lightpaths because of the wavelength continuity constraint.

Our e-MLDA sets the lightpaths on the shortest routes in terms of the propagation delay between nodes, which is the same route selection as the MLDA does. In addition, we make the number of the intermediate nodes (i.e., hop count over the logical topology) for the same node–pair identical. As a result, we expect that IP packets, which flow on the shortest-path in terms of the propagation delay, can flow on any of the lightpaths. If we do not make their hop count identical, IP packets will flow only on the lightpaths whose hop counts are minimum.

The wavelength chosen for the lightpaths is based on a First–Fit policy, that is, the e-MLDA selects the wavelength with the lowest index of λ among those wavelengths that are not assigned to lightpaths yet. First–Fit is preferable in our case because First–Fit gives priority to selecting the wavelength available by already installed fiber amplifier in the situation where the indexes of wavelengths in the same wave–band are sequential. Note that the wavelengths that are not used are left in our algorithm while MLDA uses all the wavelengths on each fiber because the MLDA aims at maximizing the throughput while ours finally aims at minimizing the number of optical fiber amplifiers to be installed.

We use the following notations to explain our algorithm.

t, v: Originating/terminating nodes of a lightpath. Note that the lightpath is a part of multi–hop lightpaths between nodes i and j. Our algorithm recursively try to set up multi–hop lightpath; if a direct lightpath cannot be set up between node i and j, $\{t, v\}$ is first set to $\{i, x\}$, then to $\{x, j\}$. The x is an intermediate node on the shortest path from node i to node j.

q_{ij}: Traffic volume that is requested for node–pair (i, j).

B_{ij}: A node connected to node j along the shortest path from node i to node j.

T_{ij}: The total available bandwidth in existing lightpaths between nodes i and j.

Using these notations, we now explain our e-MLDA algorithm. This is followed by some additional comments on the algorithm.

Step 1 Select a pair of nodes (i', j') such that element $q_{i'j'}$ of the traffic–distribution matrix Q is the largest. We start by selecting a node pair that is directly connected by fiber to ensure the reachability. If $q_{i'j'} = 0$, then the lightpaths are prepared between all the nodes. Thus, we can terminate our algorithm in finite steps. Otherwise, go to Step 2.

Step 2 Initialize the variables as $t \leftarrow i'$, $v \leftarrow j'$. Then, go to Step 3 and try to set lightpaths of adequate capacity between nodes t and v.

Step 3 If $t = j'$, the lightpaths have enough capacity to accommodate the traffic from node i' to node j'. Then, set $q_{i'j'} \leftarrow 0$, and go back to Step 1. Otherwise, go to Step 4.

Step 4 Try to accommodate $q_{i'j'}$ on the existing lightpaths between nodes t and v according to the following two conditions.

1. If $T_{tv} \geq q_{i'j'}$, then we can accommodate $q_{i'j'}$ by using the existing lightpaths between nodes t and v. That is, set $t \leftarrow v$, $v \leftarrow j'$ and go back to Step 3.
2. If $T_{tv} < q_{i'j'}$, on the other hand, it is not possible to accommodate $q_{i'j'}$ on the existing lightpaths. Thus, go to Step 5 and try to set new lightpaths between nodes t and v.

Step 5 Try to set $\lfloor (q_{i'j'} - T_{tv})/C \rfloor$ lightpaths between nodes t and v. If it is possible to set the lightpaths, go to Step 5.1. Otherwise, go to Step 5.2.

Step 5.1 After setting up the lightpaths between nodes t and v, we cut the lightpath at node v if another lightpath passes through nodes t and v. Then, we set $t \leftarrow v$, $v \leftarrow j'$ and go back to Step 3.

Step 5.2 If nodes t and v are directly connected via fiber, we are unable to set up lightpaths between nodes t and v. In this case, it is not possible to accommodate the requested traffic between nodes i' and j', and we terminate our algorithm. If nodes t and v are not directly connected, on the other hand, we try to accommodate the traffic by creating lightpaths between node t and inter-node v. Set $v \leftarrow B_{tv}$ and go back to Step 4.

Comments on e-MLDA

In Step 1, the e-MLDA selects a node–pair (i', j') in descending order of traffic volume, which is the same way of selecting the node–pair as MLDA does. Though there are other ways of selecting the node–pair to be accommodated (e.g., longest first, random), the effect of the order of node–pair to be accommodated on the performance is little (difference among the various ways are bellow 10% [9]). To ensure that traffics are able to reach any nodes, we start by setting up lightpaths between the pairs of neighboring nodes. Step 4 checks whether or not existing lightpaths are capable of accommodating the traffic $q_{i'j'}$. If the available bandwidth T_{tv} is insufficient to transport the IP traffic, new lightpaths are set up in Step 5. Since T_{tv} is already available by existing lightpaths, the number of lightpaths required to accommodate the requested traffic volume is $\lfloor (q_{i'j'} - T_{tv})/C \rfloor$.

Step 5.1 deals with the case where we are able to set up enough lightpaths to accommodate the requested traffic. However, in IP over WDM network, we must consider the property of the IP, that is, only the shortest path is utilized by IP traffic, even if multi–hop lightpaths with larger hop count are available. To avoid the situation where multi–hop lightpaths with different hop counts are set up between any node–pair, we divide any lightpaths that originate at node t and pass through node v at node v. In Step 5.2, if we are unable to set up the required lightpaths because too few wavelengths are available, we set $v \leftarrow B_{tv}$ and go back to Step 4 in order to accommodate q_{ij} between nodes t and B_{tv}. Note that, after $q_{i'j'}$ has been accommodated between t and B_{tv}, Step 5.1 sets t to B_{tv} and v to j'. We then try to set up a lightpath between nodes B_{tv} and j'.

3. Designing the logical topology with consideration of the available wave–bands

3.A. Objective Function

The conventional design methods, including our e-MLDA, are based on the assumption that a fixed number of wavelengths is available on each fiber. However, the number of wavelengths available on a fiber depends on the number of optical fiber amplifiers prepared on the fiber. We therefore propose a new method for the design of logical topologies. The method aims at minimizing the number of optical fiber amplifiers within the WDM network, rather than the number of wavelengths required. We call this algorithm the MALDA (Minimum number of fiber Amplifiers Logical topology Design Algorithm).

In our MALDA, W_1 ($< W$) wavelengths are initially set for carriage by each fiber. When there is no available wavelength on a certain fiber during the subsequent design of the logical topology, W_i wavelengths are added by introducing an additional fiber amplifier i ($2 \leq i \leq N_{max}$). Here, we assume that N_{max} kinds of fiber amplifiers may be deployed on the fiber. If the maximum number of wavelengths that can be multiplexed on a fiber is W, we obtain the following relationship for fiber f,

$$\sum_{i=1}^{N_f} W_i \leq W, \tag{1}$$

where N_f ($1 \leq N_f \leq N_{max}$) is the number of fiber amplifiers deployed on fiber f. The objective function of the MALDA is,

$$minimize \qquad \sum_{f \in F} N_f. \tag{2}$$

3.B. Detailed description of MALDA

In the MALDA, fiber amplifiers are added to fiber when too few wavelengths are available to set up new lightpaths. The algorithm terminates when all the traffic demand has been accommodated and the load on all the IP routers become under their processing capacity. Accordingly, we expect that the smallest possible number of fiber amplifiers will then be deployed in the WDM network. The MALDA is similar to the e-MLDA described in Section 2. The point of difference between the e-MLDA and the MALDA is that the latter only deploys an additional fiber amplifier when the wavelengths are too few to accommodate the traffic. For this purpose, we need to modify Step 5.2 of the e-MLDA. Once a fiber amplifier has been added to a fiber, we are able to connect a lightpath that uses the newly available wavelengths. Whether or not a new amplifier should or may be added is checked in the new step, Step 6. The following two steps are one of the two differences between the e-MLDA and the MALDA. Another difference is described in the next subsection.

Step 5.2 If nodes t and v are directly connected via a fiber, we may be able to set up lightpaths between nodes t and v. In this case, we try to accommodate $q_{i'j'}$ by deploying a new fiber amplifier on the fiber, so we go to Step 6. If nodes t and v are not directly connected, on the other hand, then we set $v \leftarrow B_{tv}$ and go back to Step 4.

Step 6 Check the number of fiber amplifiers currently deployed on the fiber between nodes t and v. If N_{max} amplifiers have already been used, it is not possible to accommodate the required traffic and we terminate our algorithm. Otherwise, we add an additional fiber amplifier to increase the number of available wavelengths on the fiber, and connect the existing lightpaths (see Sec. 3.D. for more detail). We then set $v \leftarrow j'$ and go back to Step 4 in order to check whether or not we are able to set up new lightpaths between nodes t and v by adding a fiber amplifier.

3.C. Reducing the Traffic load at IP router

We next consider further adding optical fiber amplifiers to decrease the traffic load on the over–burdened IP routers after the MALDA finishes. This is necessary since the MALDA does not ensure that the load on all IP routers are not beyond the processing capacity. For safer operation, we might limit the maximum amount of traffic accommodated at the IP router to, e.g., 70% of its processing capability. By connecting lightpaths until the load on the IP router fails below the processing capacity of the IP router, we accommodate more traffic. To explain this, we introduce the following notations.

N_{high}:	Set of nodes at which the traffic load on the IP router is beyond its processing capacity.
$N_{available}$:	Set of nodes that have non-utilized wavelength(s) on the fibers to which the node is connected.
N_{heavy}:	Node that has the heaviest traffic load among the set of nodes, chosen from $N_{high} \cap N_{available}$.

We perform the following steps after setting up the lightpaths enough to accommodate all the traffic demand according to the MALDA.

Step A: Set $N_p \leftarrow N_{high} \cap N_{available}$. If N_p is an empty set, then go to Step C. Otherwise, go to Step B.

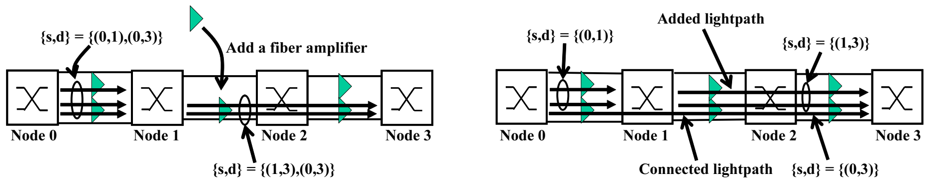
Step B: Randomly choose one fiber from the fibers that are connected to N_{heavy}. Add an optical fiber amplifier to this fiber. Then, try to connect lightpaths through this fiber (see the connecting lightpaths above), and go back to Step A.

Step C: If some nodes have a traffic load that is above the limit of its processing capacity, then the requested traffic cannot be accommodated, and the algorithm is terminated. Otherwise, the new logical topology has successfully accommodated the traffic and the algorithm is terminated.

The above three steps decrease the loads on overloaded IP routers by connecting lightpaths and bypassing IP routers. If too few wavelengths are available to reduce the load, we deploy additional optical fiber amplifiers. If a node remains in the N_{high} condition even after all possible optical fiber amplifiers have been deployed, we are unable to accommodate the requested traffic.

3.D. Connecting Lightpaths

In this subsection, we explain the algorithm for connecting lightpaths after a new fiber amplifier has been added. As we mentioned in Sec. 3.C., the motivation of connecting lightpaths is to prevent IP routers relaying the packets from being over-burdened by setting up multi-hop lightpaths. We connect lightpaths at the node selected in descending order



(a) Before connecting lightpaths

(b) After connecting lightpaths

Fig. 3. An example of connecting lightpaths

of the traffic load on the two nodes, between which a new fiber amplifier is added on the link, since more loaded one will limit the throughput of the network. We can expect this to decrease the load on the IP routers on those nodes.

Let us define x as the node at which we are trying to connect lightpaths. To decrease the traffic load on node x, we try to connect lightpaths in set of lightpaths that terminate at node x and those in a set of lightpaths that originate at node x, i.e., bypass the packet processing at node x. Hereafter, we denote LP_{tx} as a set of lightpaths that originate from node t and terminate at node x, and LP_{xv} as a set of lightpaths that originate from node x and terminate at node v. The operation of the connecting lightpaths is as follows. For any two nodes (say i and j), we try to create LP_{ij} by connecting lightpaths in LP_{ix} and those in LP_{xj}. To do this, we first select the set of node–pairs $\{s, d\}$ that use both LP_{ix} and LP_{xj}. Then, we check whether enough wavelengths are available to connect lightpaths that accommodate the summation of the traffic of node–pairs $\{s, d\}$, i.e., $\sum_{ab\in\{s,d\}} q_{ab}$. If this check is satisfied, there are enough available wavelengths to connect the lightpaths. However, this check is not enough to connect the lightpaths. After we connect the lightpaths, the number of lightpaths in LP_{ix} and LP_{xj} decreases. The traffic overflows by connecting lightpaths. Therefore, we further check whether we are able to accommodate that traffic transmitted via LP_{ix} (or LP_{xj}) that overflows from the connected lightpaths. Only if those two checks are satisfied, we connect the $\lfloor \sum_{ab\in\{s,d\}} q_{ab}/C \rfloor$ lightpaths in LP_{ix} and LP_{xj}.

Figure 3 shows a simple example of the connection of lightpaths. Suppose that the newly added fiber amplifier makes two wavelengths available. Further suppose that $C = 10$ Gbps, and the traffic demands on node pairs $\{0, 1\}$, $\{0, 3\}$, and $\{1, 3\}$ are 15, 7, and 12 Gbps, respectively. The traffic of node pair $\{0, 3\}$ is transmitted via a lightpath in LP_{01} and one in LP_{13} since it is not possible to directly set up a lightpath from node 0 to node 3 because of the lack of wavelengths (see Fig. 3(a)). After the fiber amplifier has been added to the fiber between nodes 1 and 2, we try to connect lightpaths at node 1 and node 2. Firstly, we try to connect lightpaths in LP_{01} and those in LP_{13} at node 1 on which the IP router is more over–burdened. Now we are trying to connect a lightpath that can accommodate the traffic volume for node pair $\{0, 3\}$. We first check whether or not it is possible to accommodate traffic that overflows to other lightpaths. If we connect a lightpath on node 1, the number of lightpaths in LP_{01} changes to 2 and that in LP_{13} does to 1. A lightpath in LP_{13} is unable to accommodate the traffic of node pair $\{1, 3\}$ (12 Gbps is required, but only 10 Gbps is available). Therefore, We next check whether or not it is possible to accommodate the traffic of node pair $\{1, 3\}$ by setting up a new lightpath between node 1 and node 3. Since this is possible in the current case, we set up a new lightpath in LP_{13} and connect a lightpath in LP_{01} and one in LP_{13} as shown in Fig. 3(b).

4. Numerical Examples

In the previous section, we proposed a method for the design of the logical topology that has objective function of minimizing number of fiber amplifiers. This section is devoted to

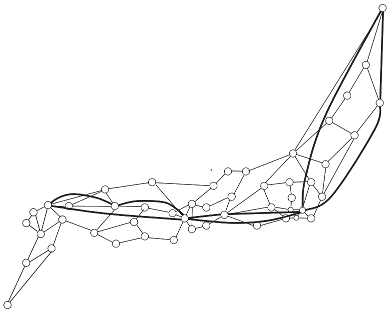


Fig. 4. Network model

a comparative evaluation of the MLDA, the e-MLDA, and the MALDA. We introduce the following notations to represent the logical topologies designed by each algorithm.

LT_{MLDA}: A logical topology designed by the MLDA

LT_{e-MLDA}: A logical topology designed by the e-MLDA

LT_{MALDA}: A logical topology designed by the MALDA

4.A. Network Model

In this evaluation, we use NTT's 49-node backbone network in Japan (Fig. 4) as the network model and two different traffic patterns, P_1 and P_2. P_1 is the publicly available data provided by NTT [10] that is the traffic matrix for conventional telephone calls. The traffic pattern P_2 is randomly determined. The value of each element in P_2 is uniformly distributed between 0 Mbps and 1 Mbps. Since the total traffic loads are small (around 3 Gbps in P_1 and 1.2 Gbps in P_2), we introduce a scale–up factor α. We set the actual requested traffic as α times the elements of P_1 and P_2. The bandwidth of each wavelength is set to 10 Gbps, and up to 1,000 wavelengths can be multiplexed on a single fiber. The processing capacities of the electronic routers (see Fig. 2(b)), expressed as μ, are set to 5.6 Tbps [11] and 16 Tbps.

4.B. Evaluation Metrics

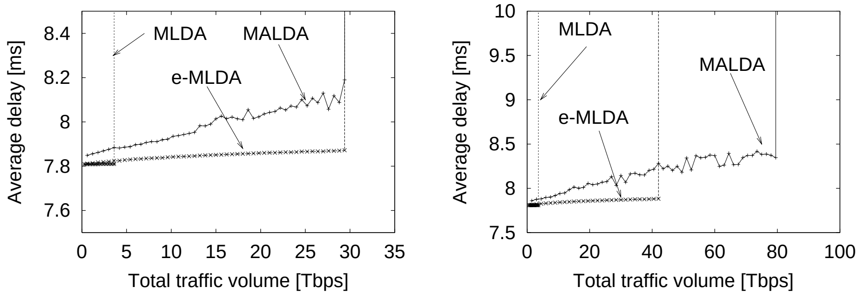
We evaluate the respective logical topology by deriving the average delay, throughput, and number of fiber amplifiers obtained by the corresponding algorithms. The average delay is defined as follows.

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

where N is the number of nodes in the network and D_{sd} is the delay on traffic between nodes s and d. In our architectural model shown in Fig. 2(b), the delay experienced at a node consists of the processing delay, the transmission delay, and the propagation delay.

4.C. Numerical Discussions

To obtain the numerical results, we use the following assumption and parameter settings. For the MLDA, we assume that 1,000 wavelengths are always used. For the e-MLDA and the MALDA, we set the utilization rate of each lightpath to be under 70%. If the rate of utilization of a lightpath is greater than that value, we set up new lightpaths. In the case of the e-MLDA, the logical topology is built on the assumption that 1,000 wavelengths are available. Then, we have simply removed the unnecessary optical amplifiers after the



(a) μ = 5.6 Tbps

(b) μ = 16 Tbps

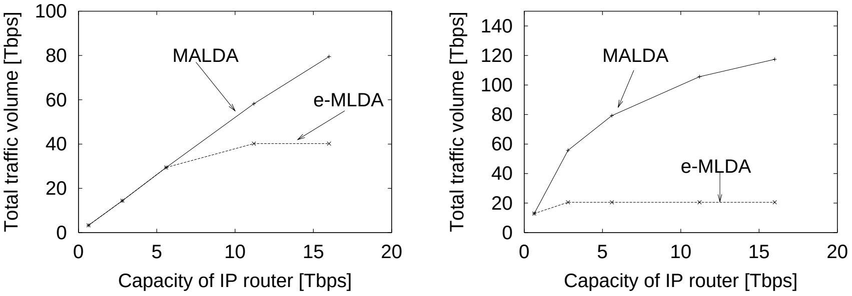
Fig. 5. Average delay with traffic pattern P_1

logical topology has been built for fair comparison with the MALDA. In the MALDA, the number of amplifiers on each fiber is determined by the algorithm presented in Section 3. For this, we have assumed that $W_1 = 200$, $W_i = 100$ and $N_{max} = 9$.

Figures 5(a) and 5(b) show the dependence of average delay on the total requested traffic for the traffic matrix P_1. Each figure depicts the case for IP routers with one of the two capacities. From these figures, we can see that the average delays on LT_{e-MLDA} and LT_{MALDA} may decrease even when the requested traffic volume increases. This is because both of those logical topologies change according to the requested traffic volume. In Figs. 5(a) and 5(b), the delay on LT_{MALDA} is always larger than that on LT_{e-MLDA} because the MALDA tries to accommodate traffic by using existing lightpaths, whereas the e-MLDA sets up new lightpaths since the e-MLDA is able to utilize more wavelengths than the MALDA is on each fiber. This results in a higher rate of utilization of lightpaths by LT_{MALDA} than by LT_{e-MLDA}. LT_{MLDA} shows the smallest delay since the MLDA always utilizes all the wavelengths regardless to the requested traffic volume when it constructs the LT_{MLDA}. When we use the traffic pattern of P_2, the same results are obtained.

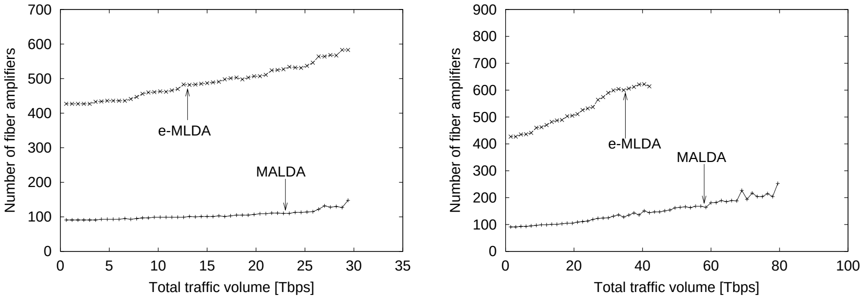
We next discuss the throughput of each of the logical topologies. Here, the throughput is defined as the minimum requested traffic volume (more precisely, the scale–up factor α) such that the average delay reaches saturation. In Fig. 5(a) ($\mu = 5.6$ Tbps), LT_{MALDA} accommodates as much traffic as LT_{e-MLDA}. This is because the bottleneck for the network in these cases is the processing capacity of the IP router. When the processing capacity of the IP router is large ($\mu = 16$ Tbps), LT_{MALDA} shows a higher throughput than LT_{e-MLDA} in Fig. 5(b). In this case, the large capacity of the respective IP routers means that the bottleneck for the network is not this capacity but the link capacity.

LT_{MLDA} shows much lower throughput than others because the MLDA sets up one–hop lightpaths while the MALDA and the e-MLDA set up multi–hop lightpaths. Setting up one–hop lightpaths leads to poor utilization rate of each lightpath because the lightpath each packet flows on is limited while the lightpath is shared when multi–hop lightpaths are set up. To see the above discussions clearly, we show the throughput values dependent on the capacity of the IP router in Figs. 6(a) (traffic pattern of P_1 is used) and 6(b) (traffic pattern of P_2 is used). The results show that LT_{MALDA} accommodates more traffic than LT_{e-MLDA} as the processing capacity of the IP router increases. LT_{e-MLDA} shows constant throughput in spite of increase of the capacity of the IP router due to a lack of wavelengths. On the other hand, the throughput of LT_{MALDA} increases as the capacity of the IP router becomes high since only the IP router's capacity is the network bottleneck of the logical topology. The upper bound on the throughput of LT_{e-MLDA} when P_1 is used (40.2 Tbps) is about twice as much as that when P_2 is used (20.5 Tbps). In P_1, the traffic



(a) Throughput with traffic pattern P_1 (b) Throughput with traffic pattern P_2

Fig. 6. Throughput of each logical topology



(a) μ = 5.6 Tbps (b) μ = 16 Tbps

Fig. 7. Number of optical fiber amplifiers needed by each logical topology with traffic pattern P_1

volume requested by neighboring nodes are relatively larger than others. As a result, a lot of lightpaths are set up between neighboring nodes that can be shared by IP packets, which leads to higher throughput in P_1 than that in P_2. Overall, the MALDA can more effectively utilize the bandwidth of the lightpaths than the e-MLDA does.

Required numbers of optical fiber amplifiers are shown in Figs. 7(a) and 7(b) for P_1. The result of LT_{MLDA} is eliminated since it always utilizes all the optical fiber amplifiers. Note that the number of optical fiber amplifiers does not always increase as the total traffic volume increases. This is because more lightpaths with shorter hops are set up between node–pairs, when total traffic volume is large, than when traffic volume is small, and setting up more lightpaths with shorter hops results in decreasing the number of optical fiber amplifiers. In this case, the probability of getting two wavelengths available in the same wave–band becomes larger as the hop count of lightpaths to be set up get larger because of the wavelength continuity constraint. We see that LT_{MALDA} only requires for about one–fifth of optical fiber amplifiers that LT_{e-MLDA} needs. We also obtained same results when we use P_2.

5. Conclusion

In this paper, we have proposed the e-MLDA, a new heuristic algorithm for the design of logical topologies to be overlaid on WDM networks. The resulting topology is based on the actual levels of node–to–node traffic demand. We went on to propose the MALDA, the objective function of which is to minimize the number of fiber amplifiers deployed in the logical topology. Our algorithms are evaluated by comparing them with the conventional method in terms of average delay, throughput, and number of optical fiber amplifiers deployed in the network. The results have shown that the MALDA only needs about one–fifth of fiber amplifiers that the e-MLDA does, while the MALDA is able to accommodate as much traffic as the e-MLDA. Furthermore, when the processing capacity of IP router is high, the MALDA can accommodate more traffic than the e-MLDA does. Our results indicate that the MALDA is preferable in terms of designing a low–cost logical topology.

In our research, it is assumed that traffic flow is placed on the path with the lowest propagation delay, which is different from the situation for actual IP routing. We need to consider how IP routing affects the performance of the logical topology as a topic for our future research.

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