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

Yukinobu Fukushima (contact author)

Graduate School of Information Science and Technology, Osaka University,

1-5 Yamadaoka, Suita, Osaka 560-0871, Japan

Tel: +81-6-6850-6863, Fax: +81-6-6850-6868, Email: y-fukusm@ist.osaka-u.ac.jp

Shin'ichi Arakawa

Graduate School of Economics, Osaka University,

1-7 Machikaneyama, Toyonaka, Osaka 560-0043, Japan

Tel: +81-6-6850-6863, Fax: +81-6-6850-6868, Email: arakawa@econ.osaka-u.ac.jp

Masayuki Murata

Graduate School of Information Science and Technology, Osaka University,

1-5 Yamadaoka, Suita, Osaka 560-0871, Japan

Tel: +81-6-6879-4542, Fax: +81-6-6879-4544, Email: murata@ist.osaka-u.ac.jp

June 28, 2005

Abstract

We deal with the problem of designing the logical topology in IP-over-WDM networks. Many conventional methods for designing the logical topology assume that a constant number of wavelengths will 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 while deploying additional wave–bands and their corresponding optical 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 a slight increase of average packet delays.

keywords – IP-over-WDM, logical topology, RWA, fiber amplifier, wave–band.

1 Introduction

WDM technology, in which multiplexed wavelength channels are carried 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–packets, 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 two 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.

Having more wavelengths multiplexed on each fiber allows the network to accommodate more lightpaths. Thus, the number of wavelengths available on a single fiber is an important parameter in the design of the logical topology. In the near future, multiplexing of 1,000 wavelengths on a fiber is possible by using a spectral range of 1290–1690 nm [2, 3]. Figure 1 shows the amplifiers required across the spectral range to realize 1,000 wavelengths. As the figure shows, deploying additional optical fiber amplifiers makes a number of low loss regions (e.g., 1530–1610 nm) available. We require several kinds of optical fiber amplifiers to utilize more wavelengths on top of those considered in previous work [4].

[Figure 1 about here.]

A lot of work has dealt with methods for the design of the logical topology [5, 6]. Most of these work have been based on the assumption that a constant number of wavelengths is available on each fiber, and then minimize the congestion of the network [5]. In the design of a cost–effective network, however, it is preferable to provide only the wavelengths that are actually needed on the fibers. Utilizing a constant number of wavelengths requires installing all kinds of amplifiers for the entire spectral range. On the other hand, we can minimize the number of optical amplifiers by deploying them only on fibers that are short of wavelengths. For this purpose, 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.

Some approaches aim to minimize the number of wavelengths required within a Wavelength Routed Optical Network (WRON) for the given traffic demands [7]. In a WRON, each lightpath is directly set up from the source to the destination. It seems that minimizing the number of wavelengths leads to minimizing the number of wave–bands (optical amplifiers). However, there exist wavelengths that remain unused on fibers because they do not satisfy the *wavelength continuity constraint*. The wavelength continuity constraint means that a lightpath must consist of the same wavelength across all fibers that it traverses. Thus, we need to deploy additional optical amplifiers even if there exist available wavelengths on the fibers. In IP-over-WDM networks, on the other hand, we do not need to directly set up lightpath from the source to the destination. Instead, we split the lightpath into two parts; a lightpath (denote L_A) from the source node to an intermediate node and a lightpath (denote L_B) from the intermediate node to the destination node. In this case, we can assign different wavelengths to L_A and L_B, which leads to relaxation of the wavelength continuity constraint. As a result, we expect to decrease the number of optical amplifiers. However, the processing capacity of the intermediate nodes should also be of concern because cutting a lightpath at an intermediate node increases the packet processing load of it.

In this paper, we propose a new algorithm called MALDA (Minimum number of fiber Amplifiers Logical topology Design Algorithm) for IP-over-WDM networks. This algorithm is in contrast to earlier approaches in that it minimizes the deployment of optical fiber amplifiers on the fiber under the constraint that the load of all the nodes should be kept under their processing capacity. As far as we know, this is the first work that tries to minimize the number of fiber amplifiers.

The paper is organized as follows. In Section 2, we extend the conventional method for designing the logical topology to indirectly 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 done in Section 3. Section 4 contains 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 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 [5]. We do this extension in order to propose a new logical topology design algorithm (1) that ensures the accommodation of the traffic demand and (2) that incorporates IP's route selection mechanism, i.e., the packet traverses on the shortest path. We call our new algorithm e-MLDA (extended MLDA).

The design problem of a logical topology in WDM networks is traditionally called the RWA (Routing and Wavelength Assignment) problem. RWA solves the following problem. Given (1) a physical network, (2) a 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), 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 or the number of wavelengths utilized) is optimized. Note that the above mentioned traffic matrix is determined by long-term measurements. When the traffic matrix is different from the real one, we can cope with it by performing a reconfiguration of the logical topology with minimal disruption [8, 9].

Since MLDA heuristically sets up lightpaths without considering the traffic volume that a lightpath can accommodate, the logical topology designed by MLDA may not accommodate the traffic demand. 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 e-MLDA sets up enough lightpaths to accommodate the volume of the required traffic. For each lightpath, MLDA sets up a "one–hop" lightpath. Here, the term "one–hop" lightpath means that a lightpath is directly set up from the source node to the destination node without terminating on intermediate nodes. Setting up only one–hop lightpaths is not desirable because that needs more wavelengths to overcome the wavelength continuity constraint. Thus, our e-MLDA approach sets up "multi–hop" ligthpaths. The term "multi–hop" lightpath means that the lightpath is split at some intermediate nodes. At those intermediate nodes, the traffic on the lightpath is processed by an IP router and it can be assigned to the lightpaths that use another wavelength.

We need these extensions 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 depends 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, 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 fibers, 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 performs 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 from 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.

[Figure 2 about here.]

Now we show our e-MLDA algorithm. We introduce the following notations to represent the physical network.

N: Number of nodes in the WDM network.

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

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

C: Bandwidth of each wavelength.

W: Number of wavelengths multiplexed on a single fiber.

Given these parameters, 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 one–hop lightpaths from source node to destination, we can set up fewer lightpaths because of the wavelength continuity constraint. Furthermore, we can decrease the number of wave–bands by assigning traffic to the lightpaths that use the wavelengths in the same wave–band at an intermediate node.

Our e-MLDA sets lightpaths on the shortest routes in terms of the propagation delay between nodes, which is the same route selection as 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 when more than one lightpaths are set up between a node–pair. 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 wavelengths chosen for the lightpaths is based on a First–Fit policy, that is, e-MLDA selects the wavelength with the lowest index of λ among those wavelengths that are not yet assigned to lightpaths. First–Fit is preferable in our case because it gives priority to selecting the wavelength available by already installed fiber amplifiers.

We use the following notations to explain our algorithm.

s, d: Source/destination nodes of a lightpath to be set up. Our algorithm recursively tries to set up multi–hop lightpaths; if a direct lightpath cannot be set up between node i and j, $\{s, d\}$ 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}: Node connected to node j along the shortest path from node i to node j.

T_{ij}: Total available bandwidth in the 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 Among node–pairs that are directly connected by the fiber, select a pair of nodes (i', j') such that element $q_{i'j'}$ of the traffic–distribution matrix Q is the largest. If $q_{i'j'}$ is larger than 0, go to Step 2 and try to set up lightpaths for the connected node–pair $i'j'$. Otherwise, select (i', j') again such that $q_{i'j'}$ is the largest among node–pairs that are not directly connected. If $q_{i'j'} = 0$, then the lightpaths are selected between all the nodes. Thus, we terminate our algorithm in finite steps. Otherwise, go to Step 2.

Step 2 Initialize the variables as $s \leftarrow i'$, $d \leftarrow j'$. Then, go to Step 3 and try to set lightpaths of adequate capacity between nodes s and d.

Step 3 If $s = j'$, 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 s and d according to the following two conditions.

1. If $T_{sd} \geq q_{i'j'}$, then we can accommodate $q_{i'j'}$ by using the existing lightpaths between nodes s and d. That is, set $s \leftarrow d$, $d \leftarrow j'$ and go back to Step 3.

2. If $T_{sd} < q_{i'j'}$, 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 s and d.

Step 5 Try to set $\lfloor (q_{i'j'} - T_{sd})/C \rfloor$ lightpaths between nodes s and d. If it is possible to set the lightpaths along the shortest route, go to Step 5.1. Otherwise, go to Step 5.2.

Step 5.1 After setting up the lightpaths between nodes s and d, we split the lightpaths that originate at node s and pass through node d at node d. Then, we set $s \leftarrow d$, $d \leftarrow j'$ and go back to Step 3.

Step 5.2 If nodes s and d are directly connected via fiber, we are unable to set up lightpaths between nodes s and d because we have already checked that there exists no available wavelength between nodes s and d. In this case, it is not possible to accommodate the requested traffic between nodes i' and j', and we terminate our algorithm. If nodes s and d are not directly connected, on the other hand, we try to accommodate the traffic by creating lightpaths between node s and inter-node B_{sd}. Set $d \leftarrow B_{sd}$ and go back to Step 4.

Comments on e-MLDA

In Step 1, e-MLDA gives priority to setting up lightpaths between node–pairs that are directly connected by fiber. This operation is necessary to ensure the reachability between nodes. The e-MLDA approach 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–pairs to be accommodated (e.g., longest first, random), the effect of the order of node–pairs to be accommodated on the performance is small (the difference among the various ways is bellow 10% [10]). Step 4 checks whether or not existing lightpaths are capable of accommodating the traffic $q_{i'j'}$. If the available bandwidth T_{sd} is insufficient to transport the IP traffic, new lightpaths are set up in Step 5. Since T_{sd} is already available by existing lightpaths, the number of lightpaths required to accommodate the requested traffic volume is $\lfloor (q_{i'j'} - T_{sd})/C \rfloor$.

Step 5.1 deals with the case where we are able to set up enough lightpaths to accommodate the requested traffic. However, in an IP-over-WDM network, we must consider the property of IP, that is, 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, any lightpaths originating at node s and passing through node d are split at node d. In Step 5.2, if we are unable to set up the required lightpaths because there are too few wavelengths available, we set $d \leftarrow B_{sd}$ and go back to Step 4 in order to accommodate q_{ij} between nodes s and B_{sd}. Note that, after $q_{i'j'}$ has been accommodated between s and B_{sd}, Step 5.1 sets s to B_{sd} and d to j'. We then try to set up a lightpath between nodes B_{sd} and j'.

We now evaluate the complexity of e-MLDA. For $N(N-1)$ node–pairs, e-MLDA tries to set up multi–hop lightpaths. In order to set up multi–hop lightpaths for a node–pair, e-MLDA searches the available wavelengths among W wavelengths for $\sum_{i=0}^{H-1}(H-i)$ times at most (H is a hop count of a route between a node–pair). This is because e-MLDA tries to set up lightpaths that are one–hop shorter than those that e-MLDA tried to set up before. As a result, e-MLDA tries to set up lightpaths with $H, H-1, \ldots, 1$ hop counts in turn until e-MLDA finds enough wavelengths. The total complexity of e-MLDA is $O(N^2H^2W)$.

3 Design of Logical Topology Considering Available Wave–Bands

3.1 Objective Function

As we mentioned in Section 1, we need to install only the different types of fiber amplifiers on a fiber, which would otherwise not fulfill the required bandwidth. In this way, the most cost–effective logical topology can be achieved. In this section, we propose a new method for the design of logical topologies that minimizes the number of optical amplifiers deployed. We call this algorithm MALDA (Minimum number of fiber Amplifiers Logical topology Design Algorithm).

In our MALDA, W_1 ($< W$) wavelengths are initially set for carrying traffic 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 type i ($2 \leq i \leq N_{max}$). Here, we assume that N_{max} kinds of fiber amplifiers can be deployed on the fiber. Note that we select the wavelengths in the wave–band that is available with EDFA ($C + L$ band) as W_1. W_i and N_{max} are determined by the technological constraints as Fig. 1 shows. If the maximum number of wavelengths that can be multiplexed on a fiber is W, we obtain the following relationship for fiber f,

$$\sum_{i=1}^{N_f} W_i \leq W, \quad (1)$$

where N_f ($1 \leq N_f \leq N_{max}$) is the number of fiber amplifier types deployed on fiber f. Adding a new fiber amplifiers means to install an additional type of fiber amplifiers to increase the number of wavelengths of the fiber by an additional waveband. The objective function of MALDA is,

$$minimize \qquad \sum_{f \in F} N_f. \quad (2)$$

In practice, various components (e.g., OEO converters) are also required in addition to the optical amplifier to overcome physical impairments (e.g., noise and dispersion) [11]. In this paper, however, we simply try to minimize the number of wave–bands that are actually used because the number of these components required depends on the number of wave–bands actually used.

3.2 Detailed Description of MALDA

In 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. In addition, we expect that the smallest possible number of fiber amplifiers will be deployed in the WDM network. MALDA is similar to e-MLDA described in Section 2. The point of difference between them is that MALDA only deploys an additional fiber amplifier when there are too few wavelengths to accommodate the traffic. For this purpose, we need to modify Step 5.2 of 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 be added is checked in the new step, Step 6. The following two steps are one of the two differences between e-MLDA and MALDA. Another difference is described in the next subsection.

Step 5.2 If nodes s and d are directly connected via a fiber, we may be able to set up lightpaths between nodes s and d. 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 s and d are not directly connected, on the other hand, then we set $d \leftarrow B_{sd}$ and go back to Step 4.

Step 6 Check the number of fiber amplifiers currently deployed on the fiber between nodes s and d. 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 Section 3.4 for more detail). Note that the wavelengths used by the lightpaths from node s to node d are released and newly available wavelengths provided by the added amplifier are reassigned to those lightpaths. We then set $d \leftarrow j'$ and go back to Step 4 in order to check whether or not we are able to set up new lightpaths between nodes s and d by adding a fiber amplifier.

The reassignment of wavelengths to the lightpaths from node s to node d supposes the situation that newly available wavelengths are likely to be available only on the deployed fiber. Thus those wavelength may not be utilized by the other lightpaths that pass through more than one fiber. So those wavelengths should be used by the lightpath that passes through only one fiber.

3.3 Reducing Traffic Load at IP Router

After setting up all the lightpaths with the above steps, we next consider adding further optical fiber amplifiers to decrease the traffic load on over–burdened IP routers. This is necessary since the above steps does not ensure that the load on all IP routers are below the processing capacity. By connecting lightpaths until the load on the IP router falls below the maximum amount of traffic the IP router can process, 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 the maximum amount of traffic it can process.

$N_{available}$: Set of nodes that have non-utilized wave–band(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 above steps in 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.

The above three steps decrease the load 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.

[Figure 3 about here.]

3.4 Connecting Lightpaths

In this subsection, we explain the algorithm for connecting lightpaths after a new fiber amplifier has been added. As we mentioned in Section 3.3, the motivation of connecting lightpaths is to prevent IP routers from being over-burdened by setting up multi–hop lightpaths. We connect lightpaths at the node selected in descending order of the traffic load on the two nodes, between which a new fiber amplifier is added on the link, since the heaviest loaded node will limit the throughput of the network. We can expect to decrease the load on the IP routers of 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 the set of lightpaths that terminate at node x and those in the set of lightpaths that originate at node x, i.e., bypass packet processing at node x. Hereafter, we denote LP_{sx} as the set of lightpaths that originate from node s and terminate at node x, and LP_{xd} as the set of lightpaths that originate from node x and terminate at node d. 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 the set, 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. 3a). 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. First, 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. 3b.

3.5 Complexity of MALDA

The complexity of MALDA is larger than that of e-MLDA because MALDA adds fiber amplifiers in addition to setting up lightpaths. The complexity of adding fiber amplifiers can be obtained as follows.

A fiber amplifier can be added $L \times B$ times at most. L is the number of links in the network. B is the number of wave–bands on a fiber. When MALDA adds a fiber amplifier, it tries to connect W lightpaths at most on the nodes connected by the fiber. So the total complexity of MALDA is larger than that of e-MLDA by $O(LBW)$, that is, the complexity of MALDA is $O(N^2H^2W) + O(LBW)$.

4 Numerical Examples

In the previous section, we proposed a method for the design of the logical topology that has the objective function of minimizing the number of fiber amplifiers. This section is devoted to a comparative evaluation of MLDA, e-MLDA, and MALDA. We introduce the following notations to represent the logical topologies designed by each algorithm.

LT_{MLDA}: Logical topology designed by MLDA

LT_{e-MLDA}: Logical topology designed by e-MLDA

LT_{MALDA}: Logical topology designed by MALDA

4.1 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 information provided by NTT [12] about the traffic matrix for conventional telephone calls. In traffic pattern P_1, the volume of traffic between large cities and between adjacent cities is large. 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. 2b), expressed as μ, are set to 5.6 Tbps [13] and 16 Tbps, respectively.

[Figure 4 about here.]

4.2 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 the traffic between nodes s and d. In our architectural model shown in Fig. 2b, the delay experienced at a node consists of the processing delay, the transmission delay, and the propagation delay. Thus, D_{sd} is represented as

$$D_{sd} = \sum_{i=1}^{N} a_i^{sd} \cdot QD_i + \sum_{i=1}^{N}\sum_{j=1}^{N} b_{ij}^{sd} \cdot TD_{ij} + \sum_{i=1}^{N}\sum_{j=1}^{N} b_{ij}^{sd} \cdot PD_{sd}. \tag{4}$$

The notation used in Eq. (4) is as follows.

QD_i: Delay for processing at the IP router on node i. We determine this by using an M/M/1 queueing model.

TD_{ij}: Transmission delay experienced in the buffer of the lightpath between node i and node j. If there are several lightpaths, the IP traffic is divided into flows such that the rate of transmission is identical on each of the lightpaths. The delay at the buffer is also calculated by using an M/M/1 queueing model.

PD_{sd}: Propagation delay of lightpaths between end nodes s and d.

a_i^{sd}: If the IP router on node i processes the traffic from node s to node d, then $a_i^{sd} = 1$. Otherwise $a_i^{sd} = 0$.

b_{ij}^{sd}: If the traffic from node s to node d goes through the lightpath between node i and node j, then $b_{ij}^{sd} = 1$. Otherwise $b_{ij}^{sd} = 0$.

4.3 Numerical Discussions

To obtain the numerical results, we use the following assumptions and parameter settings. For MLDA, we assume that 1,000 wavelengths are always used. For e-MLDA and MALDA, we set the utilization rate of each lightpath to be below 70%. If the rate of utilization of a lightpath is greater than that value, we set up new lightpaths. For safer operation, we might limit the maximum amount of traffic accommodated at the IP router to, e.g., 70% of its processing capability. In this evaluation, however, we regard the IP router's processing capacity as the maximum amount of traffic accommodated by it for simplicity. In the case of 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 logical topology has been built for fair comparison with MALDA. In 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 5a, 5b, 6a, and 6b show the dependence of average delay on the total requested traffic for the traffic matrices P_1 and P_2. 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. 5a, 5b, 6a, and 6b, the delay on LT_{MALDA} is always larger than that on LT_{e-MLDA} because MALDA tries to accommodate traffic by using existing lightpaths, whereas e-MLDA sets up new lightpaths since e-MLDA is able to utilize more wavelengths than 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 MLDA always utilizes all the wavelengths regardless to the requested traffic volume.

[Figure 5 about here.]

[Figure 6 about here.]

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. When we cannot set up all the lightpaths required or we cannot make the load of all the IP routers under their processing capacity, the average delay goes to infinity. In Fig. 5a ($\mu = 5.6$ Tbps), LT_{MALDA} accommodates as much traffic as LT_{e-MLDA}. This is because the bottleneck for the network in this case 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. 5b. In this case, the large capacity of the respective IP routers means that the bottleneck for the network is not the processing capacity but the link capacity. In P_2, the node–pairs whose source nodes are apart from their destinations require more lightpaths than those in P_1. As a result, The bottleneck is the processing capacity of a IP router at the intermediate node. MALDA effectively cuts lightpaths at the different intermediate nodes so that the load of IP routers are distributed. This results in higher throughput of LT_{MALDA} than that of LT_{e-MLDA} in Figs. 6a and 6b.

LT_{MLDA} shows much lower throughput than others because MLDA sets up one–hop lightpaths while MALDA and e-MLDA set up multi–hop lightpaths. Setting up one–hop lightpaths leads to a poor utilization rate of each lightpath because the lightpath of each packet flow 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. 7a (traffic pattern P_1) and 7b (traffic pattern P_2). The results show that LT_{MALDA} accommodates more traffic than LT_{e-MLDA} does if the processing capacity of the IP router increases. LT_{e-MLDA} shows constant throughput in spite of increasing 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 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, MALDA can more effectively utilize the bandwidth of the lightpaths than e-MLDA does.

[Figure 7 about here.]

The required numbers of optical fiber amplifiers are shown in Figs. 8a, 8b, 9a, and 9b. In LT_{e-MLDA}, unnecessary optical amplifiers are removed. The results of LT_{e-MLDA} are plotted for traffic volumes below 40.2 Tbps in P_1 and 20.5 Tbps in P_2 because it cannot accommodate traffic volumes beyond 40.2 Tbps and 20.5 Tbps, respectively. The result of LT_{MLDA} is eliminated since it always utilizes all the optical fiber amplifiers (819 amplifiers). Note that the number of optical fiber amplifiers does not always increase as the total traffic volume increases. This is because the number of intermediate nodes at which lightpaths are split may increase when the total traffic volume increases. As such a intermediate node increases, the wavelength continuity constraint is more relaxed, which could result in effective utilization of the wavelengths. We see that LT_{MALDA} only requires about one–fifth of the optical fiber amplifiers that LT_{e-MLDA} needs in P_1 and P_2.

[Figure 8 about here.]

[Figure 9 about here.]

5 Conclusion

In this paper, we have proposed e-MLDA (extended 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 MALDA (Minimum number of fiber Amplifiers Logical topology Design Algorithm) for which the objective function 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 MALDA only needs about one–fifth of the fiber amplifiers that e-MLDA does, while MALDA is able to accommodate as much traffic as e-MLDA. Furthermore, when the processing capacity of IP routers is high, MALDA can accommodate more traffic than e-MLDA does. Our results indicate that MALDA is preferable in terms of designing a low–cost logical topology.

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

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List of Figures

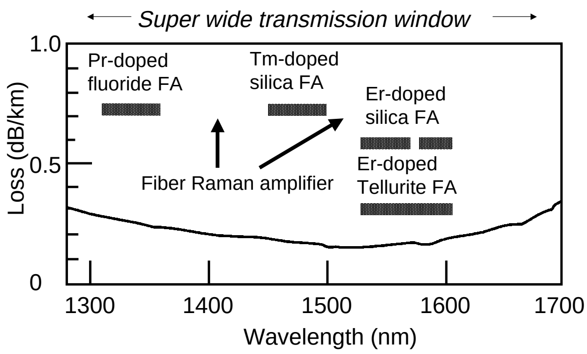
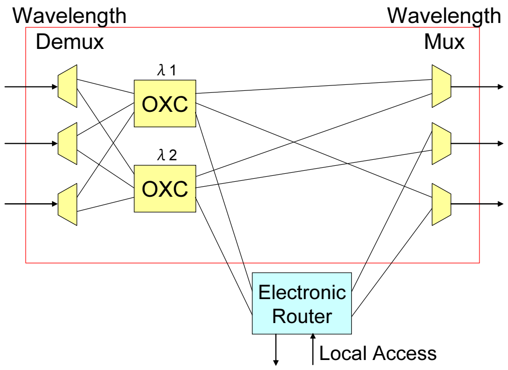
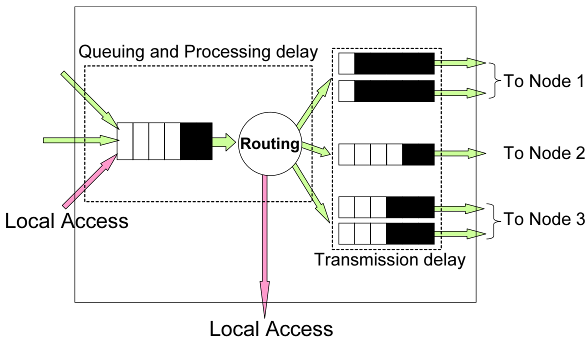


Figure 1: Loss spectrum of typical low-loss optical fiber [2]

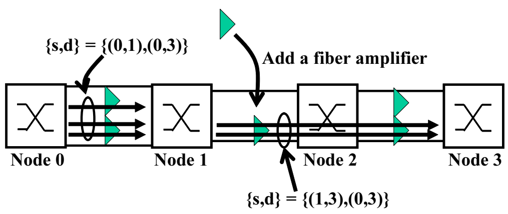


a) Node architecture

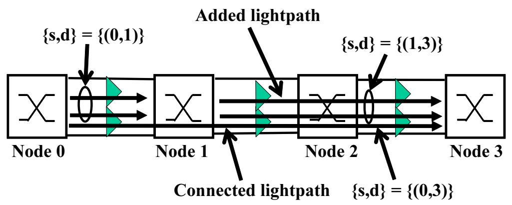


b) Model of electronic router

Figure 2: Node architecture model



a) Before connecting lightpaths



b) After connecting lightpaths

Figure 3: An example of connecting lightpaths

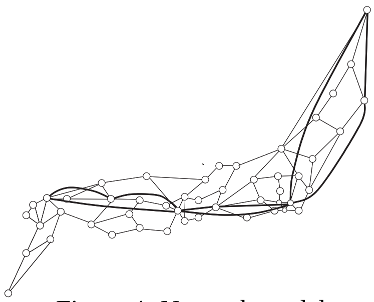
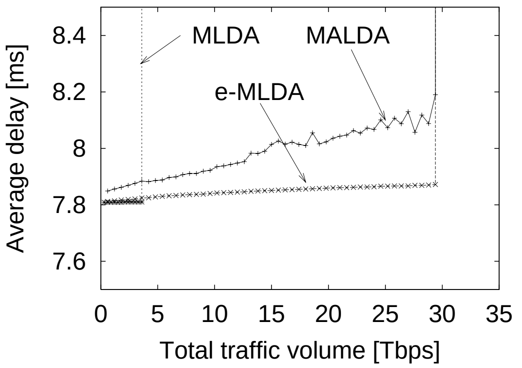
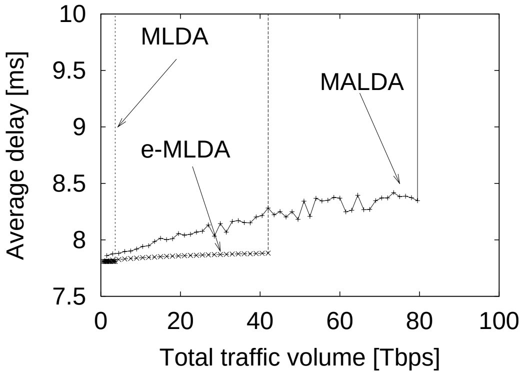


Figure 4: Network model

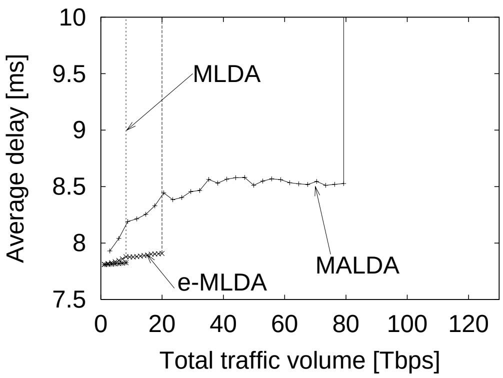


a) μ = 5.6 Tbps



b) μ = 16 Tbps

Figure 5: Average delay with traffic pattern P_1



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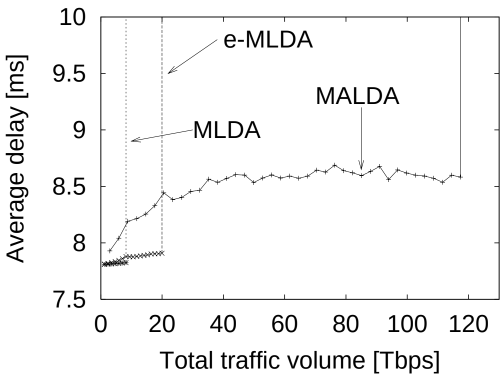
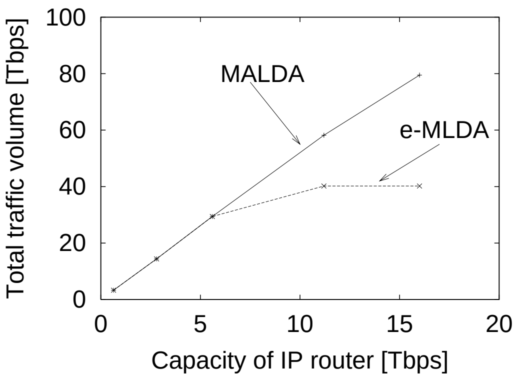
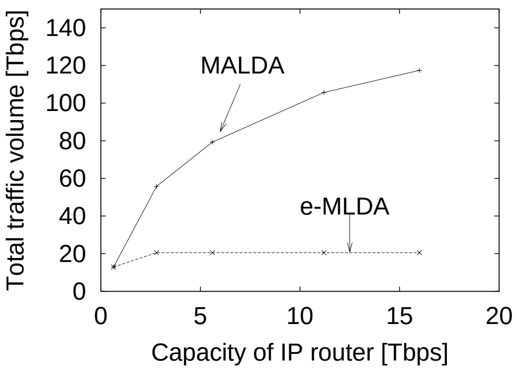


b) μ = 16 Tbps

Figure 6: Average delay with traffic pattern P_2

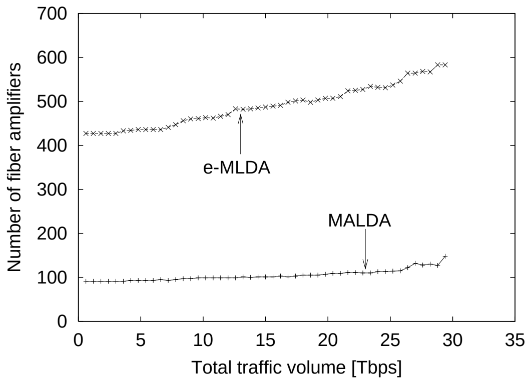


a) Throughput with traffic pattern P_1



b) Throughput with traffic pattern P_2

Figure 7: Throughput of each logical topology



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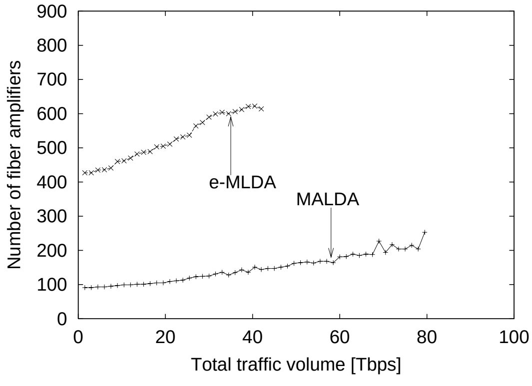
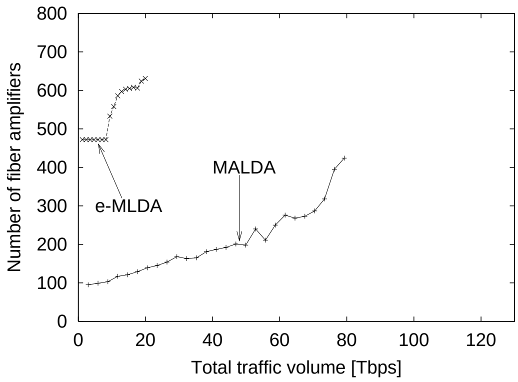


b) μ = 16 Tbps

Figure 8: Number of optical fiber amplifiers needed by each logical topology with traffic pattern P_1



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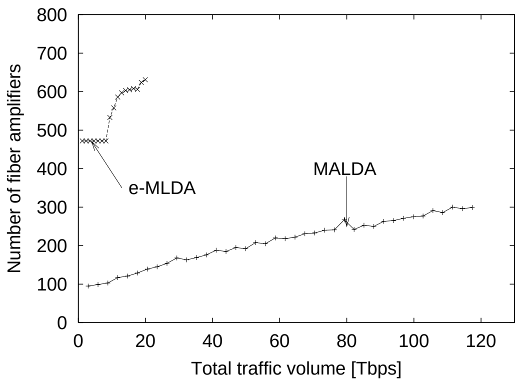

b) μ = 16 Tbps

Figure 9: Number of optical fiber amplifiers needed by each logical topology with traffic pattern P_2