Proposal for procedures to reconfigure logical topologies in reliable WDM-based mesh networks

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ABSTRACT

A Wavelength Division Multiplexing (WDM) network offers a flexible networking infrastructure by assigning the route and wavelength of optical transparent channels (also known as lightpaths). We can construct an optimal logical topology, by properly setting up the lightpaths. Furthermore, setting up a backup lightpath for each lightpath improves network reliability, i.e., tolerance against failures of network components. Most studies on methods to design a logical topology provide optimization formulations (e.g., Mixed Integer Linear Problem) and their solutions under the assumption that the traffic requirements are known in advance. In practice, traffic demand changes due to new services. When it does, a new optimal (or sub-optimal) topology should be obtained by again applying the formulation. Then, we can reconfigure the running topology to the logical topology obtained. However, during this reconfiguration, traffic loss may occur due to the deletion of older lightpaths. In this paper, we consider reconfiguring the logical topology in reliable WDM-based mesh networks, and we propose five procedures that can be used to reconfigure a running lightpath to a new one. Applying the procedures one by one produces a new logical topology. The procedures mainly focus on utilizing free wavelength resources and the resources of backup lightpaths, which are not used usually for transporting traffic. The results of computer simulations indicate that the traffic loss is remarkably reduced (in the worst case, more than 50% reduction in traffic loss) in the 14-node network we used as an example.

Keywords: WDM, lightpath, logical topology, reconfiguration, reliability

1. INTRODUCTION

The rapid growth in the volume of Internet traffic has led to demands for extra capacity in the backbone networks. Wavelength Division Multiplexing (WDM) technology, which allows multiple wavelengths to be carried on a single fiber, is expected to offers a low-cost approach to handling this increased volume of traffic. Furthermore, recent advances in optical devices, such as optical switches, have led to WDM technology with networking capabilities. Suppose that each node has an optical switch directly connecting each input wavelength to an output wavelength, so that there is no electronic processing at the packet level. That is, no electronic routing is needed at the nodes. This means wavelength path can be set up directly between two nodes via one or more optical switches.

The wavelength path (also known as the lightpath) provides networking capabilities on optical networks. Methods for designing logical topology are considered in Ref. 1, 2. Logical topologies are constructed as a sets of lightpaths, each of which is configured by properly assigning a wavelength and determining a route. In many

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past studies on designing logical topology, it has commonly been assumed that traffic demand is known in advance. However, in practice, it is difficult to predict changes in traffic demand due to factors like the start of new services in networks, such as streaming media services and contents delivery services. Required lightpaths should be increased immediately once the WDM network performance becomes inadequate. Therefore, flexible network design is an more important method than static network design.[3]

Fault tolerance against the failure of network components is another issue in WDM networks as the transmission capacity gets larger. *Protection methods* by which network resources are predetermined and reserved for backup purposes are considered to improve reliability.[4] For each traffic demand, a primary lightpath and its backup lightpath are assigned. The primary lightpath is used for transporting the data, and the backup lightpaths are used to recover from failures on network components. When network components on a primary lightpath fail, the backup lightpath is utilized immediately to transmit the data.

In Ref. 5, incremental capacity dimensioning is proposed. It is a network design method to achieve flexibility and reliability in WDM mesh networks. In this method, logical topology design is first applied for a given traffic demand. With the incremental traffic demand, a one-by-one assignment of the primary lightpath as well as the backup lightpaths based on the user's perception of performance is done. The one-by-one assignment may result in a topology far from the optimal one. Thus, we reconfigure the running topology to the optimal (or sub-optimal) logical topology obtained by again applying the design method. Then, we reconfigure the running topology to the obtained logical topology.

During reconfiguration between two logical topologies, packet loss or delayed arrival may occur due to the deletion of older lightpaths. Therefore, there is a trade-off in the reconfiguration between improved network performance obtained from the reconfiguration itself, and the traffic loss penalty due to the deletion of the lightpath during the reconfiguration.[6] There have been various studies on reconfiguration methods to minimize lightpath deletion.[6–9] However, all of these studies have been proposals for star-based WDM networks with optical passive star couplers. In this work, we propose a reconfiguration algorithm for WDM-based mesh networks to provide flexible and reliable backbones. Our algorithm is based on five procedures to set up and tear down lightpaths. In addition to simply setting up or tearing down lightpaths, we have considered three other procedures to incorporate wavelength resources for backup lightpaths. Since the backup lightpaths are not always used for transporting the actual traffic, we exploit their wavelength resources assuming that failure does not occur during reconfiguration. We evaluated the performance of the algorithm with a 14-node network. According to the results, our algorithm can dramatically reduce the incidence of traffic loss during reconfiguration, compared to a basic algorithm.

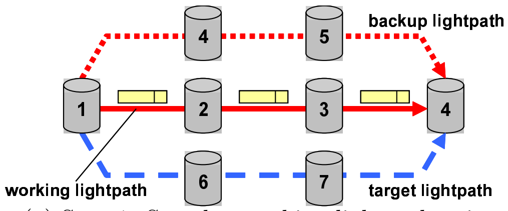
Note that fault tolerance against failure is increased by protection. However, the total capacity that a WDM network accommodate is also limited, since the wavelength resources of backup lightpaths are not used for transportation. To avoid the waste of wavelength resources for backup lightpaths, *shared protection strategy* is proposed. Using this strategy, several backup lightpaths can share wavelength resources if and only if any of the backup lightpaths are not utilized simultaneously. In this paper, we follow the lead of Ref. 5 and employ this shared strategy to effectively use wavelengths.

This paper is organized as follows. In Section 2, we introduce five procedures to reconfigure local topologies. In Section 3, we present a heuristic reconfiguration algorithm. We then evaluate the proposed algorithm in Section 4, and conclude our paper in Section 5.

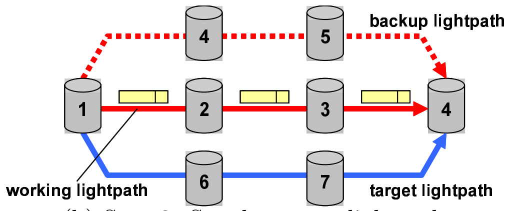
2. PROCEDURES TO RECONFIGURE LOGICAL TOPOLOGIES

In this section, we introduce five procedures to reconfigure logical topologies: SWITCH, APPEND, BACKUP, RELEASE, and DELETE. We also consider the REASSIGN procedure to ensure reconfigurations of logical topologies are implemented more smoothly.

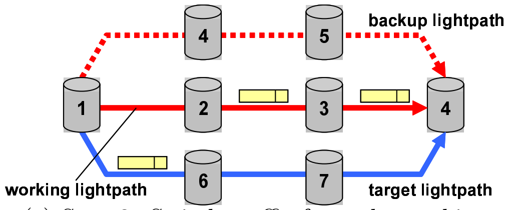
Here, we define *working lightpath* as a lightpath on a current configured logical topology on which data traffic is actually transported. We also define *target lightpath* as a new lightpath organizing a part of the new logical topology derived by a certain logical topology design algorithm.



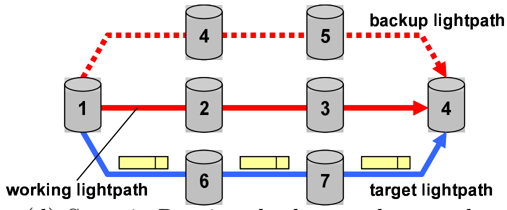
(a) Step 1: Search a working lightpath pair.



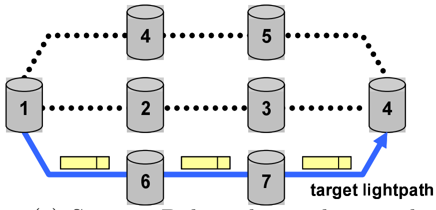
(b) Step 2: Set the target lightpath.



(c) Step 3: Switch traffic from the working lightpath to the target.



(d) Step 4: Receive the last packet on the working lightpath.



(e) Step 5: Delete the working and backup lightpaths.

Figure 1. Each step of SWITCH procedure

2.1. SWITCH Procedure

One of the fatal problems during the reconfiguration of logical topologies is traffic loss. A reconfiguration of a logical topology has to been implemented quickly and smoothly even though there may be significant traffic flow through the logical topology. When a lightpath that is used to transport traffic is deleted carelessly, the traffic is of course lost and the network performance may worsen. However the SWITCH procedure can reduce such traffic loss remarkably. This procedure is as follows:

Step 1: Search a working lightpath whose source and destination nodes are identical to the source and destination node of a target lightpath. If such a working lightpath is found, go to Step 2. Otherwise, quit this procedure.

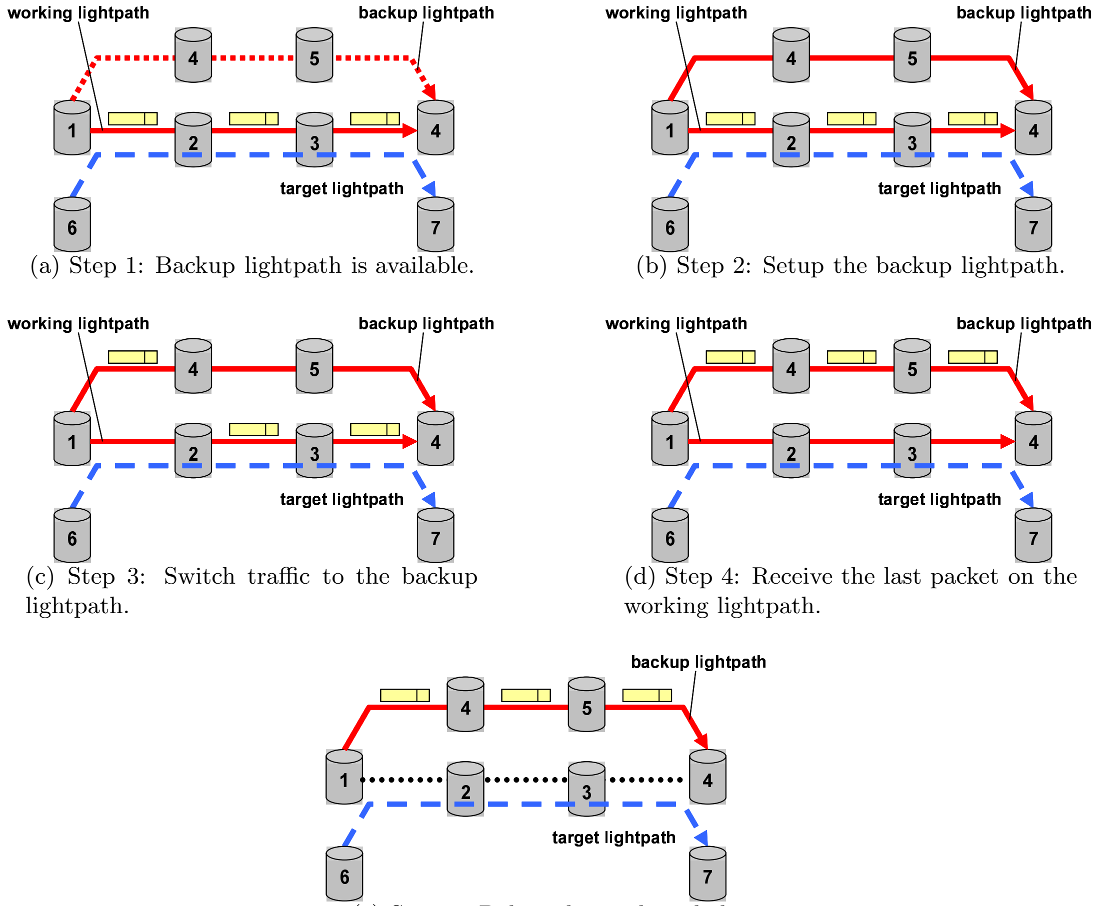
Step 2: Set the target lightpath. Go to Step 3.

Step 3: Switch the traffic on the working lightpath to the target lightpath. Go to Step 4.

Step 4: If the last packet on the working lightpath reaches the destination node, go to Step 5.

Step 5: Delete the working lightpath and its backup lightpath.

Fig. 1 details the SWITCH procedure. If a portion of the wavelength resources utilized in a working lightpath are required to set up a target lightpath, the working lightpath is to be deleted. Here, we search a target lightpath which has the same source and destination node as the working lightpath. The traffic on the working lightpath is switched to the target lightpath before the former is deleted. Thus, no traffic loss occurs.



(a) Step 1: Backup lightpath is available.

(b) Step 2: Setup the backup lightpath.

(c) Step 3: Switch traffic to the backup lightpath.

(d) Step 4: Receive the last packet on the working lightpath.

(e) Step 5: Delete the working lightpath.

Figure 2. Each step of BACKUP procedure

2.2. APPEND Procedure

If there is a target lightpath which cannot be set with the SWITCH procedure, the target lightpath is to be set with the APPEND procedure. This procedure simply set the target lightpath. We mention that the SWITCH procedure is more efficient than the APPEND procedure because the former releases the wavelength resources reserved for a working and its backup lightpath without traffic loss.

2.3. BACKUP Procedure

If a portion of the wavelength resources for a working lightpath are required by one or more target lightpaths, and if there is no target lightpath whose source and destination nodes are identical to those of the working lightpath, the working lightpath will be discarded without its traffic being protected. This usually results in traffic loss, but in a reliable WDM network, it is possible to avoid this by utilizing the backup lightpath prepared for the working lightpath (BACKUP procedure). The BACKUP procedure is as follows:

Step 1: If the backup lightpath of a working lightpath is available, go to Step 2. Otherwise, quit this procedure.

Step 2: Set the backup lightpath. Go to Step 3.

Step 3: Switch the traffic on the working lightpath to the backup lightpath. Go to Step 4.

Step 4: If the last packet on the working lightpath reaches the destination node, go to Step 5.

Step 5: Delete the working lightpath.

Fig. 2 illustrates the BACKUP procedure. Here, the working and its backup lightpath are prepared from nodes 1 to 4. Suppose that the working lightpath is not necessary in the target logical topology and that there is not a target lightpath pair for the SWITCH procedure. In this situation, the working lightpath may be finally deleted. However, if the backup lightpath of the working lightpath is available, i.e., all the wavelength resources of the backup lightpath are not shared with other backup lightpaths and are not required to set up target lightpaths, the traffic running through the working lightpath can be protected with the backup lightpath.

2.4. RELEASE Procedure

If backup lightpaths of working lightpaths to which cannot be applied the SWITCH procedure is not available, traffic of the working lightpaths tends to be lost by deleting these working lightpaths. However, with the RELEASE procedure, we can defer or avoid the deletion of working lightpaths. The RELEASE procedure releases the wavelength resources of the backup lightpath for a working lightpath. After that, the reconfiguration continues to make progress using the SWITCH or APPEND procedure with the released wavelength resources. The RELEASE procedure can put off the deletion of working lightpaths not processed with SWITCH, APPEND, or BACKUP procedure.

2.5. DELETE Procedure

The DELETE procedure deletes a working lightpath without protecting its traffic. The traffic on the deleted lightpath is lost.

2.6. REASSIGN Procedure

Reconfigurations of logical topologies can be achieved using those five procedures. However, there is plenty of room for improvement in making the reconfigurations more efficient. The REASSIGN procedure provides one means. This procedure checks the condition of the wavelength resources and, if the efficiency of the reconfiguration is had improved, re-assigns a new wavelength to a target lightpath. Suppose that the reserved wavelength resources on a wavelength (say λ_1) are required to set up a target lightpath. The REASSIGN procedure assigns another available wavelength (assume λ_i as $i \neq 1$) to the target lightpath, which solve the conflict on λ_1. After that, the SWITCH or APPEND procedure set up the target lightpath by using the new λ_i wavelength resources. This re-assignment is done when a portion of the wavelength resources to be assigned to a target lightpath are reserved for working or backup lightpaths, and when there are free wavelength resources that are not required to set up other target lightpaths. Note that the performance of the re-assigned lightpath is identical to the original because the routes of both lightpaths are the same. Therefore, this wavelength re-assignment does not have any bad effect on the reconfigurations of logical topologies.

3. RECONFIGURATION ALGORITHM

Since only the DELETE procedure leads to traffic loss, our ultimate goal is to suppress the number of DELETE procedures during a reconfiguration to zero. Here, we propose a heuristic algorithm for reconfiguring logical topologies. In this paper, we assume that no network failures occur during the reconfiguration of a logical topology.

3.1. Symbols

Let us first explain the symbols used in our algorithm.

- N: Number of nodes in a network. Each node is assigned a number from 1 to N.
- W: Degree of wavelength multiplexing. Each wavelength is represented as λ_w $(1 \leq w \leq W)$.
- L_1: Set of working lightpaths.
- L_2: Set of target lightpaths.
- $l_1^w(i,j)$: A working lightpath which is set from node i to node j with wavelength w. $l_1^w(i,j) \in L_1$.
- $l_2^w(i,j)$: A target lightpath which is set from node i to node j with wavelength w. $l_2^w(i,j) \in L_2$.
- $b^m(l_p^w(i,j))$: Backup lightpath of working lightpath $l_p^w(ij)$. m is an assigned wavelength into the backup lightpath.
- P: Number of steps in the reconfiguration process. The value of P is incremented when the SWITCH, APPEND, or BACKUP procedure is executed.

These four functions represent the condition of wavelength resources. In our algorithm, we handle wavelength resources per physical link.

- $t(l)$: If any wavelength resource for setting up lightpath l is utilized by a working lightpath, $t(l) = 1$. Otherwise, $t(l) = 0$.
- $r(l)$: $r(l)$ represents the number of wavelength resources which are reserved for a working lightpath l but are required to set up target lightpaths. The maximum value of $r(l)$ is equal to the physical hop counts of the lightpath l.
- $s(l)$: $s(l)$ represents the number of wavelength resources required to set up a target lightpath l but are reserved for backup lightpaths.
- $e(l)$: If all the wavelength resources to set up lightpath l are required by only l itself, $e(l) = 1$. If a part of those resources are required for another lightpath, $e(l) = 0$.

3.2. Reconfiguration Algorithm

The reconfiguration algorithm we propose is as follows:

Step 1: For each target lightpath $l_2^w(i,j) \in L_2$, if L_1 also includes the lightpath, delete the elements from L_1 and L_2. $P \leftarrow 0$. Go to Step 2.

Step 2: For each target lightpath $l_2^{w_2}(i,j) \in L_2$, if $t(l_2^{w_2}(i,j)) = 0$ and $s(l_2^{w_2}(i,j)) = 0$ and $e(l_2^{w_2}(i,j)) = 1$, go to Step 2.1. Otherwise, go to Step 3.

- Step 2.1: For target lightpath $l_2^{w_2}(i,j) \in L_2$, if $l_1^{w_1}(i,j) \in L_1$ then go to Step 2.2. Otherwise, go to Step 2.3.
- Step 2.2: Search a working lightpath $l_1^{w_1}(i,j)$ where $r(l_1^{w_1}(i,j)) + r(b^m(l_1^{w_1}(i,j)))$ is maximum. Apply the SWITCH procedure between $l_1^{w_1}(i,j)$ and $l_2^{w_2}(i,j)$. Delete these two element from L_1, L_2. $P \leftarrow P + 1$. Go to Step 2.
- Step 2.3: Apply the APPEND procedure to $l_2^{w_2}(i,j)$. Delete $l_2^{w_2}(i,j)$ from L_2. $P \leftarrow P + 1$. Go to Step 2.

Step 3: If $L_2 = \phi$ then go to Step 6. Otherwise, go to Step 4.

Step 4: For each working lightpath $l_1^{w_1}(i,j) \in L_1$, if a target lightpath $l_2^{w_2}(i,j)$ is not included in L_2 and $r(b^m(l_1^{w_1}(i,j))) > 0$ and $e(b^m(l_1^{w_1}(i,j))) = 1$, go to Step 4.1. Otherwise, go to Step 5.

Step 4.1: Apply the BACKUP procedure to $l_1^{w_1}(i,j)$. Delete $l_1^{w_1}(i,j)$ from L_1. $P \leftarrow P+1$. Go to Step 4.

Step 5: If $P > 0$ then go to Step 2. Otherwise, go to Step 5.1.

Step 5.1: If there is lightpath $l_1^{w_1}(i,j) \in L_1$ whose backup lightpath $b^m(l_1^{w_1}(i,j))$ is not released, go to Step 5.2. Otherwise, go to Step 5.3.

Step 5.2: Search a working lightpath $l_1^{w_1}(i,j)$ where $r(b^m(l_1^{w_1}(i,j)))$ is maximum. Apply the RELEASE procedure to $l_1^{w_1}(i,j)$. $P \leftarrow 0$. Go to Step 2.

Step 5.3: Search a working lightpath $l_1^{w_1}(i,j)$ that $r(l_1^{w_1}(i,j))$ is maximum. Apply the DELETE procedure to $l_1^{w_1}(i,j)$. $P \leftarrow 0$. Go to Step 2.

Step 6: Delete all of the remaining lightpaths $l_1^{w_1}(i,j)$ in L_1 and $b^m(l_1^{w_1}(i,j))$. Go to Step 7.

Step 7: Restore the re-assigned wavelengths of target lightpaths into the original wavelengths. Go to Step 8.

Step 8: Set up backup lightpaths for each target lightpath.

In Step 1, working lightpaths, each of which is identical to a target lightpath, are detected. These working lightpaths are left as target lightpaths. From Steps 2 to 5, setting all the target lightpaths is our goal. Backup lightpaths for each target lightpath are set in Step 8. This is based on the assumption that no network failures occur during the reconfiguration.

In Step 2, we check whether the wavelength resources to set target lightpaths are available or not. We give priority to the SWITCH procedure over the APPEND procedure because of the differences in their efficiency (see Sec. 2.2). Hence, we try to apply the SWITCH procedure in setting up the target lightpath first (Step 2.2).

In Step 2.2, the SWITCH procedure releases the wavelength resources reserved for working and its backup lightpath. We can use the released wavelength resources for setting up remaining target lightpath. We therefore choose a working lightpath as a pair of a target lightpath, such that the working lightpath holds the most amount of wavelength resources required to set up other remaining target lightpaths.

As target lightpaths are set by the SWITCH or APPEND procedure, these target lightpaths reserve their wavelength resources. And available wavelength resources are decreased. Ultimately, no target lightpaths can be set because the available wavelength resources are exhausted.

In Step 3, if all target lightpaths in L_2 have already been created, we have attained our goal and can go to Step 6. Otherwise, in Step 4, we try to find available wavelength resources by applying BACKUP procedures as many times as possible. If one or more trial succeeds, we free up and gain new available wavelength resources without traffic loss. Then we go back to Step 2 and try to set up the rest of the target lightpaths in L_2.

In Step 5, we first try the RELEASE procedure because we do not want to incur traffic loss. If the RELEASE procedure cannot be applied, we try the DELETE procedure. When a working lightpath is selected for the RELEASE or DELETE procedure, the selection is based on the similar policy as Step 2.2 to encourage the rest of reconfiguration.

The REASSIGN procedure can be applied to target lightpaths in the SWITCH or APPEND procedure and backup lightpaths in the BACKUP procedure.

In Step 6, we delete working lightpaths remained in L_1 because all the target lightpaths have already set up for accommodating the traffic in the network. We then restore the reassigned wavelengths into the original wavelengths with SWITCH procedures.

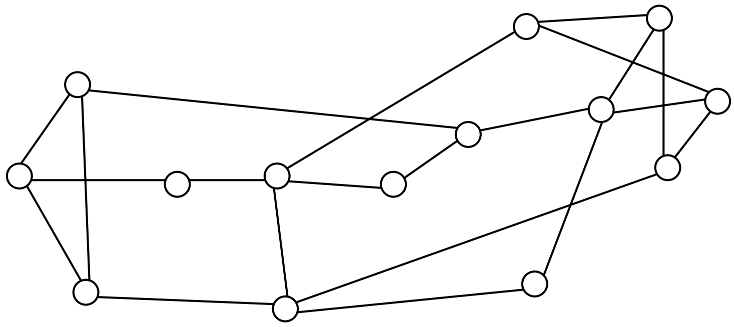


Figure 3. NSFNET (14 nodes, 21 links)

Table 1. Comparison of four algorithms. Algorithm 1 is a basic algorithm, which is composed of the SWITCH, RELEASE, APPEND, and DELETE procedures. Algorithm 2 allows the BACKUP procedure, whereas Algorithm 3 allows the REASSIGN procedure. Algorithm 4, which employs all procedures, is the proposed algorithm.

Algorithm	SWITCH	APPEND	BACKUP	RELEASE	DELETE	REASSIGN
1	Enabled	Enabled	Disabled	Enabled	Enabled	Disabled
2	Enabled	Enabled	Enabled	Enabled	Enabled	Disabled
3	Enabled	Enabled	Disabled	Enabled	Enabled	Enabled
4	Enabled	Enabled	Enabled	Enabled	Enabled	Enabled

Table 2. Properties of logical topologies to be reconfigured. The second row shows the average number of lightpaths excluding backup lightpaths in a logical topology.

Number of wavelengths	16	32	64	128	256
Number of lightpaths	210	404	779	1527	3082

4. EVALUATION

We considered four algorithms for comparison: Algorithms 1, 2, 3, and 4. Algorithm 4 is our proposed algorithm, and the first three algorithms are subsets of Algorithm 4. They are all compared in Table 1.

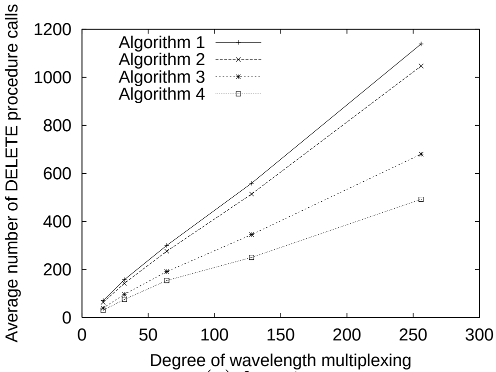
We evaluated the performances of these algorithms by the number of times the DELETE procedure call occurred.

4.1. Traffic Model

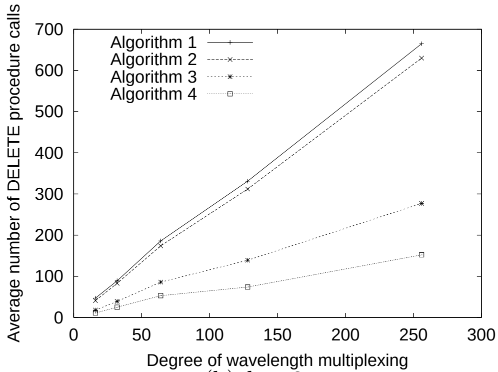
We generate series of traffic matrices $T^1, T^2, \cdots, T^k$, where the elements of each traffic matrix are set a random value between zero and the capacity of a fiber. Furthermore, we also prepared a dynamic traffic model Eqs. (1), similar to the model described in Ref. 9.

$$T^{k,l} = round\left[(1 - \frac{l}{h})T^k + \frac{l}{h}T^{k+1}\right] \tag{1}$$

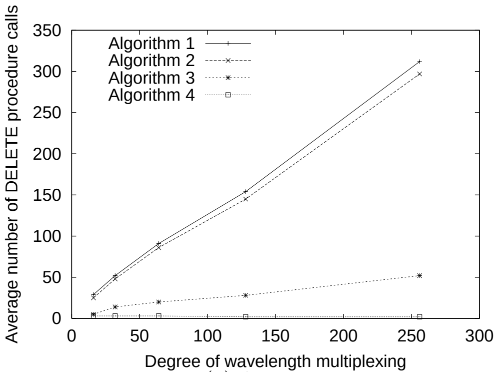
In this traffic model, the dynamic changing of traffic is represented by two parameters: k and h. In our evaluation, we set $k = 5$ and $h = 1, 2, 4, 6, 8$.



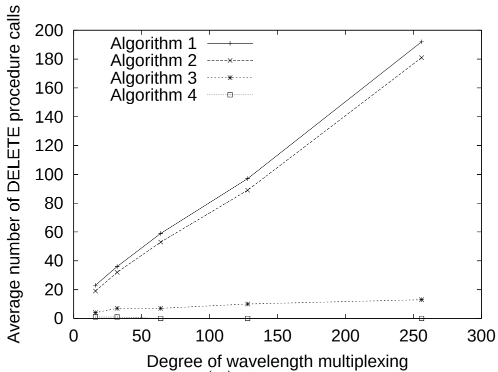
(a) $h = 1$



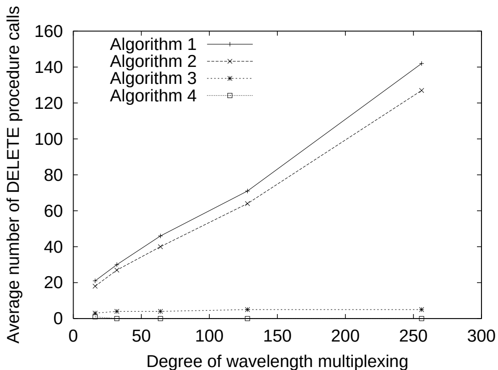
(b) $h = 2$



(c) $h = 4$



(d) $h = 6$



(e) $h = 8$

Figure 4. The average number of times DELETE procedure calls occur during a reconfiguration

4.2. Network Model

We adopted NSFNET as the network model (Fig. 3) in this evaluation. We evaluated when the degree of wavelength multiplexing would be 16, 32, 64, 128, and 256.

4.3. Logical Topology Design

To generate the logical topologies for the traffic matrices given by the methods in Sec. 4.1, we extended the logical topology design algorithm MLDA[10] to deal with backup lightpaths and shared protection strategy. Working and backup lightpaths are set up on shortest paths in terms of the propagation delay. The backup lightpaths are selected on a disjoint sets of links of the corresponding working lightpath. For each lightpath, its wavelength is assigned based on First-Fit policy. The properties of the logical topologies obtained by extended MLDA are shown in Table 2. The average utilization of wavelength resources on links is between 96% to 99%.

4.4. Simulation Results

Fig. 4 has the results of our algorithms where the average numbers of DELETE procedure calls from 5 trials ($k = 5$) are dependent on the degree of wavelength multiplexing. The figure shows five cases of parameter h: i.e., $h = 1, 2, 4, 6, 8$.

From Fig. 4, traffic loss decreasing in order from Algorithm 1 to 2 to 3 to 4. As observed in the figure, there is a large gap between Algorithms 2 and 3. This result shows that the REASSIGN procedure, i.e., wavelength re-assigning, is useful in reconfigurations of logical topologies. On the other hand, the BACKUP procedure is still less effective than the REASSIGN procedure on reconfigurations. We believe that the shared protection strategy makes the BACKUP procedure less effective.

In Fig. 4, the number of DELETE procedure calls gets smaller as the value of h becomes larger. This is mainly because there is a smoother change in traffic demand. In Fig. 4(a), the number of DELETE procedure calls increases as the degree of wavelength multiplexing increases. This relationship holds for each h in Algorithms 1, 2, and 3. However, the results for Algorithms 4 show the decrease in the number of DELETE procedure calls for $h = 4, 6, 8$. The reason is as follows. When the degree of wavelength multiplexing is large, the number of backup lightpaths also becomes large. The wavelength resources released by the RELEASE procedures also increase, which shows the effectiveness of the REASSIGN procedure.

When h is greater than 4, our proposed algorithm reduces the number of DELETE procedure calls to a few or zero, i.e., no traffic loss. This means that reconfigurations of logical topologies must be made at some interval if our intension is to maintain an optimal logical topology with no traffic loss. Another approach is to develop a design algorithm to obtain a logical topology such that the number of DELETE operations is minimized, which is our future research topic.

5. CONCLUDING REMARKS

In this paper, we proposed an algorithm to reconfigure logical topologies in reliable WDM mesh networks. The algorithm has five procedures to set up or tear down lightpaths. The SWITCH, BACKUP and RELEASE procedures exploit wavelength resources that are reserved for backup lightpaths. The evaluations were made with randomly generated traffic matrices, and the results indicate that our algorithm can reduce the number of DELETE procedures that lead to traffic loss. We also evaluated our algorithm with a dynamic traffic model, and showed that the advantages our algorithm has increase as the change of traffic gets smoother.

Our algorithm is based on the static design algorithm for logical topology, which results in unnecessary DELETE procedure calls. Our future work is to develop a design algorithm to obtain a logical topology such that the number of DELETE procedures can be minimized.

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