Reconfiguration Heuristics for Logical Topologies in Wide-Area WDM Networks

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***Abstract*—We propose several heuristic algorithms that reconfigure logical topologies in wide-area wavelength-routed optical networks. Our reconfiguration algorithms attempt to keep the network availability as much as possible during the reconfiguration process. For this purpose, a lightpath is taken as the minimum unit of reconfiguration, which is an all-optical wavelength-division multiplexed (WDM) channel. The proposed algorithms are evaluated by using an NFSNET-like network model with 16 nodes and 25 links. The results show that very simple algorithms provide very small computational complexity but poor performance, i.e., bad network availability, and that an efficient algorithm provides reasonable computational complexity and very good performance. More complex algorithms may improve performance somewhat further but have unrealistically large computational complexity.**

I. Introduction

Wavelength division multiplexing (WDM) is a promising approach for using the enormous bandwidth available in an optical communication medium [1], [2]. A WDM network utilizes wavelength multiplexers and optical switches (routing nodes) so that multiple user signals can be multiplexed on a single WDM fiber and an arbitrary logical topology can be embedded on a given physical fiber network. A logical topology of a WDM network consists of a set of *all-optical* lightpaths by which data can be transferred in optical signals efficiently. For a network without wavelength conversion, *wavelength continuity* is required which implies that the same wavelength has to be used on all links of a lightpath. A routing node can provide optical-to-electric (O/E) conversion and vice versa to perform the wavelength conversion and to interface the optical network with conventional electronic equipments. However, the O/E conversion is much more inefficient than the all-optical transmission. In a multi-hop network, data from a source to a destination has to go through one or more sequence of lightpaths before reaching the destination.

In the design of a logical topology for a wavelength-routed WDM network, both the physical fiber network and the network traffic pattern are taken into account. Since the traffic pattern may change from time to time, it is vital to reconfigure the logical topology according to the changes in the traffic pattern. In order to reconfigure the logical topology from one to another in an efficient manner, it is necessary to minimize the disruption in the network, i.e., the network unavailability [2], [3], [4]. However, the exact solution to this problem can be easily shown NP-hard [5], and so heuristic approaches are needed to find realistic solutions.

Recently, some authors have studied the logical topology reconfiguration for WDM optical wide-area networks (WANs) [4], [6], [7]. They show the best logical topology for a given network traffic pattern using the modified integer linear programming (MILP) formulation or heuristic techniques. However, they present only the target logical topology without revealing the reconfiguration procedure, i.e., the transformation procedure from the old logical topology to the new one. Other authors deal with the logical topology reconfiguration but their network topologies are limited to simple models such as a local area network (LAN) with an optical coupler [8], [9], [10].

In this paper, we focus on wide-area WDM optical networks and propose several reconfiguration algorithms that attempt to shift from one logical topology to another while keeping the network availability as much as possible. Unlike previous studies, we propose new reconfiguration schemes that take a lightpath as the minimum reconfiguration unit. The proposed algorithms are evaluated by means of numerical experiments.

II. Problem Formulation

In a WDM network, routing nodes are equipped with add/drop devices and with transmitters/receivers for user inputs/outputs. A logical topology reconfiguration of a network is to establish a new logical topology on the current (old) topology diagram. Some of the current logical circuits (lightpaths) are reluctantly torn down if they use any resources in conflict with the new ones. Since this may cause packet delay or loss, it is crucial to limit the effect of reconfiguration on the network traffic as little as possible during the reconfiguration procedure. Therefore, each step of the reconfiguration process should be small enough to keep the disruption of the network minimum, i.e., to keep the network availability maximum. In this paper, we propose to use a lightpath as the minimum unit for reconfiguration, i.e., only one lightpath of the new topology is set up at a time.

It is assumed that the time for disrupting an old lightpath is negligibly small compared with that for setting up a new lightpath. It is also assumed that the time for constructing a lightpath is constant. Therefore, the time duration of each reconfiguration stage can be simply treated as a step. Thus, constructing n new lightpaths requires n steps.

Let N denote the number of nodes in the network. It is assumed that the wavelength continuity constraint is maintained and that each node has the O/E conversion capability. The numbers of transmitters and receivers at node i are denoted by T_i and R_i, respectively. In this paper, it is assumed that $T_i = R_i, 1 \leq i \leq N$. It is also assumed that each transmitter/receiver is tunable to any wavelength range. The set of new lighpaths is denoted by S. Let t_{ij} and r_{ij} denote the disrupted time duration (measured in the number of steps) of the jth transmitter and the jth receiver at node i, respectively. Then, the mean number of disrupted transceivers (pairs of a transmitter and a receiver) per step during the reconfiguration process, denoted by *MDT*, is given by

$$MDT = \frac{1}{2|S|}\sum_{i=1}^{N}\Big(\sum_{j=1}^{T_i} t_{ij} + \sum_{j=1}^{R_i} r_{ij}\Big), \quad (1)$$

where $|S|$ denotes the size of set S. An objective of the reconfiguration algorithm is to arrange a reconfiguration sequence so that *MDT* is minimized. Another performance index is the maximum instantaneous number of disrupted transceivers, denoted by *MD*. This indicates the worst case of the algorithm affecting the network availability. By letting $dis(k)$ be the instantaneous number of disrupted transceivers at the kth step, *MD* is given as follows:

$$MD = \max_{1\le k\le |S|}\big\{dis(k)\big\}. \quad (2)$$

III. Reconfiguration Algorithm

It is easy to show that the problem of solving the optimal reconfiguration for a logical topology is NP-hard since it needs $|S|!$ comparisons to find the best reconfiguration sequence. Therefore, the reconfiguration algorithms proposed in this paper are *heuristic* in nature. The following subsections describe the proposed algorithms in detail.

A. Longest lightPath First (LPF) algorithm

The LPF algorithm constructs the new lightpaths starting with the longest one and continuing to the shorter ones according to the number of hops of the lightpaths in the physical network. Since the reconfiguration procedure depends only on the path hops in the physical network, the reconfiguration sequence can be determined by simply sorting the lightpaths of the new logical topology. The longer a new lightpath is, the more it has the possibility of conflict with old lightpaths. Hence, this algorithm tends to have a large *MDT*.

B. Shortest lightPath First (SPF) algorithm

The SPF algorithm works oppositely to LPF in the sense that SPF first constructs the shortest lightpath in the new logical topology according to the number of hops in the physical network. Since a lightpath with fewer hops in the physical network may result in the less probability of conflict with the lightpaths of the old topology, this algorithm seems more efficient than LPF. Similar to LPF, the reconfiguration sequence can be determined by sorting the lightpaths based on the number of hops in the physical network.

C. Minimal Disrupted lightPath First (MDPF) algorithm

In contrast to the previous two algorithms, the MDPF algorithm takes account of the effect of each new lightpath on the network availability and attempts to find out the best sequence of lightpaths to set up so that the maximum network availability can be maintained. In order to realize MDPF, an auxiliary graph $G_a(V_a, E_a)$, where V_a and E_a denote the sets of vertices and edges, respectively, is introduced. Then, a sorting algorithm is used to select the best lightpath for reconfiguration. The computational complexity of MDPF is larger than that of LPF or SPF but its order is polynominal.

The following notation is used to present the reconfiguration algorithm of MDPF:

- l_i — ith new lightpath
- S — set of the lightpaths in the new topology in conflict with the old ones in the current topology, i.e., $S = \{l_1, l_2, ..., l_{|S|}\}$
- l'_i — ith old lightpath
- S' — set of the lightpaths in the old topology in conflict with the ones in the new topology, i.e., $S' = \{l'_1, l'_2, ..., l'_{|S'|}\}$
- $C(l_i)$ — cost for setting up a new lightpath $l_i, l_i \in S$
- $d(v)$ — degree of vertex $v, v \in V_a$
- $N(v)$ — neighborhood of vertex $v, v \in V_a$

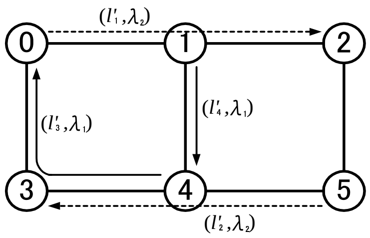
1) Creation of auxiliary graph: The auxiliary graph is an undirected bipartite graph $G_a(V_a, E_a)$, where $V_a = S \cup S'$ and $E_a = \{(l_i, l'_j)|$if $l_i \in S$ is in conflict with $l'_j \in S'$ $\}$. In the auxiliary graph, the new and old lightpaths are treated as vertices while the conflict relationship of the new and old lightpaths is represented by edges. Note that the conflict relation may come from the conflicts of wavelength, transmitter, and receiver. For example, for the conflicting new and old lightpaths on a physical network shown in Figures 1(a) and (b), an auxiliary graph is created as shown in Figure 1(c). In Figures 1(a) and (b), the tuple (l_i, λ_j) denotes a pair of a lightpath l_i and the wavelength λ_j assigned to the lightpath. The conflict relations between the new and old lightpaths due to wavelength, transmitter, and receiver are indicated by W, T, and R on edges, respectively, in Figure 1(c).

2) Reconfiguration procedure: In MDPF, the auxiliary graph is created first according to the conflict relation of the new and the old topologies. A cost for each new lightpath is associated with its degree in the auxiliary graph. Then, a sorting algorithm is used to select a new lightpath that yields the least effect on the network availability. For example, a heap tree [11] can be used for this purpose. The heap tree is rooted with the selected lightpath, and after setting up this lightpath it is deleted from the tree. The heap tree is then updated. This procedure is repeated until the tree becomes empty.

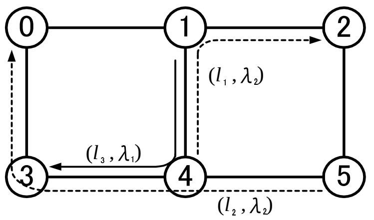
The whole reconfiguration procedure of MDPF consists of the following steps:

Step 1. Create/update the auxiliary graph $G_a(V_a, E_a)$ based on the conflict relationship of the new and old topologies.

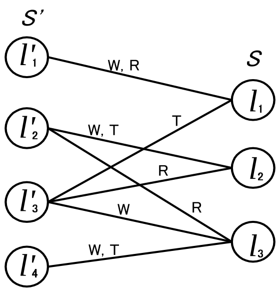
Step 2. Calculate the setup cost $C(l_i)$ for each new lightpath $l_i \in S$. The setup cost of l_i is defined as the number



(a) Old lightpaths on the physical network.



(b) New lightpaths on the physical network.



(c) Auxiliary graph for the conflicting new and old lightpaths.

Fig. 1. An example of the logical topology reconfi guration in a WDM optical network.

of the old lightpaths disrupted by l_i. That is,

$$C(l_i) = d(l_i), l_i \in S.$$

Step 3.Determine lightpath ℓ with the least setup cost:

$$\ell = \arg\min_{l_i \in S} C(l_i)$$

Step 4.Set up lightpath ℓ and update S and S' as follows.

$$\begin{aligned} S &= S \setminus \{\ell\}, \\ S' &= S' \setminus N(\ell). \end{aligned}$$

Step 5.Stop if $S = \emptyset$. Otherwise, go to Step 1.

D. Tree Search (TS) algorithm

The TS algorithm is an abbreviated version of the exhaustive search algorithm which checks the whole combinations of the reconfiguration sequence in order to find the best one. In this algorithm, a search tree is created such that each node denotes a new lightpath and each path from the root to a leaf denotes a possible reconfiguration sequence of the logical topology as shown in Figure 2. This algorithm provides better performance than MDPF but its computational complexity is much larger.

At the beginning, a pseudo-node is added as the root and its direct descendants are the whole new lightpaths. The direct descendants of a node are the new lightpaths excluding its ancestors and itself. A path from the root to a leaf is denoted by p and the set of paths is denoted by P. The *MDT* through path p is defined by

$$MDT(p) = \frac{1}{2d} \sum_{i=1}^{N} \Big(\sum_{j=1}^{T_i} t'_{ij} + \sum_{j=1}^{R_i} r'_{ij} \Big), \qquad (3)$$

where t'_{ij} and r'_{ij} denote respectively the disruption time duration of the jth transmitter and the jth receiver at node i accumulated over d levels.

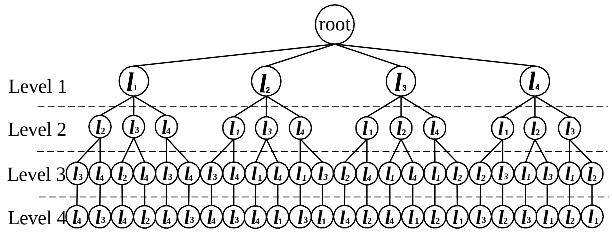


Fig. 2. A sample search tree with four levels.

The TS algorithm searches for only d levels from the root, instead of searching for the whole lightpath combinations. It consists of the following steps.

Step 1.Create/update the search tree with depth d.

Step 2.Evaluate *MDT*(p) for each reconfiguration sequence p by (3), and determine lightpath ℓ as the direct descendant of the root along path p such that

$$\min_{p \in P} MDT(p).$$

Step 3.Set up lightpath ℓ and update S as follows.

$$S = S \setminus \{\ell\}.$$

Step 4.Stop if $S = \emptyset$. Otherwise, let lightpath ℓ be the root and go to Step 1.

IV. Numerical Experiments

Numerical experiments have been conducted to evaluate the four algorithms proposed above. The network model used is an NSFNET-like network with 16 nodes and 25 links shown in Figure 3. Each node has wavelength switching functionality and each link has two fibers for duplex communication. It is assumed that every node in the network has the same number of transceivers. In order to determine the logical topology for a given traffic pattern, the max multihop (MM) algorithm proposed in [4] is used. The traffic patterns used in the experiments are randomly created. The experimentation program is developed using the C language and executed on a Sparc UNIX server with eight 400MHz CPUs.

We have performed two experiments, one for examining the computational time of the algorithms and the other for evaluating their performance. In the first experiment, the reconfiguration has been repeated 50 times with $T/R = 8, 16, 20, 40$

and $W = 8, 16, 20, 40$. Here, T/R denotes the number of transceivers at each node, and W denotes the number of wavelengths on each direction of the link in the network. In the second experiment, the reconfiguration has been repeated 50,000 times with $T/R = 4, 5, 10$ and $W = 4, 5, 10$. The results shown in the following figures are the mean values.

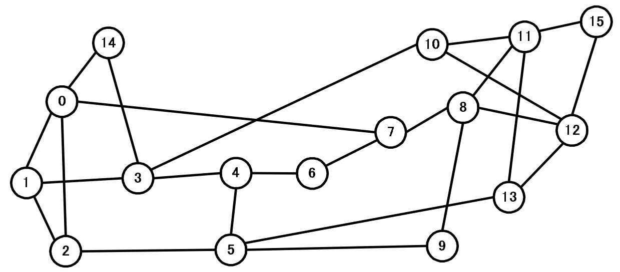


Fig. 3. Network model for numerical experiments.

A. Comparison of computational time

Table I shows the average computation time for reconfiguration. From this table, it can be seen that SPF and LPF provide similar computation time, which is shorter than MDPF and TS. It is also observed that even though the computation time of MDPF is greater than that of SPF or LPF, its value still falls in a practical range, e.g., it takes only 24s when $W = 40$. On the other hand, the computation time of TS is unrealistically large because of its complexity.

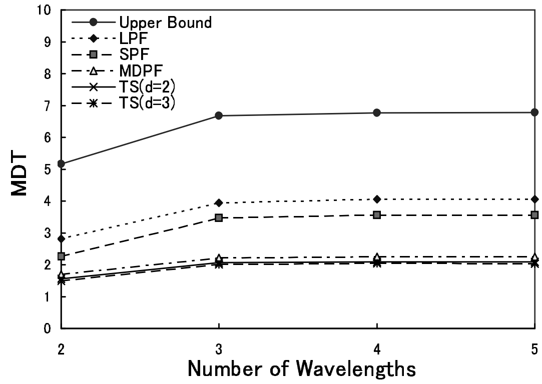
TABLE I
COMPUTATION TIME FOR RECONFIGURATION

	$T/R = 8$ $W = 8$ $\lvert S\rvert = 68$ $\lvert S'\rvert = 71$	$T/R = 16$ $W = 16$ $\lvert S\rvert = 185$ $\lvert S'\rvert = 186$	$T/R = 20$ $W = 20$ $\lvert S\rvert = 235$ $\lvert S'\rvert = 235$	$T/R = 40$ $W = 40$ $\lvert S\rvert = 292$ $\lvert S'\rvert = 292$
SPF	98ms	0.25s	0.47s	1.0s
LPF	96ms	0.25s	0.47s	1.0s
MDPF	0.26s	5.4s	10s	24s
TS($d = 2$)	28s	31m	–	–
TS($d = 3$)	21m	–	–	–

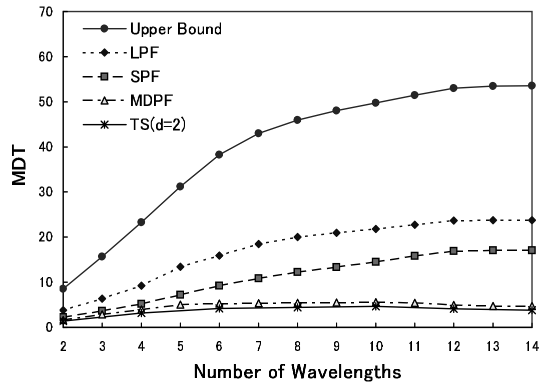
Using a data structure like a binary search tree [11], the computational complexity of SPF/LPF is $O(|S| \log |S|)$. The computational complexity of MDPF depends on how to sort the new lightpaths and the conflict relation between the new and old logical topologies. When the heap sort [11] is used and the degree of an old lightpath $d(l'_i)$ is limited, the computational complexity is $O(|S| \log |S|)$. The computational complexity of TS is $O(|S|^3)$ when $d = 2$, while it is $O(|S|^4)$ when $d = 3$.

B. Comparison of performance

We next discuss the performance of the algorithms. The upper bound shown in the figures occurs when all the old lightpaths are broken at once and then the new lightpaths are constructed one by one. Therefore, the upper bound of *MDT* is given by $(|S|+1)/2$, where S depends on the number of wavelengths.



(a)



(b)

Fig. 4. Mean disruption time: (a) $T/R = 4$; (b) $T/R = 10$.

Figures 4(a) and (b) show the *MDT* of each algorithm for $T/R = 4$ and $T/R = 10$, respectively. From these figures, it is clear that all the heuristic algorithms yield much better *MDT* than the upper bound. It is observed that SPF performs better than LPF. This is because LPF attempts to configure first the new lightpath with the largest number of hops in the physical network, resulting in the high probability of conflict with old lightpaths. It is also seen that MDPF and TS are better than LPF and SPF for any number of the wavelengths. The improvement of MDPF over LPF or SPF is significantly large. However, the improvement of TS over MDPF is nominal. This suggests that MDPF or TS with small d is preferable when the number of wavelengths increases.

Figures 5(a) and (b) show the instantaneous number of disrupted transceivers during the reconfiguration process. From these figures, it can be seen that MDPF and TS are more stable and have much smaller instantaneous number of disrupted transceivers than LPF and SPF. On the other hand, LPF and SPF perform the worst since they do not take account of the conflict relations between the new and old logical topologies.

The *MD* is another key performance index to show how good an algorithm is. A large value of *MD* means that there are many transceivers being disrupted at some time instant during the reconfiguration process. Figures 6(a) and (b) show the

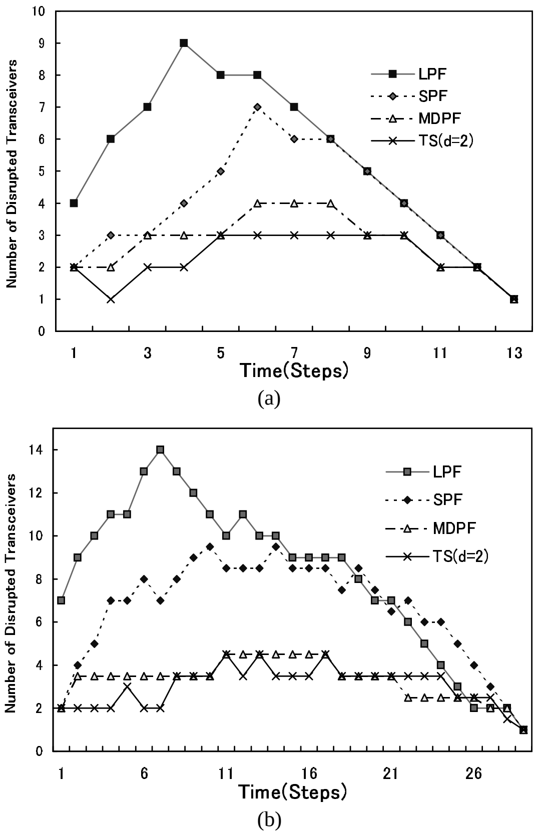


Fig. 5. Number of disrupted transceivers at each step of the reconfiguration process: (a) $T/R = 4, W = 4$; (b) $T/R = 5, W = 5$.

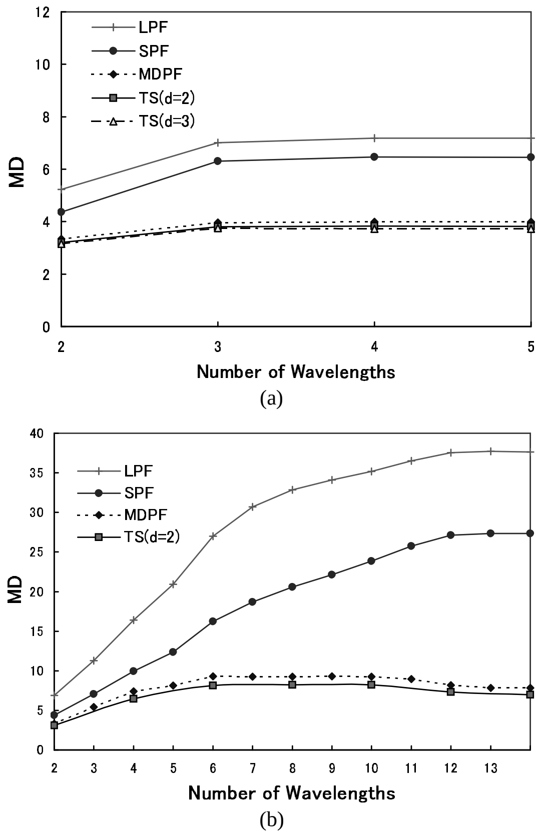


Fig. 6. Maximum disruption number during the reconfiguration process: (a) $T/R = 4$; (b) $T/R = 10$.

maximum number of disrupted transceivers (*MD*) for various numbers of wavelengths. From these figures, it is observed that MDPF and TS provide very close performance and that they outperform others. The difference in performance between MDPF (or TS) and others becomes large when the number of wavelengths increases.

V. Conclusion

In this paper, several heuristic reconfiguration algorithms are proposed and evaluated. Two simple algorithms, SPF and LPF, have low computational complexity but poor performance. A tree search algorithm TS provides very good performance with large computational complexity. This makes TS far from realistic and practical. The minimal disrupted lightpath first (MDPF) algorithm is proposed as a simple algorithm with reasonable computational complexity. It has been shown that the performance of MDPF is close to that of TS but with much lower computational complexity.

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