Virtual Topology Reconfiguration in Hierarchical Cross-Connect WDM Networks

Hsiao Yun Yeh, Chien Chen, Member, IEEE, and Ying Yu Chen

Abstract—Multigranularity optical cross-connects (MG-OXCs) have emerged as the means to save the cost of manufacturing large optical cross-connects (OXCs) used in the IP-over-WDM networks. This paper considers the virtual topology configuration problem in the MG-OXC networks that has not yet been studied. We assume that the future traffic pattern is known a priori and we are to reconfigure the original topology, without dramatically changing the current virtual topology, to the new one that is suitable for the new traffic pattern. We propose our heuristic Preference Based Reconfiguration Algorithm (PBRA) to solve the problem by constructing an auxiliary graph to help determining the addition, deletion, or keeping of the virtual links. Simulation results show that we can change less original virtual topology at the cost of small increase in blocking probability.

Index Terms—Auxiliary graph, multigranularity optical cross-connects, virtual topology, reconfiguration, WDM.

I. INTRODUCTION

With the rapid increase of IP traffic, there is no doubt that in the near future data communications will be based on optical networking. Wavelength-division-multiplexed (WDM) networks are considered to be one of the most promising future transport infrastructures to meet the ever-increasing bandwidth demand. Such networks consist of optical cross-connects (OXCs) interconnected by fiber links, with each fiber supporting a number of wavelength channels. End users in the networks communicate with each other via all-optical channels, i.e., lightpaths, where each of which may span a number of fiber links to provide a "circuit-switched" interconnection between two nodes.

A virtual topology is defined to be the set of such lightpaths in a network. Design of virtual topology is the problem of optimizing the use of network resources for the given traffic demands among all node pairs. In real networks, the traffic rates between node pairs fluctuate over time. A virtual topology optimized for a specific traffic pattern may not work as appropriate to a different one. Therefore, reconfiguration of virtual topology is needed to adjust to the new traffic pattern. A literature survey of virtual topology reconfiguration can be found in [1]. Authors in [2] and [3] show the virtual topology reconfiguration using the linear programming formulation. The formulations ensure that the new configuration is not too different from the original virtual topology so that number of reconfiguration steps can be minimized. In [4] and [5], the authors propose several reconfiguration algorithms that attempt shift from one virtual topology to another while keeping the disruption of the network minimum. They focus on the process of transforming the virtual topology from the original to the new one but not on finding the optimal virtual topology for the new given network traffic pattern.

With current technologies, the huge fiber bandwidth can be divided into 100 or more wavelengths. However, as the number of wavelength channel increases, the number of ports needed at OXCs also increases, making the size of OXCs too large to implement and maintain. Recently, several types of multigranularity optical cross-connects (MG-OXCs) [6]-[8] have been proposed to handle such scalability problem. The principle of the MG-OXC network is to bundle a group of consecutive wavelength channels together and switch them as a single unit on a specific route so that the number of ports needed by the intermediate nodes along the route can be reduced.

![Fig. 1. Architecture of an MG-OXC](image)

Although MG-OXCs are gaining more and more research...
In this paper, we study the virtual topology reconfiguration problem in such networks. In this paper, we study the virtual topology reconfiguration problem in the networks using MG-OXC architecture (shown in Fig. 1) as proposed in [6]. In such a network, a directional link consists of $F = F_1 + F_2 + F_3$ fibers, where $F_1$, $F_2$, and $F_3$ fibers are assigned as fiber-, waveband- and wavelength-switched fibers, respectively. In a waveband- or fiber-switched fiber, all the wavelengths in a waveband or a fiber have to be switched together. The tunnel-like passage formed by the grouped wavelengths that are transmitted as a single unit is termed as a waveband tunnel or a fiber tunnel, depending on the size of the grouped wavelengths. For a lightpath to utilize a tunnel, wavelength-switching ports are required both at the ingress and the egress of the tunnel.

In this paper, we assume that the future traffic pattern can be accurately predicted, i.e., known a priori and the basic traffic unit is a lightpath. Therefore, instead of reconfiguring the lightpaths in the tradition OXC networks for the sub-wavelength granularity traffic, here we concern about reconfiguring tunnels in the MG-OXC networks for the lightpaths. We consider the following problem. Given $V_T$, $T_f$, and $T_z$, where $V_T$ is a set of tunnels allocated based on current traffic pattern $T_t$, and $T_f$ is the future traffic pattern, the objective is to reconfigure $V_T$ with little changes as possible while minimizing the blocking probability for $T_f$. We propose the heuristic called Preference Based Reconfiguration Algorithm (PBRA) to solve the problem. An auxiliary graph is used to rate the preference of each existent and nonexistent tunnels by routing the future traffic pattern $T_f$ on it. According to the obtained preference, small number of tunnels will be updated to reconfigure the original virtual topology for the new traffic pattern.

The remainder of this paper is organized as follows. Section II presents details of PBRA. Simulation results are given in Section III. The paper concludes in Section IV.

II. PREFERENCE BASED RECONFIGURATION ALGORITHM

Although short tunnels are easily utilized by most of the lightpaths, the wavelength-switching ports can be used up easily since the wavelength-switching ports are required at the ingress and egress nodes of each tunnel. Long tunnels, on the other hand, though save wavelength-switching ports, may not be suitable for the requests since most of the lightpath requests are shorter than the tunnels. Therefore, we restrict that the tunnels follow the tunnel length constraint, i.e., the length of each tunnel should be the same, which is set to the minimum integer that is larger than the average distance of paths between each s-d pair in the network [6, 9].

PBRA is based on an auxiliary graph to rate for each node pair the preference of having tunnels established between them. We then determine the addition, deletion or keeping of the tunnels based on the derived preference value. Since the length constraint can be derived from the given physical topology, we can determine the set of node pairs that is qualified to be allocated tunnels easily. That is, only the node pairs whose shortest path distance equal to the length constraint could be allocated tunnels. This is reflected in the construction the auxiliary graph. The whole process comprises four stages: (a) construction of auxiliary graph, (b) cost assignment for edges in the auxiliary graph, (c) load estimation of existent and nonexistent tunnels, and (d) tunnel selection. Details are described as follows.

(a) Construction of auxiliary graph

Let $G_a(V_p, E_p)$ be the physical topology where $V_p$ denotes the set of nodes and $E_p$ is the set of all physical links connecting the nodes. The auxiliary graph $G_a(V, E_a)$ mainly comprises three layers, which are wavelength waveband and fiber layers and is obtained as follows. Each node $i \in V_p$ is replicated into wavelength, waveband and fiber layer. These nodes are denoted as $V^{w}_i$, $V^{b}_i$ and $V^{f}_i$. If edge $e \in E_p$ connects node $i$ to node $j$, $i, j \in V_p$, then node $V^{w}_i$ is connected to $V^{w}_j$ by a directed edge, termed wavelength-switching edge. For each node pair $i-j$ with existent waveband (fiber) tunnel in $V_t$, the node $V^{b}_i$ ($V^{f}_i$) is connected to $V^{b}_j$ ($V^{f}_j$) by a directed edge, termed existent waveband (fiber) tunnel edge. For each node pair $i-j$ with its shortest physical hop length lower than the length constraint and has not yet been allocated waveband (fiber) tunnel, there is also an edge connecting from $V^{b}_i$ to $V^{f}_j$ ($V^{f}_i$ to $V^{b}_j$), termed potential waveband (fiber) edge. For each node $i \in V_p$, there are bidirectional edges between $V^{w}_i$, $V^{b}_i$, and $V^{f}_i$, termed layer transition edges. Fig. 2 gives an example of construction of the auxiliary graph. Fig. 2(a) is the physical topology with its average hop distance equal to two. The corresponding auxiliary graph may be the one shown in Fig. 2(b).

(b) Cost assignment for edges in the auxiliary graph

Costs of the edges are assigned as in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>COST FOR EDGES IN $G_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existant waveband (fiber) tunnel edge</td>
<td>$D$ (Length constraint)</td>
</tr>
<tr>
<td>Potential waveband (fiber) tunnel edge</td>
<td>$D^*$ scale</td>
</tr>
<tr>
<td>Wavelength-switching edge</td>
<td>$&gt;&gt;D$</td>
</tr>
<tr>
<td>Layer transition edges</td>
<td>0</td>
</tr>
</tbody>
</table>

Since we hope to reconfigure $V_t$ with little changes, the existent tunnel edges have the smallest cost $D$ which is the tunnel length constraint. $D^*$ is used to adjust the degree of
preference on the existent tunnels where $D' \geq D$ and $D' \in Z$.
The higher $D'$ we select the less preference the existent tunnels will be used. For each potential waveband (fiber) edge, a scale is associated with it. The scale represents the degree of difficulty to construct a tunnel for the node pair associated with that edge. The more existent tunnels must be deleted to construct a tunnel for a potential tunnel edge, the larger the scale is for that potential tunnel edge. Scale for potential tunnel edge $i$ is defined to be $$(CL_i - CL_{max}) / (CL_{max} - CL_{min})$$ where $CL_i$ is the number of existent tunnels that may hinder the construction of the tunnel for the node pair associated with edge $i$, $CL_{max} = \max_j CL_j$, and $CL_{min} = \min_j CL_j$. Figure 5 illustrates the calculation of $CL$ for the potential tunnel edge. Note that the confictions between the existent and nonexistent tunnels may happen at physical links or the end nodes of the tunnels (They contend for the wavelength switching ports). In Fig. (a), the thick and dash lines represent the actual physical paths of existent and nonexistent tunnels, respectively. The nonexistent tunnel $(1, 5)$ conflicts with the existent tunnel $(0, 3)$.

![Fig. 3](image-url) Illustration of calculating $CL$. (a) Conflicts happen at physical links and at end nodes. (b) A detailed drawing of the confliction at the end nodes.

![Fig. 4](image-url) Computation of $W$. (a) Five shortest paths from node 0 to node 5. (b) The corresponding $W$.

(c) Load estimation of existent and nonexistent tunnels

After completion of stage (b), we can then route $T_2$ on the auxiliary graph to estimate the load on each edge of the auxiliary graph. We assume that the load between each node pair will be equally distributed on all its shortest paths. For example, for the network shown in Fig. 2, assume that the future traffic between node 0 and node 5 is 10 and five shortest paths are found as shown in Fig. 4(a). Then each of the five paths will be distributed 2 units of the load. After $T_2$ is routed on the auxiliary graph, for each node pair, the summation of the load of the existent/potential waveband/fiber edges for that pair will be recorded in a matrix $W$. Fig. 4(b) shows the matrix $W$ as a result of $T_2$ where $W_{0, 4} = 2$, $W_{1, 2} = 2 + 2 = 4$ and $W_{2, 5} = 2 + 2 = 4$.

(d) Tunnels selection

$W$ is used to determine the set of tunnels. The process repeatedly examine the node pair with the maximum weight to see whether there are existent tunnels for the node pair, otherwise, it tries to construct a new tunnel for the node pair. If there are already existent tunnels allocated between the selected pair, keep one of them in the virtual topology. Otherwise, construct a tunnel between the selected pair and if necessary, delete the existent tunnels that hinder the construction. Note that whether keeping or constructing a tunnel, the fiber tunnel is considered first. If a fiber tunnel is kept, or constructed successfully, weight of the corresponding node pair is decreased by $\delta_F = \sum W_{ij}(L - F(t)/D)$, where $W_{ij}$ is the weight of the node pair $(i, j)$, $L$ the number of directional links in the physical topology, $F = L + F$, the number of fibers dedicated to tunnel allocation in each directional link and $D$ the length constraint. Similarly, for the waveband tunnel, the weight is decreased by $\sum W_{ij}(L - B - F(t)/D)$, where $B$ is the number of wavebands in a fiber. If both fiber and waveband tunnels fail to be constructed, the weight is set to 0. The whole algorithm of PBRA is summarized as follows.

**Preference Based Reconfiguration Algorithm:**

**Input:**

$V_T$: Current virtual topology

$T_T$: Future traffic pattern

**Output:**

$V_T$: New virtual topology for $T_T$

**Algorithm:**

Step 1: Construct $G_n$

Step 2: Define the cost for each edge in $G_n$ and compute the weight matrix $W$ by routing the lightpath requests of $T_T$ on $G_n$

Step 3: Let $(i, j)$ be the node pair with maximal weight. Stop if $W_{ij}$ is smaller or equal to 0.

Step 4: If there are existent fiber tunnels for $(i, j)$, keep one of them, decrease the weight of the node pair by $\delta_F$, and go to Step 5. Otherwise, go to Step 8.

Step 5: If there are existent waveband tunnels for $(i, j)$, keep one of them, decrease $W_{ij}$ by $\delta_B$, and go to Step 3. Otherwise, go to Step 6.

Step 6: Try to construct a fiber tunnel for $(i, j)$. If successful, decrease $W_{ij}$ by $\delta_F$, and go to Step 3. Otherwise, go to Step 7.

Step 7: Try to construct a waveband tunnel for $(i, j)$. If successful, decrease $W_{ij}$ by $\delta_B$, and go to Step 3. Otherwise, go to Step 8.

Step 8: Set $W_{ij}$ to 0, go to Step 3.

III. SIMULATION RESULTS

Simulation experiments were conducted on the 16-node network shown in Fig. 5. The notation $(F1)F(F2)B(F3)L$ represents the experiment with F1 fibers for fiber switching, F2 fibers for waveband switching and F3 fibers for wavelength switching on each link. We assume that a fiber contains 40 wavelengths and can be divided into four fixed wavebands, with $\lambda_{1-10}$ being waveband one, $\lambda_{11-20}$ waveband two...
and $\lambda_{37}$~$\lambda_{49}$ waveband four. In the simulation, waveband conversion is not allowed while wavelength conversion within the bands is assumed. Two types of traffic patterns are used for the transition between old and new ones. 1) Ring traffic: the load for each node pair $(i, (i+1) \mod 16), i = 0, ..., 15$ is in average 10 times larger than others. 2) Uniform traffic: All traffic requests are randomly generated between each node pair.

![Fig. 5. Physical topology of our simulation environment](image)

Although not shown in the result, it is worth noting that when the new and old traffic pattern are similar, reconfiguration is unnecessary since the original virtual topology is already suitable for the new traffic pattern. Fig. 6 and Fig. 7 shows the simulation results of total number of lightpath request vs. blocking probability and percentage of unchanged tunnels under 2F1B2L and 2F2B1L. The curve “only consider $T_2$” means that the new virtual topology is designed without considering the original using the heuristic presented in [9] and serve as the best case for the comparison. “$T_2$ route on $V_1$” means that we directly route the new traffic on the $V_1$ without changing the original topology and serve as the worst case for the comparison. It can be observed that the improvement space between the two curves is rather limited. The parameter $D'$ is tuned to observe the tradeoff. When $D'$ gets higher, the percentage of unchanged tunnels and the blocking probability also raises. This is because higher $D'$ means higher difficulty to construct a nonexistent tunnel, therefore resulting in more unchanged tunnels. The more unchanged tunnels then lead to the higher blocking probability. It shows that PBRA can be performed to reserve more original tunnels at the cost of little increase in the blocking probability. For example, in Fig. 6(a), while an 23% increase in the number of the unchanged tunnel under a traffic load of 2000 lightpath requests, the blocking probability increases only 0.013.

IV. CONCLUSION

In this paper, we proposed a heuristic PBRA to solve the virtual topology reconfiguration in MG-OXC networks. We restricted that the tunnels should follow the length constraint and an auxiliary graph is constructed to determine the preference of having tunnels established for those potential node pairs. We show that the improvement space of performing reconfiguration in MG-OXC networks is limited since there is not much difference in blocking probability between reconfiguration if not performed and when performed without considering the original virtual topology. Nonetheless PBRA can still be performed to reserve more original tunnels at the cost of little increase in the blocking probability.
Fig. 7. Comparison of number of lightpath vs. blocking probability and percentage of unchanged tunnels (2F2B1L). (a) traffic pattern changed from ring to uniform (b) traffic pattern changed from uniform to ring

REFERENCES