Optimal design of virtual topology reconfiguration in WDM optical networks

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Virtual topology of WDM optical networks is often designed for some specific traffic matrix to get the best network performance. When traffic demand imposed on WDM optical networks changes, the network performance may degrade and even become unacceptable. So virtual topology need to be reconfigured. In previous works, virtual topology is reconfigured to achieve the best network performance, in which a large number of lightpaths need to be set up or torn down. In this paper, we try to get a tradeoff between the network performance and traffic disruption (or implementing cost). The problem of virtual topology reconfiguration for changing traffic patterns is formulated as an optimization problem and a mixed integer linear programming (MILP) algorithm is presented. Numerical results show that a large cost reduction of reconfiguration can be achieved at the expense of network performance.

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In WDM optical networks, virtual topology reconfiguration needs to be considered in several cases. In the first case, the network performance may degrade and even become unacceptable when the traffic demand in the higher layer changes. So lightpaths need to be rearranged for the new traffic. In second case, when the underlying physical topology changes due to network component failure or some other reasons, traffic on failed lightpaths must be rerouted. But it may not be always able to find an alternate path to reroute them with the original virtual topology. In this case, the virtual topology must be reconfigured. When a virtual topology is reconfigured, several important issues need to be considered[1]. First is the network performance, then the cost of implementing reconfiguration and the time of traffic disruption. Network performance improvement can be achieved by maximizing network throughput or minimizing network congestion. Average packet hop distance (APHD) and maximum lightpath load (maximum logical link load) are two most popular parameters to be used to describe network performance. APHD is an important metric in wavelength-routed network, which describes the average number of hop counts, a unit of traffic transverses. The implementation cost and traffic disruption are often measured by total lightpath changes from an original topology to the new one.

Design of the virtual topology reconfiguration for WDM optical networks has been studied by several researchers. In Ref. [1], the authors presented an exact linear programming formulation for virtual topology design and a reconfiguration methodology to find a new topology with minimal changes to the original one with no reduction of network performance. In Ref. [2], the authors tried to find out the virtual topology with best network performance by adding a constraint to limit the total number of lightpath (or fiber) changes within a given bound. Both of Refs. [1] and [2] tried to find a best virtual topology, but they did not study the tradeoff between network performance and traffic disruption, as we will discuss in details in the following section. In Ref. [3], the authors present a heuristics based on a two-stage approach to solve the problem similar to Ref. [2]. In Refs. [4] and [5], several iterative local search algorithms are developed to minimize the maximum logical link load. But they also did not consider the tradeoff between network performance and traffic disruption.

In this paper, we will study the tradeoff between the network performance and traffic disruption when traffic demand imposed on WDM network changes. A network state is represented as a tetrad $\langle PT$ (physical topology), WT (network resource such as wavelength and transceivers), VT (virtual topology), and T (traffic matrix)$\rangle$. Assuming there is a network state $\langle PT, WT, VT1, T1\rangle$, in which $VT1$ is designed for the traffic matrix $T1$ and an acceptable performance is achieved. Now as the traffic demand imposed by the higher layer changes, the traffic matrix transfers from $T1$ to $T2$ (the network state becomes $\langle PT, WT, VT1, T2\rangle$) and the performance of routing $T2$ on $VT1$ may become unacceptable. To improve the network performance, the virtual topology needs to be reconfigured. Some lightpaths will be set up, and other lightpaths torn down. A new topology named as $VT2$ will be derived. And the network state is transferred from $\langle PT, WT, VT1, T2\rangle$ to $\langle PT, WT, VT2, T2\rangle$. But optimizing the network performance without considering the traffic disruption or minimizing the traffic disruption without considering the performance degradation may not be cost-effective. So we aim to minimize the number of lightpath changes needed for reconfiguration with APHD within an acceptable scope and formulate it as an optimization problem.

A physical topology is assumed to be an undirected graph PT here. There are a certain amount of transceivers in each node and W wavelengths in each fiber. Each undirected edge denotes a pair of fibers in different directions. The virtual topology is denoted as a directed graph VT, in which a lightpath from s to d is not equal to the lightpath from d to s.

The traffic demand T is a random traffic matrix, in which each entry is randomly generated. F $(0 \leq F \leq$

1) fraction of traffic entries are generated at random from a uniform distribution over [0, C/α], and the other entries are uniformly distributed over [0, $C^*\gamma/\alpha$]. C is the capacity of a lightpath, α is an integer greater than or equal to 1, γ is the ratio of maximum traffic flow to the minimum one. Traffic variation is simulated by interchanging p percent entries of a traffic matrix, and two separated traffic matrices are assumed to be uncorrelated.

Given the following: (1) N: number of nodes in the network. (2) W: number of wavelengths per fiber. (3) P: physical topology matrix. P_{mn} denotes the number of fibers interconnecting node m and node n. (4) T_i: number of transceivers at node i ($T_i >= 1$). (5) C: capacity of each lightpath. (6) β: maximum load factors per lightpath, $0 < \beta < 1$. That is, at most $\beta * C$ capacity of a lightpath can be used by traffic. It restricts the queuing delay on a lightpath by avoiding excessive logical link congestion. (7) T: the new traffic matrix after p percent of traffic change takes place. T_{sd} denotes the average rate of traffic flow from node s to node d. (8) $VT1$: the original virtual topology. $VT1_{ij,q} = 1$ if qth lightpath exists between node i and j, otherwise $VT1_{ij,q} = 0$. As lightpaths between i and j may not be bidirectional, $VT1_{ij,q} = 1 \not=> VT1_{ji,q} = 1$. It needs to be noted that the original topology exists before reconfiguring and as an input to the MILP formulations. The value for the following variables needs to be found: (1) $VT2_{ij,q}$: new virtual topology variables. $VT2_{ij,q} = 1$ if qth lightpath will be set up between node i and j, otherwise $VT2_{ij,q} = 0$. (2) $CH_{ij,q}$: lightpath change variable. $CH_{ij,q} = 1$ if $VT2_{ij,q} \neq VT1_{ij,q}$, otherwise $CH_{ij,q} = 0$. (3) $\lambda^{sd}_{ij,q}$: traffic routing variables. The variable $\lambda^{sd}_{ij,q}$ denotes the amount of traffic that flow from node s to node d and employing $V_{ij,q}$ as an intermediate virtual link. (4) $p^{ij,q}_{mn}$: lightpath routing variables. The variable $p^{ij,q}_{mn}$ denotes whether the qth lightpath between node i and j will be routed through fiber link mn.

The ILP formulations without wavelength-continuity constraints are as follows.

Minimize:

$$N_{\text{ch}} = \sum_{i,j,q} CH_{ij,q}. \tag{1}$$

This objective is to minimize the number of lightpath changes from $VT1$ to the new topology $VT2$ when traffic demand changes to current traffic matrix T.

This problem should conform to the following constraints.

Lightpath change constraint:

$$CH_{ij,q} = \begin{cases} VT2_{ij,q} & \text{if } VT1_{ij,q} = 0 \\ 1 - VT2_{ij,q} & \text{if } VT1_{ij,q} = 1 \end{cases} \quad \forall i, j, q. \tag{2}$$

Network performance constraint:

$$\left(\sum_{s,d} T_{sd}\right)^{-1} \sum_{i,j,q} \sum_{s,d} \lambda^{sd}_{ij,q} \leq Optim + \Delta k. \tag{3}$$

The left of expression (3) is APHD of the network. The constraint limits the average packet hop distance of the network in a give bound and guarantees network performance in an acceptable scope. $Optim$ is the objective function value derived by solving the linear formulation proposed in Ref. [1] with the new traffic T routing on physical topology PT. Δk is the variation of performance allowed. It can be altered to observe the relation between Δk and N_{ch}.

Transceiver constraint:

$$\sum_{j,q} V_{ij,q} \leq T_i, \quad \forall i, \tag{4}$$

$$\sum_{i,q} V_{ij,q} \leq T_j, \quad \forall j, \tag{5}$$

$$\text{int } V_{ij,q} \in (0, 1), \quad \forall i, j, q. \tag{6}$$

The above expressions ensure that the number of lightpaths emerging from or terminating at a node is less than or equal to the number of transceivers at that node.

Physical route constraints:

$$\sum_n P^{ij,q}_{mn} - \sum_n P^{ij,q}_{nm} = \begin{cases} V_{ij,q}, & \text{if } i = m \\ -V_{ij,q}, & \text{if } j = m \\ 0, & \text{otherwise} \end{cases} \quad \forall i, j, q, m, \tag{7}$$

$$\sum_{i,j,q} P^{ij,q}_{mn} \leq W \times P_{mn}, \quad \forall m, n, \tag{8}$$

$$\text{int } P^{ij,q}_{mn} \in (0, 1), \quad \forall i, j, m, n, q. \tag{9}$$

The first expression here is to make sure that the lightpaths are routed by conforming to multicommodity-flow theory. The second enforces that there are at most W lightpaths routing on a fiber link. No wavelength continuity constraint is implemented here.

Traffic routing constraints:

$$\sum_{j,q} \lambda^{sd}_{ij,q} - \sum_{j,q} \lambda^{sd}_{ji,q} = \begin{cases} T_{sd}, & \text{if } s = i \\ -T_{sd}, & \text{if } d = i \\ 0, & \text{otherwise} \end{cases} \quad \forall s, d, i, \tag{10}$$

$$\lambda^{sd}_{ij,q} \leq T_{sd} \cdot V_{ij,q}, \quad \forall s, d, i, j, q, \tag{11}$$

$$\sum_{s,d} \lambda^{sd}_{ji,q} \times V_{ij,q} \leq \beta V_{ij,q} C, \quad \forall i, j, q. \tag{12}$$

The above expressions enable the traffic be routed on the virtual topology in a proper way (conforming to multicommodity-flow theory) and specify the capacity constraint in a lightpath.

In all the above expressions, $0 < i, j, m, n, s, d \leq N$ and $0 < q \leq M$.

A six-node seven-link network shown in Fig. 1(a) and used in Ref. [6] is used to demonstrate the numerical results. The parameters are set to $T_x = R_x = W = 2$, $C = 20$, $\beta = 0.8$. The traffic matrix $T1$ is generated with $F = 0.7$, $\gamma = 10$ and $\alpha = 20$. Figure 1(b) shows the traffic matrix $T1$ that imposed on PT. According to method proposed in Ref. [1], to solve the linear formulation for the initial traffic matrix, a virtual topology $VT1$ (as Fig. 1(d)) and APHD value (1.125147) are derived with no wavelength continuity constraints. When traffic demand changes from $T1$ to $T2$ (40% entries interchanged), as shown in Fig. 1(c), APHD value will be 1.528001 by routing $T2$ on $VT1$. Each unit of traffic of $T2$ needs to traverse about 0.40 more hops than that of $T1$.

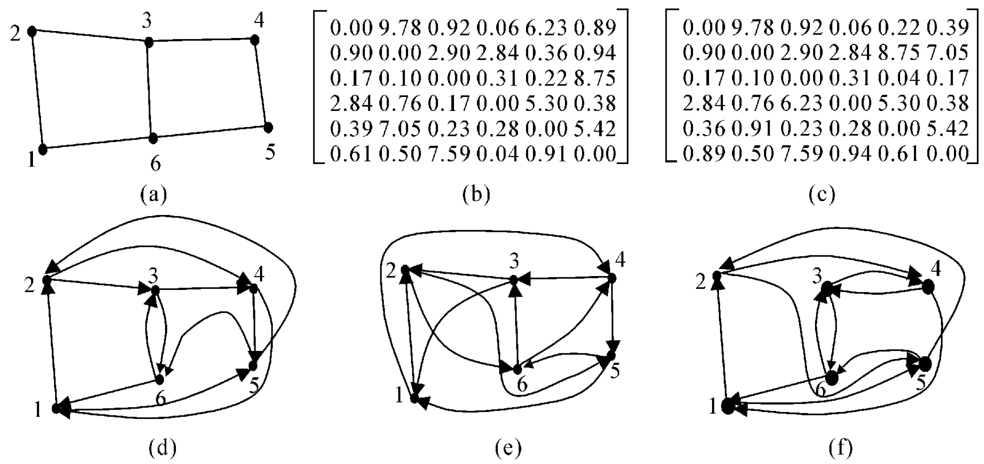

Fig. 1. A simple example. (a) Physical topology; (b) traffic matrix $T1$; (c) traffic matrix $T2$ (derived by 40% traffic variation); (d) $VT1$ for $T1$; (e) $VT2$ for $T2$ (APHD = 1.237176, $N_{\text{ch}} = 16$, $\Delta k = 0$); and (f) $VT2'$ for $T2$ (APHD = 1.347176, $N_{\text{ch}} = 4$, $\Delta k = 0.11$).

To improve the performance of network, we redesign the virtual topology specifically for $T2$. The new virtual topology $VT2$ (as shown in Fig. 1(e)) and APHD value (1.237176, which is the value of *Optim* in expression (3)) can be derived. APHD value is improved by 0.290825 with 8 lightpaths set up and 8 lightpaths torn down. Although network performance is greatly improved, the number of lightpath changes seems to be too large, in which 67% of all lightpaths have been set up or torn down. It will make the total traffic disruption time and implementation cost unacceptable in topology transition period.

To get a tradeoff between the number of changes and network performance, the ILP formulations (1)−(12) are proposed in this paper. By changing Δk in expression (3) by step 0.01, Table 1 is derived. As an example, a virtual topology derived with $\Delta k = 0.11$ is shown in Fig. 1(f) with only two lightpaths set up and another two lightpaths torn down. From Table 1, we can see that when relaxing the network performance constraint (that is, increasing the value of Δk), the number of lightpath changes N_{ch} decreases. So it is meaningful to find out the relationship between N_{ch} and Δk.

To analyze the relationship between N_{ch} and Δk, the following steps are executed to acquire data (25 random traffic matrices are generated for each percent p):

1) Derive the initial virtual topology $VT1$. According to method proposed in Ref. [1], solve the linear formulation for the initial traffic matrix and record the derived virtual topology as $VT1$.

2) Derive the best performance $Optim_i$ for each new traffic matrix i ($1 <= i <= 25$). That is, the virtual topology is fully reconfigured without considering $VT1$. Similar to 1), solve the linear formulation for traffic matrices T_i ($1 <= i <= 25$) and record the objective function value as $Optim_i$.

3) Derive the objective function value $Optim2_i$ with T_i routing on $VT1$ (that is, the original virtual topology must be kept unchanged). It would be done by solving the linear formulations in above with objective function changed to minimize APHD, adding a constraint $N_{\text{ch}} = 0$, and deleting expression (3).

Step 2) and 3) are two extreme cases for virtual topology reconfiguration. The former does not consider the traffic disruption, the latter maintains the initial virtual topology unchanged and just rerouting the traffic on the virtual topology.

4) Varying Δk from 0 to $\Delta \text{APHD}_i = Optim2_i - Optim_i$, a list of N_{ch} values can be obtained.

As performance degrades more when big percent of traffic changes happen, the same Δk value for different p accounts different. So a relative impact of Δk value is analyzed, in which Δk is chosen to be $k \times \Delta \text{APHD}_i/30$, k is an integer and $1 <= k <= 30$. Some results are shown in Figs. 2, 3 and 4.

Figure 2 shows the tradeoff between Δk and N_{ch} (in which k is used instead of Δk for X axis). It can be seen that N_{ch} decreases as expected when increasing Δk. That is, average number of lightpath changes for reconfiguration can be cut down if network performance constraint is relaxed.

Figure 3 shows the relation between N_{ch} and p when Δk is equal to certain different values. It is easy to see that N_{ch} is big when p is equal to or greater than 30% for $\Delta k = 0$. For example, when 40% of traffic variations happen, average 8.21 lightpaths need to be set up or torn down. The higher the percent of traffic changes, the more the number of lightpath changes needed. For each special value of Δk, N_{ch} increases when p increases.

Figure 4 shows N_{ch} reduction in different Δk areas. It can be seen that for any percent of traffic changes, N_{ch} reduction in $\Delta k1$ is greater than that in other areas. In fact, most N_{ch} reductions take place in small areas. So it is more effective to reduce the number of lightpath

Table 1. The Relation Between Δk and the Number of Lightpath Changes N_{ch}

Δk	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07
N_{ch}	16	16	15	13	11	10	9	8
Δk	0.08	0.09	0.10	0.11 − 0.22		0.23 − 0.29		0.30
N_{ch}	8	7	6	4		3		0

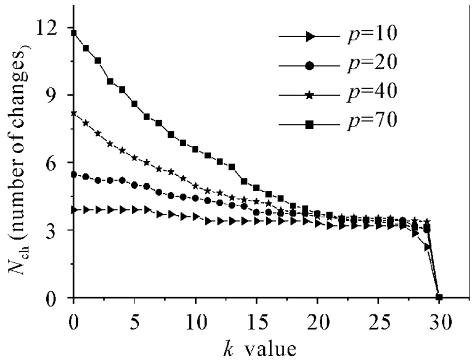

Fig. 2. N_{ch} vs Δk (relative).

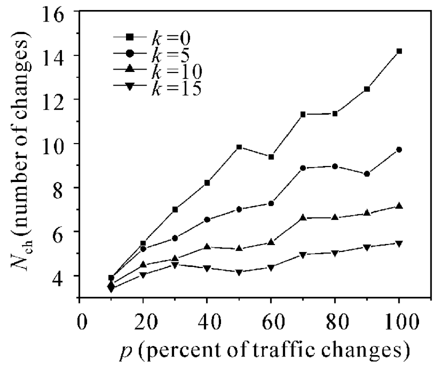

Fig. 3. N_{ch} vs p (relative).

changes in small Δk area than that in big one, and it is possible that a large cost reduction of reconfiguration can be achieved by just giving up a small amount of network performance. In addition, N_{ch} decreases fast for big percent of traffic changes, which illuminates that design of reconfiguration is more effective for big percent of traffic change.

A six-node seven-link network is selected to demonstrate the relationship between the network performance and number of lightpath changes. It is shown that most N_{ch} reductions take place in small value of Δk. That is, by degrading a small amount of network performance, a large cost reduction can be achieved. In addition, the

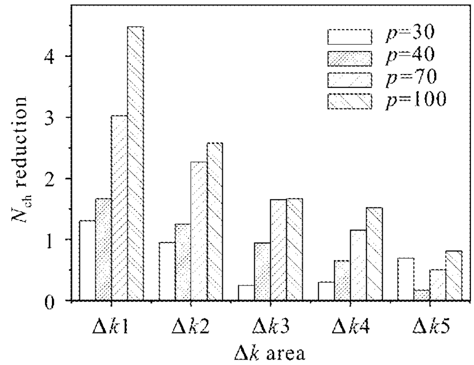

Fig. 4. N_{ch} reduction in different areas. Here Δk_i refers to the area from $k = (i-1) \times 5$ to $i \times 5$. For example, Δk_1 refers to the area from $k = 0$ to 5. And $N_{ch}(\Delta k_i) = N_{ch}((i-1) \times 5) - N_{ch}(i \times 5)$. That is, $N_{ch}(\Delta k_i)$ is the number of reduced lightpath changes when varying k from $(i-1) \times 5$ to $i \times 5$.

number of lightpath changes needed for reconfiguration is also the percent of traffic change related. The number of lightpath changes needed for reconfiguration increases when percent of traffic change increases.

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