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# 다중 파장 광 네트워크 상에서 트래픽 예상 기법 기반 다단계 가상망 재구성 정책

정회원 장 린, 이 경 희, 윤 찬 현*, 심 은 보**

# Traffic Prediction based Multi-Stage Virtual Topology Reconfiguration Policy in Multi-wavelength Routed Optical Networks

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## 요 약

본 논문에서는 광 인터넷 망의 가상망 재구성을 위하여 최적의 망 재구성 정책을 고려한 보상-비용 함수를 최대화하는 다단계 결정 문제로 정의 하였다. 그리고 트래픽 요구사항을 만족하기 위해서 노드 교환 기법에 근거한 새로운 휴리스틱 알고리즘을 제안하였다. 또한 트래픽 예측 기법을 사용하여 휴리스틱 알고리즘에 의해 발생하는 근사 문제를 해결 하고, 이를 바탕으로 트래픽 예측 다단계 재구성 정책을 제안하였다. 실험결과 다단계 재구성 정책은 물리적 자원이 제한된 환경에서 기존의 방법에 비해 뛰어난 성능을 보였다.

## ABSTRACT

This paper studies the issues arising in the virtual topology reconfiguration phase of Multi-wavelength Routed Optical Networks. This reconfiguration process means to change the virtual topology in response to the changing traffic patterns in the higher layer. We formulate the optimal reconfiguration policy as a multi-stage decision-making problem to maximize the expected reward and cost function over an infinite horizon. Then we propose a new heuristic algorithm based on node-exchange to reconfigure the virtual topology to meet the traffic requirement. To counter the continual approximation problem brought by heuristic approach, we take the traffic prediction into consideration. We further propose a new heuristic reconfiguration algorithm called Prediction based Multi-stage Reconfiguration approach to realize the optimal reconfiguration policy based on predicted traffic. Simulation results show that our reconfiguration policy significantly outperforms the conventional one, while the required physical resources are limited.

## I. Introduction

Virtual topology design over a wavelength-routed optical network is intended to combine the best features of optics and electronics. This type of architecture has been called *almost-all-optical,* since traffic is carried from source to destination without electronic switching as far as possible. This

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architecture uses clear channels between nodes, called *lightpaths*, which can carry the information traversing several physical links optically end-to-end. Design of efficient virtual topologies for Optical networks is an important problem that has been addressed by several researchers [1] [7]. However, when the traffic on the network changes, it is vital to transit from one virtual topology to another in an efficient manner to minimize the disruption in the network. This kind of network operation is called *reconfiguration.*

Clearly, this reconfiguration operation should not be very frequent, since unnecessary reconfiguration affects the performance encountered by the users. However, postponing a necessary reconfiguration also has adverse effects on the overall performance. Since the network does not operate at an optimal point, it takes longer to clear traffic demands, causing longer delays and/or buffer overflows [3]. It is important to have a performance criterion that can capture the above tradeoffs in an appropriate manner and allow simultaneous optimization.

In this paper, we identify the reconfiguration as on-line process and it provides a tradeoff between the objective function value and the number of changed lightpaths in the virtual topology. The objective function, which is set to minimize the average hop count, decides how best the virtual topology suited for the coming traffic demand, while the number of changed lightpaths shows the extent of the disruption of the traffic when changing to the new virtual topology. We formulate the traffic matrix and virtual topology as time-related matrix variables, which naturally leading the formulation of this reconfiguration problem as a multi-stage decision-making process, that is, how to reconfigure the network sequentially in time, so as to maximize the expected reward and cost function over an infinite horizon.

The problem of designing virtual topology for a given static traffic demand is computationally intractable [7]. In reconfiguration process, apart from minimizing the objective function, it is also required to consider the number of changed lightpaths. Hence, the problem of reconfiguration is also computationally intractable. That is why we must consider some simple and computationally efficiently heuristic algorithm. We develop a new heuristic algorithm based on node-exchange to reconfigure the virtual topology to meet the traffic requirement. To counter the continual approximation problem brought by heuristic approach, we take the traffic prediction into consideration. We further propose a new heuristic reconfiguration algorithm called Prediction based Multi-stage Reconfiguration approach to realize the optimal reconfiguration policy based on predicted traffic.

The rest of the paper is organized as follows. We introduce the previous work on the design of virtual topology and reconfiguration algorithm proposed so far in section 2. In section 3, we discuss general reconfiguration problem and formulate the multi-stage decision-making reconfiguration policy. In section 4.1, we propose a new heuristic algorithm based on node-exchange scheme to reconfigure the virtual topology in a way to minimize the average packet hop distance, then in section 4.2, we provide a new heuristic algorithm called Prediction based Multi-stage Reconfiguration approach using predicted traffic to counter the continual approximation problem brought by conventional heuristic approach. Finally the numerical results obtained from sample network topology are discussed in section 5. Section 6 presents the conclusions drawn from our work.

## Ⅱ. Previous Works

Reconfiguration in an optical WDM network is the process of rearranging the lightpath connections to optimize the network dynamically. The process of reconfiguration involves tearing down the existing lightpath connections that are no longer necessary, and setting up new ones. The reconfiguration phase involves the transition from the first logical connection graph to the second one. Traditionally reconfiguration of optical networks has been studied in the two different contexts: wavelength-routed networks [1][2] and broadcast optical networks [3].

In [1], the authors provide a mathematical way of finding the best network configuration for the changed traffic demand in a wavelength-routed optical network. The formulation ensures that the new configuration is not too different from the existing configuration, thereby minimizing the number of re-tuning necessary.

In [8], the authors propose a sequence of steps involved in the transition of an optical network from one configuration (virtual topology) to another. And it proposes a minimally disruptive approach that changes the network through a sequence of branch exchange operation, so that only two links are disrupted at any given time. A branch-exchange operation can be defined as the swapping of destination nodes between two source-destination pairs.

## Ⅲ. Reconfiguration Process Formulation

### 1. Problem Description

In this paper, we consider a packet-switched multi-hop WDM network with N nodes, below we will define the parameters used in the problem formulation.

- *s* and *d* used as subscript or superscript denote source and destination of a packet, respectively.
- *i* and *j* denote originating and terminating nodes, respectively, in a light-path.
- *m* and *n* denote endpoints of a physical link that might occur in a light-path.
- Number of nodes in the network is *N*.
- Number of wavelength per fiber is *W*.
- Physical topology matrix P, in which the element $P_{mn}$ denotes the number of fiber links interconnection nodes *m* and *n*.
- Traffic matrix *T(t)*, in which the element $T_{sd}(t)$ denotes the traffic flow from node *s* to node *d* at time *t*.
- Virtual topology *R(t)*, in which the element $R_{sd}(t)$ denotes whether a light-path exists from node *s* to node *d* in the virtual topology at time *t*.
- Traffic routing $\lambda_{ij}^{sd}(R(t),T(t))$, which denotes the traffic flowing between node *i* and node *j* carrying the traffic from source node *s* to destination node *d* under traffic matrix *T(t)* and virtual topology *R(t)*.
- Logical Hops $h_{sd}(R(t))$, which denotes the number of lightpath that make up the route from node s to node d in the virtual topology *R(t)*.
- Virtual degree $\Delta$, denotes the number of light-paths connecting that node to other nodes, constrained by the number of optical transmitters and receivers implemented at each node. We assume this degree to be same for all nodes of the whole network.
- $N_{ch}$ denotes the number of lightpaths added and the number of lightpaths deleted to change from one virtual topology *R(t)* to new virtual topology *R'(t)*.

Since total achievable throughput is a critical performance measure for local and wide area network, a possible design objective should consist of finding the network connectivity and partitioning the flow of traffic among the links created in order to maximize this throughput. We will use the average weighted hop count as the objective function, which is to be minimized. The average weighted hop count is the average number of hops on the virtual topology traversed by a unit of traffic, it is computed as follows,

$$h_{avg}(R(t),T(t)) = \frac{\sum_{s,d} h_{sd}(R(t)) \times T_{sd}(t)}{\sum_{s,d} T_{sd}(t)} \tag{1}$$

Subject to:

Traffic Constraints:

$$\sum_j \lambda_{ij}^{sd}(R(t),T(t)) - \sum_j \lambda_{ji}^{sd}(R(t),T(t)) = \begin{cases} T_{sd}(t) \ \ if \quad s = i; \\ -T_{sd}(t) \ \ if \quad t = i; \ \forall i, j, t \\ \quad 0 \quad otherwise; \end{cases} \tag{2}$$

Degree Constraints:

$$\sum_d R_{sd}(t) \le \Delta, \forall d \tag{3}$$

$$\sum_s R_{sd}(t) \le \Delta, \forall s \tag{4}$$

## 2. Multi-stage Decision-making Reconfiguration Policy

The network status is defined as follows:

[*Definition 1*] Network status is presented as combination of topology and traffic matrix given in network at specific time.

$$\text{Network State::=}(R(t),T(t)). \tag{5}$$

Where *R(t)* is the current virtual topology and *T(t)* is the prevailing traffic matrix. A network in state $(R(t),T(t))$ will enter state $(R(t+\Delta t),T(t+\Delta t))$ if the traffic matrix changes to $T(t+\Delta t)$. Implicit in the state transition is that the system makes a decision to reconfigure to a new virtual topology $R(t+\Delta t)$.

The former hot topic in virtual topology reconfiguration research field is to find this $R(t+\Delta t)$ if given the current virtual topology *R(t)* and the new traffic matrix $T(t+\Delta t)$ under some objective function, such as to decrease the average hop count and the number of changed lightpaths is lower than a predefined threshold. Actually, using heuristic algorithms can always find more than one acceptable results. We define these results into the set of alternative new virtual topology.

[*Definition 2*] The set of alternative possible new virtual topologies is defined as *A*, in which:

$A(t+\Delta t)=\{R(t+\Delta t)\mid$ $R(t+\Delta t)$ is acceptable according to predefined objective function}

If we further give some limit to the size of, $A(t+\Delta t)$, $|A(t+\Delta t)|\leq S$, for some simplicity consideration, so the first *S* near-optimal $R(t+\Delta t)$ will be held in $A(t+\Delta t)$. In order to completely represent the state transitions associated with our model, we need to establish next virtual topology decisions. To formulate this decision problem, we need to specify reward and cost functions according to the time variant *t*.

[*Lemma* 1] If we consider a network in state $(R(t),T(t))$ that takes a transition to state $(R(t+\Delta t),T(t+\Delta t))$, then the expected reward acquired by network is given by,

$$\begin{aligned}&\alpha(R(t),T(t))\\&=\alpha((R(t+\Delta t),T(t+\Delta t)),(R(t),T(t+\Delta t)))\\&=\frac{h_{avg}((R(t),T(t+\Delta t))-h_{avg}(R(t+\Delta t),T(t+\Delta t))}{h_{avg}(R(t),T(t+\Delta t)}\end{aligned}, \tag{6}$$

which means the degree of average hop count decreased by the reconfiguration operation.

*Proof:* As shown in previous part, the average weighted hop count equals to,

$$h_{avg}(R(t),T(t))=\frac{\sum_{sd}h_{sd}(R(t))\times T_{sd}(t)}{\sum_{sd}T_{sd}(t)} \tag{7}$$

If we keep the current topology *R(t)* constant at time $t+\Delta t$, then the average weighted hop count is as below

$$h_{avg}(R(t),T(t+\Delta t)=\frac{\sum_{sd}h_{sd}(R(t))\times T_{sd}(t+\Delta t)}{\sum_{sd}T_{sd}(t+\Delta t)} \tag{8}$$

and else if we take the transition from topology *R(t)* to new topology $R(t+\Delta t)$ at time $t+\Delta t$, then the average weighted hop count is as below

$$h_{avg}(R(t+\Delta t),T(t+\Delta t)=\frac{\sum_{sd}h_{sd}(R(t+\Delta t))\times T_{sd}(t+\Delta t)}{\sum_{sd}T_{sd}(t+\Delta t)} \tag{9}$$

Therefore we can have the reward $h_{avg}(R(t),T(t+\Delta t))-h_{avg}(R(t+\Delta t),T(t+\Delta))$ by reconfiguring the virtual topology *R(t)* to new topology $R(t+\Delta t)$ at time $t+\Delta t$. And to make consideration of rate of change it is divided by average weighted hop count of $(R(t),T(t+\Delta t))$. #

[*Definition 3*] We define the reconfiguration cost as follows:

$\beta(R(t))=\beta(R(t),R(t+\Delta t))=\{$the number of light-paths added + the number of light-paths deleted | $R(t)\rightarrow R(t+\Delta t)$ },

which denotes the number of changed lightpaths from *R(t)* to $R(t+\Delta t)$.

So, the optimal policy to reconfigure the network is to select *R(t)* $(R(t)\in A(t),\forall t)$ according to the changing traffic to reconfigure the network sequentially so as to maximize the expected reward-cost function over an infinite horizon. The formal definition of the reward-cost function exists as follows:

[*Definition 4*] The optimal policy in network reconfiguration problem to select $R(t)$ $(R(t) \in A(t), \forall t)$ is to maximize the expected reward-cost function $F(\cdot)$ over an infinite horizon:

$$F = \max_{R(t) \in A(t)} \left( \int_0^t (a \times \alpha(R(t), T(t)) - b \times \beta(R(t))) dt \right) \qquad (10)$$

where $a$ and $b$ are parameters.

The overall reward-cost function (Eq.10) captures the fundamental tradeoffs in the maximization of network performance of the virtual topology reconfiguration problem over an infinite horizon. The presence of a reward which increases as the average hop count decreases provides the network with an incentive to associate with a new *R(t)* that performs well for the current traffic load. On the other hand, the introduction of a cost incurred at each reconfiguration instant discourages frequent reconfigurations and suggests the network to choose the best possible new *R(t)* to decrease this cost as small as possible. What's more, if we only consider one transition from state $(R(t), T(t))$ to the very next state $(R(t+\Delta t), T(t+\Delta t))$, this continuous-state approaches the discrete-state one, as many papers have considered.

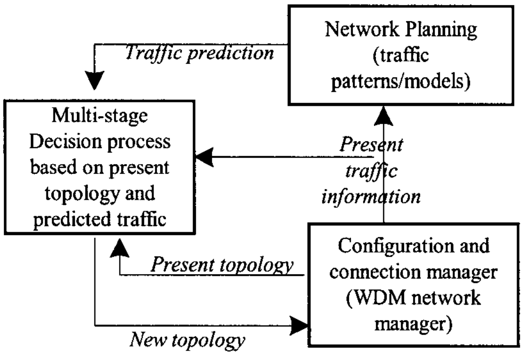


Fig. 31 Flowchart of multistage reconfiguration process

Since former papers did not consider traffic prediction in such reconfiguration policy, it is very difficult to consider how to reconfigure the network sequentially over an infinite horizon. Traffic prediction is known as possible and efficient in the case of multiplexing traffic, such as Internet backbone traffic. Internet traffic analysis has been proven to be efficient and accurate enough to predict the future of Internet backbone traffic. Now if we introduce the Internet traffic analysis, such as Auto-Regressive Moving Average (ARMA) Model [9] model to make some traffic prediction and get some traffic information in advance, we can make a much better reconfiguration policy over a time interval, not only based on one traffic change, as shown in Figure.3-1.

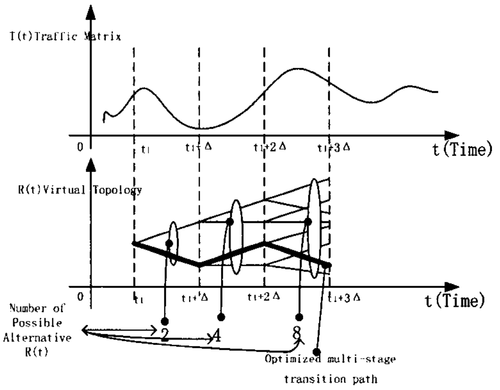


Fig. 32 multi-stage virtual topology reconfiguration process example

Figure 3-2 shows a simple example of the choosing of virtual topology transition path, in which the traffic changes for 4 times $(T(t_1) \rightarrow T(t_1+\Delta) \rightarrow T(t_1+2\Delta) \rightarrow T(t_1+3\Delta))$, and the number of possible new virtual topologies considered at every instance is set to 2 (that is, $|A(t)|=2$). So for $R(t_1+\underline{?}t)$, we have 2 choices, for $R(t_1+2\underline{?}t)$, 4 choices, and for $R(t_1+3\underline{?}t)$, 8 choices. The multi-stage reconfiguration process decides an optimal transition path for *R(t)* $(R(t_1) \rightarrow R(t_1+\Delta) \rightarrow R(t_1+2\Delta) \rightarrow R(t_1+3\Delta))$ according to Eq.10, which is shown as the bold line in Figure 3-2.

## Ⅳ. Heuristic Reconfiguration Approach

### 1. Enhanced Node-Exchange Algorithm

In a virtual topology designed for a particular traffic, if node pairs with high traffic were far apart in the virtual topology in terms of the number of hops, the routed traffic would increase, and the same to the load on links in the virtual topology. Intuitively, it can be seen that reconfiguration should establish lightpath between node pairs that have large traffic in order to reduce the routed traffic and hence the average weighted hop count. And we must consider the cost occurred by tearing down unusable lightpaths and setup new lightpaths for the new virtual topology. For the node pair *(s,d)* which has the largest traffic delay $T_{sd}(t)$, the heuristic approach tries to move node *s* to the neighbor location of node *d* in the new virtual topology or vice versa. This operation may cause the creations of some new lightpaths and deletions of exiting lightpaths. The total number of changed lightpaths is limited by a predefined value. The proposed enhanced node exchange heuristic algorithm is as below.

① For some traffic matrix, initial optimized virtual topology $V_T^{opt}$ is established by using linear programming package.

② $V_T := V_T^{opt}$

③ As traffic changes, decide whether the virtual topology reconfiguration must be done or not according to the reconfiguration policy

④ Sort the node pair in decreasing order of $\lambda_{sd}(R(t),T(t))\times h_{sd}(R(t))$. (=1,2, ... , *N*, (*s*, *d*) is excluded if *s*=*d*, or $h_{sd}(R(t))=1$.)

⑤ validate the node exchange effect with each node pair.

a. incumbent node *x* = *s*, *y*={nodes in neighborhood of node *d*}

*b. x* is moved to the location y, namely, x is exchanged with node in the location y in the virtual topology $V_T$. The new topology $V_T^{'}$ is created by this node exchange.

c. After node swapping, calculate the objective function $F_{obj}$.

i. if it is smaller than current average hop count, $V_T^{'}$ becomes one of candidate virtual topology $V_T$. The incumbent node *x* is node *d*, *y* is set of nodes in neighborhood of node *s*.

ii. else if, all node pairs are validated, Goto 7.

iii. else, target node is next pair created in step 5. Goto number 6.

⑥ Choose the best result $V_T^{'}$ according to the objective function.

⑦ If there are residual transceivers in $V_T^{'}$, try to establish another lightpaths according the ordered node pair list decreasing traffic as many as possible.

⑧ New $V_T := V_T^{'}$.

This Enhanced Node-Exchange method is also used in multi-stage reconfiguration approach as basic scheme in the following.

### 2. Prediction-based Multi-stage Reconfiguration Approach

Conventional heuristic approaches have the inherent drawback of continual approximation. This may lead to an increase or decrease in the difference between the theoretical optimal solution and the current solution, as approximations are applied every time. Whether the difference increases or decreases is very difficult to determine. To take care of this, traffic prediction is introduced to compensate for this continual approximation in this study.

In this section, we present a heuristic algorithm that realizes the multi-stage decision-making process, which tries to counter the continual approximation by using predicted traffic. Consider a network with *N* nodes and $\Delta_l$ transceivers and a multi-stage reconfiguration process with parameter *S* and *m* where *m* is the number of possible traffic prediction stages and *S* is the size of $A(t+\Delta t)$ at each stage and $S \le N\Delta_l$. Then we can get an optimized transition path and policy to reconfigure the wavelength routed network as follows.We assume that the traffic matrix specifying the traffic between each pair of nodes at a specific time is given by the mentioned traffic predictor. We will only consider discrete case for the simplicity in this simulation phase, that is, if current network state is $(R(t_1),T(t_1))$, and Internet traffic analysis provides the future traffic change as $(T(t_1)\rightarrow T(t_1+\Delta)\rightarrow\cdots\rightarrow T(t_1+m\Delta)$.

**[Theorem 1]**

For a limited number of traffic matrix changes, $(T(t_1)\rightarrow T(t_1+\Delta)\rightarrow\cdots\rightarrow T(t_1+m\Delta)$, there exists an optimized transition path for *R(t)*, that is, $R(t_1)\rightarrow R(t_1+\Delta)\rightarrow\cdots\rightarrow R(t_1+m\Delta)$, according to the expected reward-cost function (Eq. (10)), and the size of alternative possible transition path for *R(t)* is also limited by $(N\Delta_l)^m$. Therefore the multi-stage decision reconfiguration policy improves the probability to reconfigure to the optimized virtual topology from $\left(\frac{1}{N\Delta_l}\right)^m$ to $\left(\frac{S}{N\Delta_l}\right)^m$ compared to the single-stage reconfiguration.

*Proof*: From Definition 4, the expected reward-cost function can be expressed in the following for easiness:

$$F(g)=\max_{R(t)\in A(t)}\left(\int_t^{t+\Delta t}(\alpha(R(t),T(t))-\frac{b}{a}\times\beta(R(t)))dt\right) \quad (11)$$

Since *a* and *b* are integer parameters, we have $0\le\frac{b}{a}\le+\infty$.

So if $\frac{b}{a}=+\infty$, which means that any change to the existing virtual topology brings unacceptable cost for the networks. Under a such parameter setting, the transition path for *R(t)* will be the initial virtual topology according to the initial traffic; on the other hand, if $\frac{b}{a}=0$, which means it is free to change the lightpath to get a better fitness for the changing traffic. Under such circumstance, the transition path for *R(t)* will be the virtual topology results from the existing virtual topology design method. So the upper bound for the transition path for *R(t)* under changing traffic is that *R(t)* is set to the results from virtual topology design method at every instance, while the lower bound is that *R(t)* is kept constant as the initial virtual topology for all traffic changes. Since the lower and upper bound for the transition path for *R(t)* exist, an optimized transition path for *R(t)* under other parameter setting also exists.

According to the network settings, a network with *N* nodes and $\Delta_l$ transceivers at most has $N\Delta_l$ links, so there exist at most $N\Delta_l$ alternative possible new virtual topologies for one instance of traffic change, so totally the size of alternative possible transition path for *R(t)* is also limited by $(N\Delta_l)^m$.

The appearance of the optimized transition for *R(t)* is assumed to be random with uniform distribution among the set of alternative possible transition path. So the probability to get the optimized transition path under single-stage reconfiguration equals to $\left(\frac{1}{N\Delta_l}\right)^m$.

According to our multi-stage decision-making reconfiguration policy, each virtual topology by result of each reconfiguration instant can effect to the performance of next reconfiguration process. The reason is that one reconfiguration process limits the possible next virtual topology set $A(t+\Delta t)$ and decides one operating virtual topology $R(t+\Delta t)$ that will work during the next time scale $t+\Delta t$. The selected virtual topology $R(t+\Delta t)$ affect $A(t+2\Delta t)$ also, therefore one virtual topology design is affected by the previous virtual topology and affect next all virtual topologies successively. The different current virtual topology $R_1(t)$ and $R_2(t)$ makes different next virtual topology set $A_1(t+\Delta t)$ and $A_2(t+\Delta t)$ respectively, and each topology set is no larger than *m*. Therefore the number of all possible virtual topology selection paths is at most $S^m$ through the entire reconfiguration process. So the multi-stage decision-making reconfiguration policy has a higher probability to get the optimized one since it has a larger search space, whose size equals $S^m$, and the probability to get the optimized transition path equals to $\left(\frac{S}{N\Delta_l}\right)^m$. Therefore the multi-stage decision reconfiguration policy improves the probability to reconfigure to the optimized virtual topology from $\left(\frac{1}{N\Delta_l}\right)^m$ to $\left(\frac{S}{N\Delta_l}\right)^m$ compared to the single-stage reconfiguration. (Q.E.D.)

According to the theorem 1, it has larger number of candidate virtual topology by traffic prediction multi-stage reconfiguration than without traffic prediction reconfiguration. It means that reconfiguration can be done in a way to the more traffic adaptive way.

We first produce the set of alternative possible new virtual topology set $A(t+\Delta)$ by Enhanced Node exchange scheme. Then we use the traffic matrix provided by predictor as input. We will only consider discrete case for the simplicity in this simulation phase, that is, if current network state is $(R(t_1),T(t_1))$, and Internet traffic analysis provides the future traffic change as $(T(t_1)\rightarrow T(t_1+\Delta)\rightarrow \mathrm{L}$ $\rightarrow \mathrm{L}\ \rightarrow T(t_1+m\Delta)$. And we further set the upper limit of the size of $A(t+\Delta)$ equals to $S$ where $S$ and $m$ are integer constants. The heuristic algorithm below tries to find the transition paths for *R(t)* ccording to the multi-stage reconfiguration policy F(*?*) (Eq.10).

*Step1.* For every traffic change from $T(t)\rightarrow T(t+\Delta)$, find the most $S$ near-optimal next virtual topology $R(t+\Delta)$; save these $R(t+\Delta)$ to ; $A(t+\Delta)$ record the transition path $R(t)\rightarrow R(t+\Delta)$:

1) Sort the node pair (*s*, *d*) in decreasing order of $\lambda_{sd}(R(t),T(t))\times h_{sd}(R(t))$. (*s*, *d*=1,2... *N*, (*s*, *d*) is excluded if $s=d$, or $h_{sd}(R(t))=1$.)

2) validate the node exchange effect with each node pair.

a. incumbent node $x = S$, $y$={nodes in neighborhood of node *d*}

*b.* $x$ is moved to the location y, namely, x is exchanged with node in the location y in the virtual topology *R(t)*. The new topology $R(t+\Delta)$ is created by this node exchange.

c. After node exchange operation, calculate the average hop count under $R(t+\Delta)$ and $T(t+\Delta)$:

i. if it is smaller than current average hop count, $R(t+\Delta)$ becomes one of candidate next virtual topology. The incumbent node $x$ is node *d*, *y* is set of nodes in neighborhood of node *s*.

ii. else if, all node pairs are validated, Goto 3).

iii. else, target node is next pair created in 1).

3) If there are still free transceivers in $R(t+\Delta)$, try to establish more lightpaths according to the ordered node pair list as many as possible.

4) Sort $R(t+\Delta)$ in decreasing order of the number of changed lightpath.

5) Save the first $S$ near optimal $R(t+\Delta)$ to $A(t+\Delta)$; record the transition path.

*Step2.* for every elements in $A(t+\Delta)$, repeat the *step 1.*

*Step3.* m=m-1, If *m*=0, continue; otherwise, go to *step 2.*

*Step4.* calculate the reward-cost function of all possible transition paths saved as $R(t_1)\rightarrow R(t_1+\Delta)\rightarrow \mathrm{L}\ \rightarrow R(t_1+m\Delta)$ (at most $S^m$); choose the maximum benefit path as the optimal transition path.

## V. Simulation Results and Discussions

In this section, we compare our proposed approaches with the Path-add heuristic implemented in [6] by simulation results. As mentioned previously, we consider the wavelength-routed optical networks as the network model. And we assume each lightpath is unidirectional channel. Simulation model is 14-node NSFNET described in Figure 5-1. The number of node, N, equals to 14, and the number of transmitters and receivers at each node is set to 5. And wavelength constraint is considered with various values. Wavelength conversion is not permitted at any node. The traffic model we used is the same with that in [6]. The number of different traffic used in the simulation is set to 50.

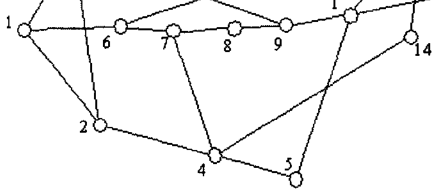


Fig. 5-1 14-node NSFNET T1 backbone network topology

### 1. Enhanced Node-Exchange Reconfiguration Scheme

As it was discussed before, Enhanced Node-Exchange scheme induces relatively many lightpaths changes. So, in this network model, it is almost impossible to reconfigure the network if the number of changing lightpaths is set as low as twice of the number of transceivers at each node. Therefore we perform the simulation with the limit of changed lightpaths 20.

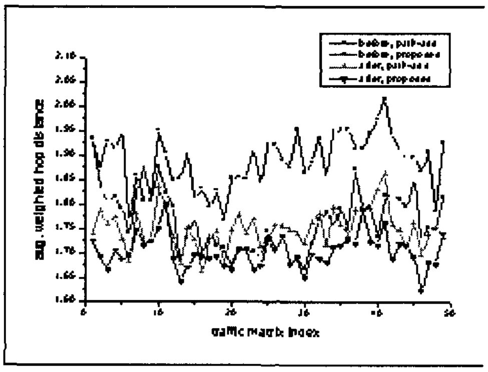


Fig. 5-2 Change of average hop count with traffic matrix change when W=10, $N_{ch\_lim}$=20

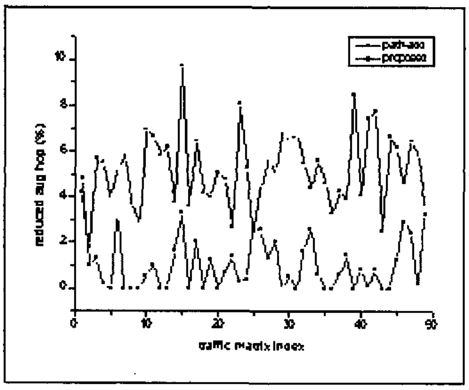


Fig. 5-3 Performance improvement by average hop count decrease when W=10, $N_{ch\_lim}$=20

Figure 5-2 shows the average weighted hop count when traffic changes under our Enhanced Node-Exchange scheme and the Path-add heuristic. From the results we can find that the Path-add heuristic shows the largest perturbation when traffic changes. The reason is that Path-add heuristic focuses new lightpath establishment only to most high traffic at one point. Therefore it can reduce the average weighted hop count a lot, but if traffic changes overall, its performance deterioration is remarkable large. Contrastively, our proposed Enhanced Node-Exchange shows the relatively low perturbation.

While 50 classes of traffic matrix changes, the average of $h_{avg}$ of Path-add heuristic and Enhanced Node-Exchange scheme is 1.7376, 1.6380 respectively. It is remarkable that our Enhanced Node-Exchange keeps the average weighted hop count very low, although it fails 16 times to reconfigure the virtual topology with given constraints and be left constant with the former one, which is shown in the Figure 5-3. It means that the created virtual topology by our Enhanced Node-Exchange scheme is relatively stable according to the traffic changes compared with path-add heuristic.

Table 5-1 shows the information about the traffic load on lightpaths. Path-add heuristic could not guarantee the usage of the transceivers that the network node has, while our Enhanced Node-Exchange scheme tries to establish more lightpaths with free transceivers. Therefore the usage of transceiver in Path-add heuristic is always less then the usage under our Enhanced Node-Exchange scheme. It results the heavier average traffic load compared with our scheme.

When the limit of changed lightpaths is relatively large ($N_{ch}$=60) and the number of available wavelength is relatively small (W=5), the performance comparison is presented in Figure 5-4 and Figure 5-5, respectively. Simulation results show that although in such environment, reconfiguration happens less frequently under Enhanced Node-

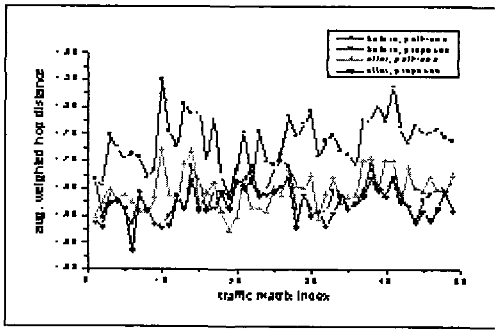


Fig. 5-4 Variation of average hop count with traffic matrix change when W=5, $N_{ch\_lim}$=60

Table 5-1. Comparison of network performance with reconfiguration, while traffic pattern varies 50 times

| constraint | | | proposed algorithm | path-add heuristic |
|---|---|---|---|---|
| W=10<br>$N_{ch\_lim}$=20 | Average of number of total lightpath | | 67.7755 | 58.3673 |
| | Average percentage of transceiver utilization | | 96.82% | 83.38% |
| | Average number of changed lightpath | | 14.0909 | 19.8367 |
| | $h_{avg}$ | before | 1.63801 | 1.73760 |
| | | after | 1.62091 | 1.64684 |
| | Variation of $h_{avg}$ change | | 0.000945 | 0.002231 |
| W=10<br>$N_{ch\_lim}$=40 | Average number of total lightpath | | 68.0204 | 61.1020 |
| | Average percentage of transceiver utilization | | 97.17% | 87.29% |
| | Average number of changed lightpath | | 34.73469 | 37.06122 |
| | $h_{avg}$ | before | 1.637551 | 1.701807 |
| | | after | 1.582974 | 1.581302 |
| | Variation of $h_{avg}$ change | | 0.000959 | 0.002079 |

Exchange because of wavelength constraint, our scheme shows the better performance than the Path-add heuristic, as shown in Figure 5-4. Above all, our Enhanced Node-Exchange algorithm gets benefits by shuffling the topology with same change limit compared with Path-add heuristic.

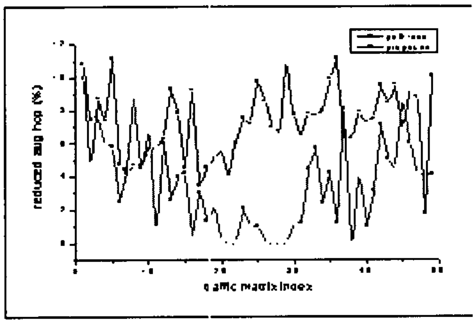
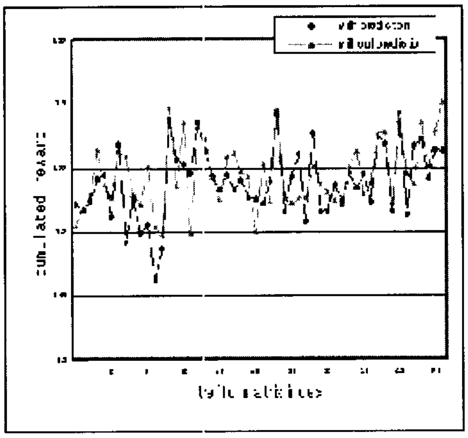
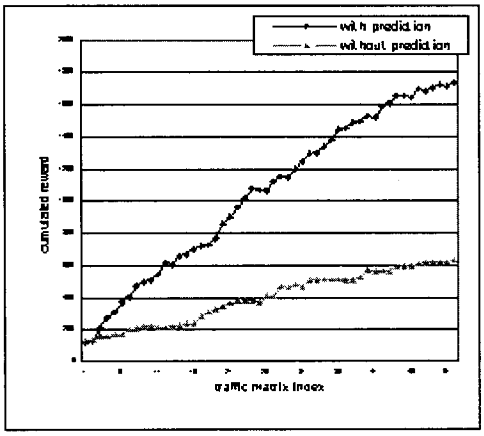


Fig. 5-5 Performance improvement by average hop count decrease when W=5, $N_{ch\_lim}$=60



(a)



(b)

Fig. 5-6 Comparison of performance where $a$=1500, $b$=1, $s$=3, $m$=4. (a) average weighted hop count ; (b) cumulated reward

## 2. Multi-stage Reconfiguration Heuristic

In this section, we demonstrate the properties of the optimal policies realized by Prediction-based Multi-stage Reconfiguration Approach proposed in section 4.2. We also compare the long-term reward acquired by the network when this optimal policy is employed with the reward acquired by Path-add heuristic. The settings of parameters in heuristic algorithm are as follows, the reward parameter $a$ is set to 1500, and the cost parameter $b$ is set to 1.

Figure 5-6 (a) and (b) provide the performance comparison between our Prediction-based Multi-stage Reconfiguration Approach and the Path-add heuristic according to average hop count and cumulated reward criterion when the prediction stage $m$ is set to 4. From Figure 5-6 (a) we can find that although the criterion average hop count is not considered separately in the reward-cost function of our proposed algorithm, our algorithm gets a very good performance compared to the Path-add heuristic. During the simulation results, in 86% of 50 cases our algorithm produces lower average hop count. Figure 5-6 (b) shows the cumulated reward comparison. Since the proposed algorithm tries to maximize the reward-cost function for multi-stage, it gets some worse results in the first 2 traffic change stages. But from the number 3 traffic change stage, our proposed algorithm produces a better performance, and as time goes on, the results shows much better performance.

## Ⅳ. Conclusion

Virtual topology reconfiguration is recently a hot topic in Optical Internet network management. The objective of virtual topology reconfiguration is to improve the network performance by satisfying the time-variant incoming traffic with the most suitable virtual topology in optical Internet. We formulate the reconfiguration problem as a multi-stage decision-making problem to maximize the expected reward and cost function over an infinite horizon. Then we propose a new heuristic algorithm called Enhanced Node-Exchange to reconfigure the virtual topology in a way to minimize the average packet hop distance. To counter the continual approximation problem brought by heuristic approach, we further propose a new heuristic reconfiguration algorithm called Prediction based Multi-stage Reconfiguration approach to realize the optimal reconfiguration policy based on predicted traffic. Finally, using simulation, we have quantified the benefits and effectiveness of the proposed approaches in terms of important performance measures such as average hop count and cumulated reward. Simulation results show that our algorithms significantly outperform the conventional reconfiguration approach, while the required physical resources are limited. The convergence and the complexity property of our reconfiguration algorithm are currently under investigation. To extend our proposed approach into Optical Virtual Private Network (OVPN) can be addressed in future research.

## Acknowledgement

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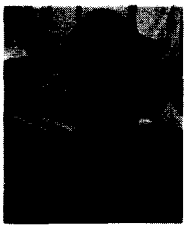

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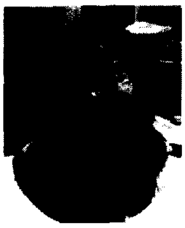

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