다단계 재구성 가능한 광 네트워크상에서 가상 토폴로지 관리 정책

(A Virtual Topology Management Policy in Multi-Stage Reconfigurable Optical Networks)

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요 약 본 논문에서는 광 인터넷의 가상 토폴로지 재구성을 효과적으로 관리하는 정책을 제시한다. 기존의 휴리스틱 기법의 근사 문제를 해결하기 위해 트래픽 예측 기반 다단계 재구성 알고리즘을 바탕으로 트래픽 패턴과 망 혼잡 정도 의 변화에 따라 적응적인 토폴로지 재구성 기법을 제시한다. 이 알고리즘은 네트워크의 상태를 고려하여 적정 재구성 시기를 결정함으로써 가상망의 관리를 단순화 한다. 시뮬레이션 결과, 제안된 가상망 관리 정책이 물리적인 자원 사용이 제한될 때 기존의 방법에 비해 좋은 성능을 보인다.

키워드 : 광 인터넷, 파장 분할 다중 방식, 망관리 정책, 네트워크 관리 정책 성능 분석

Abstract In this paper, we develop an analytical model to evaluate the virtual topology reconfiguration phase of optical Internet networks. To counter the continual approximation problem brought by traditional heuristic approach, we take the traffic prediction into consideration and propose a new heuristic reconfiguration algorithm called Prediction based Multi-stage Reconfiguration approach. We then use this analytical model to study the different configuration operation policies in response to the changing traffic patterns in the higher layer and the congestion level on the virtual topology. This algorithm persists to decide the optimal instant of reconfiguration easily based on the network state. Simulation results show that our virtual topology management policy significantly outperforms the conventional one, while the required physical resources are limited.

Key words : WDM networks, Reconfiguration Policy, Network Management, Performance Analysis

1. 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 architecture uses clear channels between nodes, called *lightpaths*, which can carry the information traversing several physical links optically end-to-end.

Designing of efficient virtual topologies for Optical Internet networks is an important problem that has been addressed by several researchers [1]. The initial *call setup phase* is a static optimization problem where the network capacity is optimized, given the physical topology and a traffic matrix to be provisioned on the network. However, when the traffic amount 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. We call this phase as the *virtual topology reconfiguration phase*. Clearly, this

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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 [2, 3]. It is important to have a performance criterion that can capture the above tradeoffs in an appropriate manner and allow simultaneous optimization.

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. Some former proposed reconfiguration algorithms [4, 5] use a heuristic method to recover this. The possible problem of former proposed reconfiguration algorithms is that the former ones has to make decision on every traffic change, and since they have no knowledge about the future traffic, the optimization operation can only be done under past and current traffic, which result in possible unnecessary and inefficient reconfiguration operations. And the heuristic algorithm implemented by these former ones will also bring in a continual approximation problem, which will make the results further worse.

In this paper, we identify the average hop count and the number of changed lightpaths as two important objectives in the design of reconfiguration policies. As time-related matrix variables we consider the traffic matrix and virtual topology which naturally lead the formulation of this reconfiguration problem as a multi-stage decision-making problem. This problem is how to reconfigure the network sequentially in time, so as to maximize the expected reward and cost function over an infinite horizon.

The above optimization problem can also be treated as a static formulation that optimizes the network performance for the complete demand set, which includes the current working demands and the new demands. This treatment provides the best physical resource usage, but all the current connections maybe disrupted, which should be done only at the instance when the network capacity utilization degrades to an unacceptable point. We call this phase as the *virtual topology new-design phase.*

N. Sreenath, etc in [6] proposed a two-stage approach for this reconfiguration problem in which a reconfiguration stage and a new design stage are considered. We think this kind of definition is not so reasonable, because the reconfiguration and new-design are different network management operations, that is why we use "*phase*" instead of "*stage*" in this paper. We also introduce a simple threshold to divide these two different phases. What's more, a multi stage decision making solution is implemented during virtual topology reconfiguration phase.

To the best of our knowledge, none of the existing methods captures these network operational phases and relevant performance criterion in an appropriate manner in the problem formulation. Moreover, we must consider the fact that in the IP over WDM context, the routing strategy is assigned as a '*priori*', not a variable of the problem. This key observation led us to the optimization of the logical topology design problem, assuming that the IP routing algorithm is fixed. In this paper, we chose the shortest path routing.

The rest of the paper is organized as follows: in the next section we describe our network model and assumptions, then we formulate the multi stage decision-making reconfiguration process. In section 3, we provide a new heuristic algorithm to realize the optimal configuration policy proposed in former section and then use it to study the different configuration operation policies mentioned before. Finally the numerical results obtained from sample network topology are discussed in section 4. Section 5 presents the conclusions drawn from our work.

2. Reconfiguration Process Formulation

2.1 problem description

Let's consider a packet-switched multi hop WDM network, and assume that the traffic matrix specifying the traffic between each pair of nodes at any specific time is given. Below we define the traffic matrix and virtual topology as time-related matrix variables, and other criterion 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.
- Traffic matrix T(t), in which the item $T_{sd}(t)$ denotes the traffic flow from node s to node d at time t.
- Virtual topology R(t), in which the item $R_{sd}(t)$ describes 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 stands for 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).
- Physical Hops $h_{s,d}(R(t))$, which symbolizes the number of physical links that make up the light-path from node s to node d with virtual topology R(t).
- Virtual degree , which denotes the number of light-paths connecting one 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.

Since total achievable throughput is a critical performance criterion 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 unit traffic, it is computed as follows,

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

which is subject to the following constraints:

- Degree Constraints:

$$\sum_{d} R_{sd}(t) \leq \Delta, \forall d \qquad (2)$$

$$\sum_{s} R_{sd}(t) \leq \Delta, \forall s \qquad (3)$$

- Traffic Constraints:

$$\sum_{j} \lambda_{ij}^{sd}(R(t), t(t)) - \sum_{j} \lambda_{ji}^{sd}(R(t), T(t))$$

$$= \begin{cases} T_{sd}(t) & \text{if} \quad s = i; \\ -T_{sd}(t) & \text{if} \quad t = i; \forall i, s, t, \\ 0 & otherwise; \end{cases} \qquad (4)$$

2.2 Multi-stage Decision-making Process Formulation

According to the former parameters, we can define the state of the network as follows:

[Definition 1] Network State::=$(R(t), T(t))$ (5)

Where $R(t), T(t))$ 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 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.

[Definition 2]

The set of alternative possible new virtual topologies is defined as A, in which: $A(t+\Delta t)$={$R(t+\Delta t)$ is acceptable according to predefined objective function} (6)

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 , then the expected reward acquired by network is given by,

$$a((R(t+\triangle t), T(t+\Delta t)), (R(t), T(t+\Delta t)))$$

$$= \frac{h_{avg}(R(t), T(t+\Delta t)) - h_{avg}(R(t+\Delta t), T(t+\Delta t))}{h_{avg}(R(t), T(t+\Delta t))}, \qquad (7)$$

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,

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

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

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

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

$$h_{avg}(R(t+\Delta t),\ T(t+\Delta t)) = \frac{\sum_{sd} h_{sd}(R(t+\Delta t)) \times T_{sd}(t+\Delta t)}{\sum_{sd} T_{sd}(t+\Delta t)}, \tag{10}$$

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 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:

$\beta(R(t), R(t+\Delta t))$ = {the number of light-paths added + the number of lightpaths deleted | $R(t) \rightarrow R(t+\Delta t)$}, (11)

which denotes the number of changed light-paths from $R(t)$ to $R(t+\Delta t)$.

Let Z represent the set of admissible policies. The optimal policy to reconfigure the network sequentially in time exists as follows:

[Lemma 2] The optimal policy $z^* \in Z$ 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:

$$F = \max_{R(t) \in A(t)} \left(\int_t^{t+\Delta t} (a(R(t),\ T(t)) - \mu \times \beta(R(t)))dt \right) \tag{12}$$

where μ are parameters.

Proof: The first term(i.e. lemma 1, equation (7)) in the right hand of Equation (12) is the reward obtained by using a particular R(t), and the second term(i.e. equation (11) in the definition 3,) is the cost incurred at each instant of time that reconfiguration is performed. 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. Thus, the overall reward-cost function captures the fundamental tradeoffs in the maximization of network performance of the virtual topology reconfiguration problem over an infinite horizon.

Internet traffic analysis has been proven to be efficient and accurate enough to predict the future of Internet backbone traffic. By introducing the Internet traffic analysis, such as Auto-Regressive Moving Average (ARMA) Model [7] 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.

3. Heuristic Virtual Topology Management Approach

3.1 Prediction-based Multi-stage Heuristic Reconfiguration Approach

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 determined. 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.

Consider a network with N nodes and Δ_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 $S \leq N\Delta_l$.

Then we can get an optimized transition path and policy to reconfigure the wavelength routed network as follows.

[Theorem 1] For a limited number of traffic matrix changes, $(T(t_1)\rightarrow T(t_1+\varDelta) \to \sqcap \to T(t_1+m\varDelta))$, there exists an optimized transition path for $R(t)$, that is,, $R(t_{1)} \to R(t_1+\varDelta) \to \sqcap \to R(t_1+m\varDelta)$, according to the expected reward-cost function (Equation (12)), and the size of alternative possible transition path for R(t) is also limited by $(N\varDelta_1)^m$. Therefore the multi-stage decision reconfiguration policy improves the probability to reconfigure to the optimized virtual topology from $\left(\frac{1}{N\varDelta_1}\right)^m$ to $\left(\frac{S}{N\varDelta_1}\right)^m$ compared to the single-stage reconfiguration.

Proof:

From Equation (12), since $\varDelta$ is integer parameters, we have $0 \leq \varDelta \leq +\infty$. So if $\varDelta = +\infty$, 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 $\varDelta = 0$, 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 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 $\varDelta_l$ transceivers at most has $N\varDelta_l$ links, so there exist at most 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 $(N\varDelta_l)^m$

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 $\left(\frac{1}{N\triangle_1}\right)^m$.

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 $A(t+\varDelta t)$ and decides one operating virtual topology that will work during the next time scale . The selected virtual topology $R(t+\varDelta t)$ affect $A(t+2\varDelta t)$ 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 $A_1(t+\varDelta t)$ and $A_2(t+\varDelta t)$ 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 $\left(\frac{S}{N\varDelta_1}\right)^m$. Therefore the multi-stage decision reconfiguration policy improves the probability to reconfigure to the optimized virtual topology from $\left(\frac{1}{N\varDelta_1}\right)$ to $\left(\frac{S}{N\varDelta_1}\right)$ compared to the single-stage reconfiguration. (Q.E.D.)

Fig.1 shows a simple example of the choosing of virtual topology transition path, in which the parameters m equals to 3 and S equals to 2. The chosen transition path for virtual topology is shown as the bold line in Fig. 1.

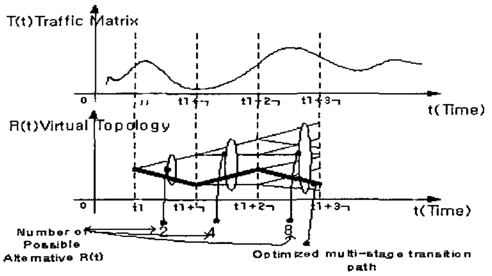

Fig. 1 Multi-stage decision-making process of the proposed algorithm

3.2 State-based Virtual Topology Management Heuristic

When the virtual topology reconfiguration problem is solved, we will now mention the virtual topology management question, that is when to reconfigure the virtual topology and when such reconfiguration operation could not improve the network performance efficiently. In this part, we will use the maximum congestion level in the network as the network performance criterion, which is computed as follows,

$$\int \max(t) = \frac{\max_{i,j}\sum_{s,d}\gamma_{ij}^{sd}(R(t),\, T(t))}{C \cdot W}, \tag{13}$$

We further use this maximum congestion level to define the thresholds between different network phases. The threshold between the *call setup phase and the logical topology reconfiguration phase* is called f_{max_LT}, while the threshold between the logical topology reconfiguration phase and the logical topology redesign phase is called $f_{max\ HT}$. Since $f_{max}(t) \in [0,1]$, then we have $0 < f_{max\ LT} \le f_{max\ HT} < 1$. So the next virtual topology operation decision can be denoted as a function of the network state $(R(t), T(t))$ and the congestion level $f_{max}(t)$ as follows,

- If $f_{max}(t)$ the is not bigger than $f_{max\ LT}$,, we think the existing logical topology is still fit for the new traffic, logical topology need not any change.
- If $f_{max}(t)$ is now bigger than $f_{max\ LT}$ but still smaller than f max_HT,, it shows that the network performance degrades to some extent that logical topology reconfiguration is needed.
- If $f_{max}(t)$is bigger than $f_{max\ HT}$,, the network capacity utilization degrades to an unacceptable point that a logical topology redesign phase is needed.

In order to get the satisfied confidence level to guarantee credence of the threshold value, we apply the 90% statistical confidence level formulation for the decision interval of $f_{max\ LT}$ and $f_{max\ HT}$.

$$Th_{\max} \pm 1.645\left(\frac{\alpha}{\sqrt{n}}\right), \tag{14}$$

Where $Th_{\max}$ is the point that indicates the maximum reward-cost function value and is the standard deviation of the obtained reward-cost function value by verifying the threshold, n is the number of comparing the thresholds.

To decide the virtual topology management operation with obtained congestion level thresholds by using the above method, our proposed heuristic algorithm is as follows,

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

Step 2: $V_r = V_T^{opt}$

Step 3: As traffic changes, calculate f max(t)

1. If $f_{max}(t) \le f_{max\ LT}$, then go to step 4
2. If $f_{max\ LT} < f_{max\ HT}$, then go to step 5
3. If $f_{max}(t) > f_{max\ HT}$, then go to step 6

Step 4: Keep the current virtual topology

Step 5: Reconfigure the virtual topology adopting new traffic matrix by Prediction-based Multi-stage Heuristic Reconfiguration Approach.

Step 6: Redesign a logical topology according to the current traffic matrix by using linear programming package.

4. Simulation Results

In this section, the performance of the proposed Heuristic approaches is studied by simulation results. The simulation model is wide-area Internet backbone with 14 nodes. So the number of nodes in simulation is 14, and the number of transmitters and receivers in every node is set to 5. The number of different traffic used in the simulation is set to 50.

Fig.2 and Fig.3 provide the performance

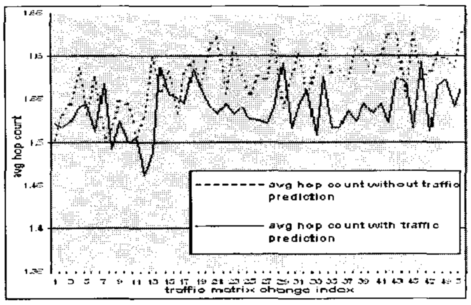

Fig. 2 Average Hop Count Comparison with and without prediction(prediction stage 4)

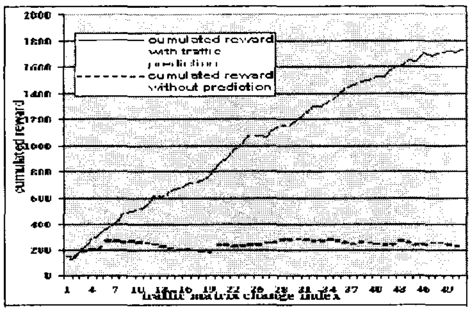

Fig. 3 Cumulated Reward Comparison with and without prediction(prediction stage-4)

comparison between our proposed Prediction-based Multi-stage Heuristic Reconfiguration Approach and a *former reconfiguration algorithm* [6] according to average hop count and cumulated reward criterion. Fig.2 shows the average hop count comparison between the traffic prediction case and the former algorithm without prediction. The prediction stage is set to 4. From this figure 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 old one. From the simulation results, in 86% of 50 cases our algorithm produces lower average hop count Fig.3 shows the cumulated reward comparison under the traffic prediction case and the old algorithm. Since the proposed algorithm tries to maximize the reward cost function for multi-stage, it shows 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.

Our algorithm does show a little complex in computation than others because our algorithm has to compute several times in order to decide the target network topology. But according to the overall complexity, we think our prediction-based multi-stage can save the total work, because the *management decision is based on cumulated* reward cost function, our algorithm can avoid the unnecessary reconfiguration and make the current reconfiguration operation based on future traffic changes. What's more, our simulation does show that the number of this multi-stage computation is also limited; the simulation can result in an acceptable result if this number only be set to 4.

Fig.4 shows the determination process of the congestion level thresholds that decide the different virtual topology management operations. According to the simulation results, the 90% confident interval

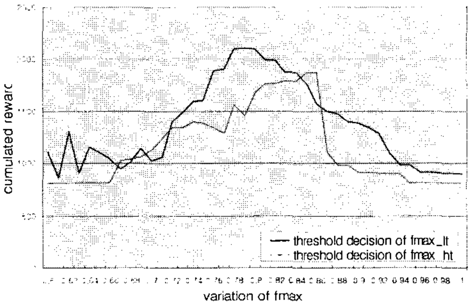

Fig. 4 Determination Process of fmax threshold

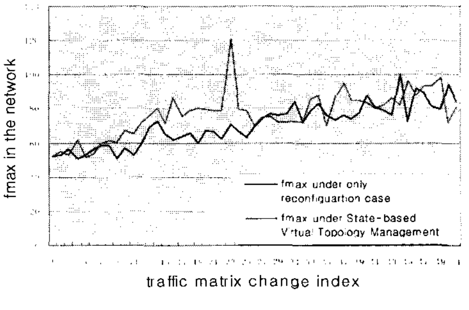

Fig. 5 Congestion Level Comparison under different heuristic approach

of f_{max_LT} and f_{max_HT} can be obtained as some value in [0.78,0.80] and [0.83,0.86] respectively. In our simulations, we choose the value of f_{max_LT} as 0.79 and the value of f_{max_HT} as 0.85. Fig.5 shows the congestion level comparison under the Prediction-based Multi-stage Heuristic Reconfiguration Approach and the State-based Virtual Topology Management Heuristic. Since the latter one introduces different operations according to the congestion level in the network, it improves the network performance more efficiently compared to the reconfiguration only approach. During the simulation results, in 84% of 50 cases our algorithm produces lower congestion level which means it shows stable performance compared with the other case.

5. Conclusion

This paper studies the issues arising in the logical topology configuration management of optical Internet networks. This configuration management means to change the logical topology in response to the changing traffic patterns in the higher layer and the congestion level on the logical topology. We develop an analytical model to evaluate the virtual topology reconfiguration operation and present a heuristic algorithm called Prediction based Multi-stage Reconfiguration approach. We then use this analytical model to study the different configuration operation policies to release the congestion level in the network. Finally, using simulation, we have quantified the benefits and effectiveness of the proposed approaches in terms of important performance measures. Simulation results show that our algorithm significantly outperforms the conventional reconfiguration approach, while the required physical resources are limited.

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