Adaptive Virtual Network Topology Control in WDM-based Optical Networks

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***Abstract*—Virtual Network Topology (VNT) is one efficient way to transfer the IP packet over the wavelength-routed optical networks. In resent years various new services have emerged, and IP traffic has been highly fluctuated. Therefore, adaptability against changes of traffic is one of the most important characteristics to accommodate the IP traffic efficiently. To achieve the adaptability, we have proposed a method for virtual topology controls using an attractor selection model. In this paper, we investigate the adaptability of our virtual topology control via computer simulations. Simulation results indicate that our virtual topology control can successfully adapt to changes of traffic around twice higher variance comparing with conventional virtual topology controls. We also demonstrate that our virtual topology control achieves one-tenth of control duration.**

***Keywords*-WDM; Virtual Topology Control; Virtual Topology Reconfiguration; Attractor Selection; Internet Protocol.**

I. Introduction

Wavelength Division Multiplexing (WDM) networks offer a flexible network infrastructure by using wavelength-routing capabilities. In wavelength-routed WDM networks, a set of optical transport channels, called lightpaths, are established between nodes via optical cross-connects (OXCs). One approach to accommodate IP traffic on a wavelength-routed WDM network is to configure a virtual network topology (VNT), which consists of lightpaths and IP routers [1].

The approaches to accommodate traffic demands in wavelength-routed WDM networks can be classified into two approaches: offline approaches and on-line approaches. In offline approaches, VNTs are statically constructed to efficiently accommodate one or multiple traffic demand matrices. The offline approaches inherently assume that the traffic demand matrices are available before the VNT is constructed or assume that changes in the traffic demand matrices are predictable. However, it is obvious that offline approaches cannot efficiently handle unexpected changes in traffic demand since VNTs are configured for a certain set of traffic demand matrices. In contrast with offline approaches, on-line approaches dynamically reconfigure VNTs based on their detection of degraded performance or periodic measurements of the network status without a priori knowledge of future traffic demand. Existing on-line VNT control methods assume that traffic demand is changing gradually with a period of more than several hours [2]. However, with the growth of the Internet, new services, such as peer-to-peer networks, voice over IP, and video on demand have emerged and these applications cause large fluctuations on traffic demand in networks [3], [4]. For example, Koizumi et. al [4] points out that when there are overlay networks on top of the network controlled by the VNT control mechanism, traffic demand fluctuates greatly and changes in traffic demand are unpredictable.

We therefore developed an adaptive VNT control method based on the on-line approach to be adaptive against changes in network environment [5], [6]. Our method uses an attractor selection that models behavior where living organisms adapt to unknown changes in their surrounding environments and recover their conditions. The fundamental concept underlying the attractor selection is that a system is driven by stochastic and deterministic behavior, and these are controlled by simple feedback of current condition. This characteristic is one of the most important differences between the attractor selection and other existing heuristic algorithms and optimization approaches.

Koizumi et. al [5], [6] demonstrated that the VNT control based on attractor selection can reconfigure VNT with fast reaction and adaptation against changes in traffic demand. In this paper, we evaluate the adaptability of our VNT control method against unknown and/or unexpected changes in surrounding environments. We conduct simulations with various changes of traffic demand and topologies, and quantitatively show that our VNT control method can adapt to more various traffic changes than the existing heuristic method.

The rest of this paper is organized as follows. Section II briefly explains our VNT control based on attractor selection. Section III shows the evaluation results and the performance our VNT control method. Finally, we conclude this paper in Section IV.

II. VNT Control Based on Attractor Selection

In this section, we briefly explain VNT control methods based on attractor selection. Please refer to Ref. [5] for the details. Attractors are a part of the equilibrium points in the solution space in which the current condition is preferable. In our VNT control method, we regard the attractor as VNT, and then select it based on the attractor selection model.

A. Attractor Selection

In a cell, there are gene regulatory and metabolic reaction networks. Each gene in the gene regulatory network has an expression level of proteins and deterministic and stochastic behaviors in each gene control the expression level. An attractor selection model is consists of regulatory behaviors having attractor which is determined by activation and inhibition between each genes, growth rate as feedback of the current condition of the network, and noise, which is stochastic behavior [7].

Attractors are a part of the equilibrium points in the solution space in which the current condition is preferable. The basic mechanism of an attractor selection consists of two behaviors: deterministic and stochastic behaviors. When the current condition is suitable for the current environment, i.e., the system state is close to one of the attractors, deterministic behavior drives the system to the attractor. When the current condition is poor, stochastic behavior dominates over deterministic behavior. While stochastic behavior is dominant in controlling the system, the system state fluctuates randomly due to noise and the system searches for a new attractor.

When the current condition has recovered and the system state comes close to an attractor, deterministic behavior again controls the system. These two behaviors are controlled by simple feedback of the current condition in the system. In this way, attractor selection adapts to environmental changes by selecting attractors using stochastic behavior, deterministic behavior, and simple feedback. In the following section, we introduce attractor selection that models the behavior of gene regulatory and metabolic reaction networks in a cell.

B. VNT Control Method

In the cell, the gene regulatory network controls the metabolic reaction network, and the growth rate, which is the status of the metabolic reaction network, is recovered when the growth rate is degraded due to changes in the environment. In our VNT control method, the main objective is to recover the performance of the IP network by appropriately constructing VNT when performance is degraded due to changes in traffic demand. Therefore, we interpret the gene regulatory network as a WDM network and the metabolic reaction network as an IP network (Figure 1).

Outline of our VNT control method is as follows:

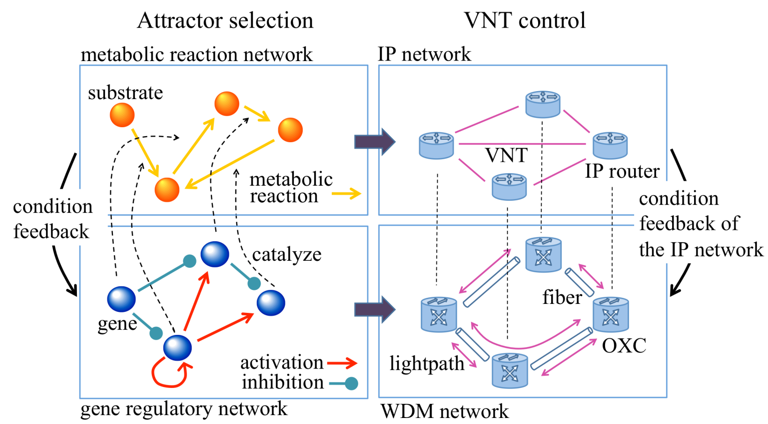

Figure 1. VNT control based on the attractor selection

Step. 1 Measure the load on lightpaths via SNMP.

Step. 2 Determine growth rate from the load on lightpaths. Growth rate express if IP network is in good condition or not. We describe detail of how to determine growth rate in Section II-C. Note that the degree of influence of deterministic behaviors and stochastic behaviors is determined by the growth rate.

Step. 3 The number of lightpaths is determined based on the expression level of each gene. Then, the VNT is reconfigured. We describe how to decide the number of lightpaths in Section II-C.

Step. 4 Transfer the IP traffic over the newly constructed VNT. Consequently the load on lightpaths changes again, so we repeat these steps again.

C. Interaction in VNT Control

This section describes our VNT control method in detail. We consider the dynamical system that is driven by the attractor selection. We place genes on every source-destination pair (denote p_{ij} for nodes i and j) in the WDM network, and the expression level of the genes $x_{p_{ij}}$ determines the number of lightpaths on between nodes i and j. To avoid confusion, we refer to genes placed on the network as *control units* and expression levels as *control values*. The dynamics of $x_{p_{ij}}$ is defined by the following differential equation,

$$\frac{dx_{p_{ij}}}{dt} = v_g \cdot f\left(\sum_{p_{sd}} W(p_{ij}, p_{sd}) \cdot x_{p_{sd}} - \theta_{p_{ij}}\right) - v_g \cdot x_{p_{ij}} + \eta \quad (1)$$

where η represents Gaussian white noise, f is the sigmoidal regulation function, and v_g is the growth rate which indicates a condition of the IP network.

The number of lightpaths between node pair p_{ij} is determined according to value $x_{p_{ij}}$. We assign more lightpaths to a node pair that has a high control value than a node pair that has a low control value. $\theta_{p_{ij}}$ in the sigmoidal regulation function f is the threshold value to control the number of lightpaths.

The regulatory matrix W represents relations of the activation and inhibition between control units. Each element in the regulatory matrix, denoted as $W(p_{ij}, p_{sd})$, represents the relation between node pair p_{ij} and p_{sd}. The value of $W(p_{ij}, p_{sd})$ takes a positive number α_A, zero, or a negative number α_I, each corresponding to activation, no relation, and inhibition of the control unit on p_{ij} by the control unit on p_{sd}. For example, if the lightpath on p_{ij} is activated by that on p_{sd}, increasing $x_{p_{sd}}$ leads to increasing x_{ij}. That is, node pair p_{sd} increases the number of lightpaths on p_{ij} in our VNT control method. In our method, we define α_A as $\alpha_A = 1.08N/N_A$, α_I as $\alpha_I = 1.08N/N_I$, where N is the number of control units, N_A is the number of control units that is activated, and N_I is the number of control units that is inhibited. These are based on the parameter settings given in Ref [7].

We consider three motivations for defining the regulatory matrix in WDM networks. First, when we assign a new lightpath to detour traffic from node i to j for substitute of another lightpath, the traffic passing from node i to j will be transmitted by the new lightpath. Therefore, the control units on each node pair along the route of the lightpath from node i to j activate the control unit on p_{ij}. Next, we consider the situation where a path on the IP network uses the lightpaths on p_{ij} and p_{sd}. In this case, some traffic on p_{ij} is also transported on p_{sd}. If the number of lightpaths on p_{ij} is increased, the number of lightpaths on p_{sd} should also be increased to transport IP traffic efficiently. Therefore, the control units on p_{ij} and p_{sd} activate each other. Finally, we consider the situation that node pairs share a certain fiber. Here, if the number of lightpaths on one node pair increases, the number of lightpaths on the other node pairs should decrease because of limitations on wavelengths. Therefore, the control unit on p_{ij} is inhibited by the control unit on p_{sd} if lightpaths between these node pairs share the same fiber.

The growth rate indicates the current condition of the IP network, and the WDM network seeks to optimize the growth rate. In our VNT control method, we use the maximum link utilization on the IP network as a metric that indicates the current condition of the IP network. To retrieve the maximum link utilization, we collect the traffic volume on all links and select their maximum value. This information is easily and directly retrieved by SNMP. Hereafter, we will refer to the growth rate defined in our VNT control method as *activity*. Figure 2 indicates the function determining the activity. The activity must be an increasing function for the goodness of the current condition of networks. We therefore convert the maximum link utilization on the IP network, $u_{\max}$, into the activity, v_g, by the following equation.

$$v_g = \begin{cases} \frac{\gamma}{1+\exp(\delta\cdot(u_{\max}-\zeta))} & \text{if } u_{\max} \geq \zeta \\ \frac{\gamma}{1+\exp(\delta'\cdot(u_{\max}-\zeta))} & \text{if } u_{\max} < \zeta \end{cases} \tag{2}$$

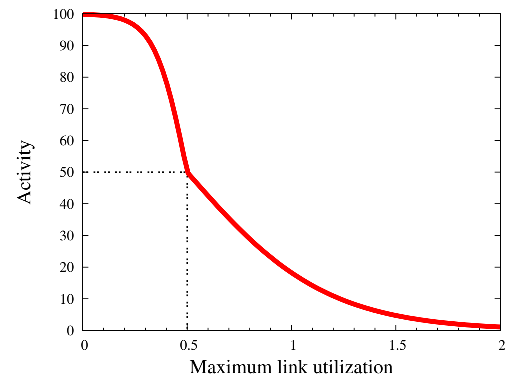

Figure 2. Activity function

Here, γ is the parameter that scales v_g and δ represents the gradient of this function. The constant number, ζ, is the threshold for the activity. If the maximum link utilization is more than threshold ζ, the activity approaches 0 due to the poor condition of the IP network. Then, the dynamics of our VNT control method is governed by noise and search for a new attractor. If the maximum link utilization is less than ζ, we increase the activity. Then the system is driven by deterministic behavior and the system will be stable.

D. The Number of Lightpaths

The number of lightpaths between node pair p_{ij} is calculated from $x_{p_{ij}}$ that is the expression level of gene placed for p_{ij}. To simplify the model of our VNT control method, we assume that the number of wavelengths on optical fibers will be sufficient and the number of transmitters and receivers of optical signals will restrict the number of lightpaths between node pairs. Each node has P_R receivers and P_T transmitters. We assign transmitters and receivers to lightpaths between p_{ij} based on $x_{p_{ij}}$ normalized by the total control values for all the node pairs that use the transmitters or the receivers on node i or j. The number of lightpaths between p_{ij}, $G_{p_{ij}}$, is determined as

$$G_{p_{ij}} = \min\left(\lfloor P_R \cdot \frac{x_{p_{ij}}}{\sum_s x_{p_{sj}}} \rfloor, \lfloor P_T \cdot \frac{x_{p_{ij}}}{\sum_d x_{p_{id}}} \rfloor\right) \tag{3}$$

Since we adopt the floor function for converting real numbers to integers, each node has residual transmitters and receivers. We assign one lightpath in descending order of $x_{p_{ij}}$ while the constraint on the number of transmitters and receivers is satisfied. Note that other constraints derived from physical resources can easily be considered for determining $G_{p_{ij}}$. For instance, when we pose a constraint on the number of wavelengths on fibers, we assign wavelengths on fibers through which the lightpath passes based on $x_{p_{ij}}$ normalized by the sum of expression levels on the corresponding fiber.

III. Performance Evaluation

We next evaluate the adaptability of our VNT control method against changes of traffic demand via computer

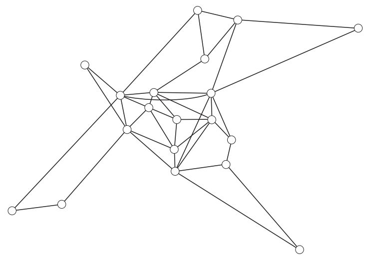

Figure 3. EON topology

simulations. For comparison purpose, we first introduce an existing heuristic method in Section III-A and then present some simulation results.

A. Existing Heuristic Method

Gencata and Mukherjee proposed a heuristic VNT control method, which we call "ADAPTATION" [2]. ADAPTATION aims at achieving adaptability against changes in traffic demand. This method reconfigures VNTs according to the load on links and the traffic demand matrix. ADAPTATION has a lower limit and a upper limit for link utilization and reconfigure VNT to put link utilization in the region. ADAPTATION measures the actual load on links every 5 minutes and adds a new lightpath to the current VNT when congestion occurs. This method places a new lightpath on the node pair with the highest traffic demand among all node pairs that use the congested link.

ADAPTATION uses the information of traffic demand matrix to identify the node pair that has the largest traffic demand. However, collecting the information of traffic demand matrix is difficult in general because measurements of individual flows in a real-time manner are required. In this paper, we use the tomogravity method [8] that estimates the traffic demand matrix based on the information of link utilization, and we apply the estimated traffic demand matrix to the ADAPTATION. Note that both our VNT control method and ADAPTATION use only the information of link utilization that we can get easily by SNMP to calculate the activity of the IP network, but our VNT control method does not estimate the traffic demand matrix.

B. Simulation Conditions

We use the European Optical Network (EON) topology as shown as shown in Figure 3. The EON topology has 19 nodes and 39 bidirectional fibers. Each node has eight transmitters and eight receivers.

We focus on changes in traffic demand in the IP network as the environmental changes. For the evaluation, we prepare the traffic demand matrices where traffic demand from node i to j, d_{ij}, follows a lognormal distribution. We set the variance of logarithm of d_{ij} to be σ^2 and with the mean to be 1. Then, we change the σ^2 to evaluate the adaptability against the changes of network environments. Each traffic

Table I
Parameter settings of our VNT control method.

Name	Values
γ	100
δ	13
δ'	3
ζ	0.5
μ	1

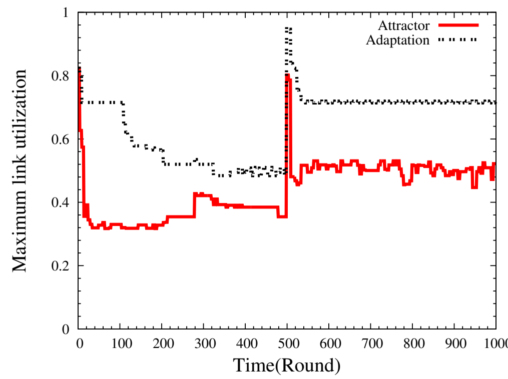

Figure 4. Changes of maximum link utilization

demand matrix is normalized such that the total amount of traffic, $\sum_{p_{ij}} d_{p_{ij}}$, is the same.

In the simulation, our VNT control method collects information about the load on links every 5 minutes by SNMP. The parameter settings of our VNT control method are shown in Table I. ζ corresponds to the target value of maximum link utilization and we set it to 0.5. We conducted several simulations in EON topology and obtained the best parameter settings used for the activity function. Note that the activity function should be carefully designed to achieve adaptive VNT control. We confirmed that the above parameter settings also show a good performance in Abilene topology (See Figure 8). η used in Equation 1 follows normal distribution with variance of 0.2 and the mean of 0.

For the parameter settings for the ADAPTATION method, we set the lower limit to 0.1 and the upper limit to 0.5. ADAPTATION measures the actual load on links every 5 minutes and control VNT in the simulation.

C. Simulation Results

We first show the maximum link utilization dependent on time in Figure 4. In obtaining the figure, we set σ^2 to 2.0 and change the traffic demand at time 500 by setting the different value of random seed for d_{ij}. In both methods, the maximum link utilizations gradually decrease after the change of traffic demand occurs, while our VNT control method sharply decreases the maximum link utilization. In the figure, our VNT control method successfully decreases the maximum link utilization to be lower than 0.5, while the ADAPTATION cannot decrease. We regard that the VNT control is successful when the maximum link utilization is

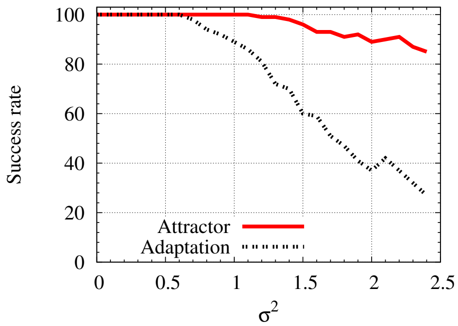

Figure 5. Success rate of VNT reconfigurations in EON topology

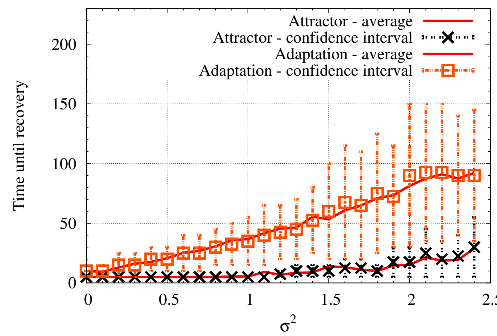

Figure 6. Average and 90% confidence interval of control duration in EON topology

decreased to less than 0.5. Otherwise the control is fail.

We evaluate the success rate of VNT reconfigurations by changing the parameter σ^2 from 0 to 2.4, and conducting the simulation 100 times for each value of σ^2. The results are shown in Figure 5 where the horizontal axis represents the value of σ^2 and the vertical axis represents the average of success rate.

We observe that our method achieves 100% success rate when σ^2 is less than 1.1. Comparing with the results of the ADAPTATION method, our virtual topology control can successfully adapt changes of traffic demand around twice higher variance comparing with the ADAPTATION method. In both methods, the success rate more decreases as σ^2 takes larger values. However, when σ^2 is 2.4, the success rate of our method is higher than 80%, while that of the ADAPTATION method decreases significantly.

We next discuss the control duration, defined as the time from when the traffic change occurs to when the maximum link utilization becomes less than 0.5. Figure 6 shows the average and 90% confidence interval of the control duration dependent on σ^2. For calculating the control duration, we use only the cases when VNT reconfigurations are successful. We observe that our method achieves lower control duration comparing with the ADAPTATION method. As the σ^2 increases, the difference between our method and ADAPTATION method increases. Looking at the results when σ^2 is 2.4, the averaged control duration of the ADAPTATION method is 90 minutes, while the averaged control duration of our method is only 30 minutes. More importantly, the confidence interval of the ADAPTATION is wide: the interval ranges from 30 minutes to 150 minutes. However, results of our method are ranging from 5 minutes to 60 minutes.

A disadvantage of our method is shown in Figure 7. The figure shows the maximum value of control durations. When σ^2 is 1.1 and 1.5, the control duration of our method is larger than that of the ADAPTATION method because of the stochastic behavior of our method; the noise term in Equation 1 does not work well in some cases. Note however that the success rate of our method is higher than that of the

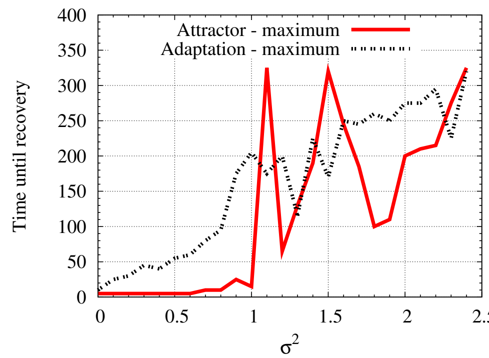

Figure 7. The maximum control duration in EON topology

ADAPTATION method when σ^2 is 1.1 and 1.5.

We next show the results of our method in the Abilene topology (Figure 8). Figure 9 shows the success rate in Abilene topology. We can see that our method achieves 100% success rate when σ^2 is less than 2.0 and our method keep high rate compared with ADAPTATION. Looking at the Figure 10 that show the time until recovery, we again observe that our method reconfigure the VNT with fast reaction; the 90% confidential interval ranges from 5 minutes to 20 minutes.

We also conduct simulations for more larger topology having 100 node and 200 bidirectional fibers that are connected randomly. Results are summarized in Table II where the total traffic volume and number of transmitter/receivers are set

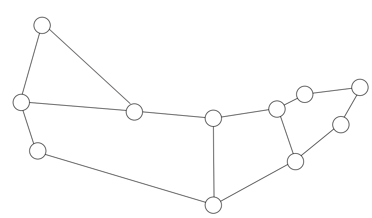

Figure 8. Abilene topology

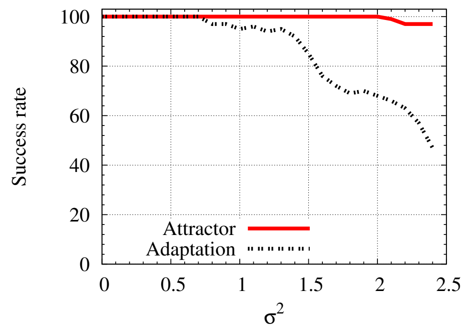

Figure 9. Success rate of VNT reconfigurations in Abilene topology

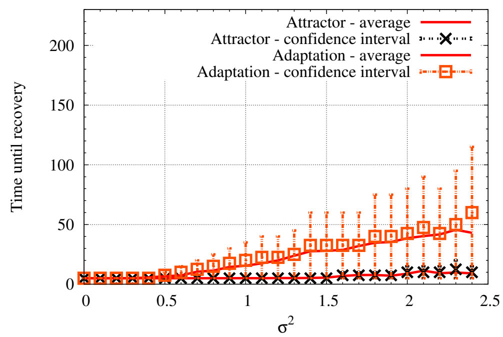

Figure 10. Average and 90% confidence interval of control duration in Abilene topology

to three times larger than previous simulation settings. Our method decreases the maximum link utilization as shown in Figure 11 and the success rate keep high rate over than 90% as shown in Table II.

IV. Conclusion and Future Work

Adaptability against changes of traffic demand is one of important characteristics. In this paper, we evaluated the adaptability of VNT control method based on the attractor selection. Simulation results showed that our VNT control method could successfully adapt changes of traffic around twice higher variance comparing with existing heuristic method. We also demonstrated that our VNT control method achieves short control duration of VNT reconfiguration in most cases.

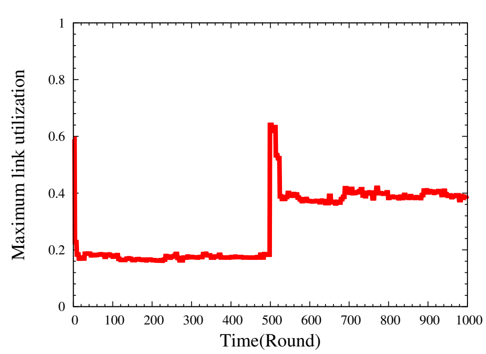

Figure 11. Attractor - Changes maximum link utilization in 100-nodes topology

Table II
Success rate of VNT reconfigurations in 100-node topology

σ^2	Success Rate
2.0	100
2.1	100
2.2	98
2.3	98
2.4	97

We revealed that our VNT control method takes long time to finish the reconfiguration due to the stochastic behaviors of attractor selection. One of future works is to investigate mechanisms to control the parameter according to, e.g., degree of traffic changes.

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