Benefits of Virtual Network Topology Control based on Attractor Selection in WDM Networks

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***Abstract*—Virtual Network Topology (VNT) is one efficient way to transfer IP packets over wavelength-routed optical networks. In recent 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 VNT control method using an attractor selection model. In this paper, we investigate the adaptability of our VNT control method via computer simulations. Simulation results on various physical topologies indicate that our VNT control method can successfully adapt to changes of traffic around twice higher variance comparing with conventional VNT control methods. We also demonstrate that our VNT control method achieves one-tenth of control duration.**

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

I. Introduction

The rapid growth in the number of users and in the number of multimedia services is dramatically increasing traffic volume on the Internet. Wavelength division multiplexing (WDM) offers high-capacity data transmission by multiplexing optical signals into a fiber. With the optical cross-connects (OXCs) that switches the optical signals in all-optical domain offers the wavelength-routing. That is, sets of optical transport channels, called lightpaths, are established between nodes. Since the Internet protocol (IP) is emerging as a dominant technology, the ability to carry the IP traffic efficiently is an important issue to enjoy the WDM-based optical networks. One approach to accommodate IP traffic on WDM networks is to configure a virtual network topology (VNT), which consists of lightpaths and IP routers, through the wavelength-routing.

Many approaches to accommodate traffic demand by configuring VNTs have been investigated. One of approaches is that VNTs are statically constructed to efficiently accommodate one or multiple traffic demand matrices [2–5]. These 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, the approaches cannot efficiently handle unexpected changes in traffic demand matrices since VNTs are configured for a certain set of traffic demand matrices. For example, the emergence of new services, such as peer-to-peer networks, voice over IP, and video on demand causes large fluctuations on traffic demand in networks [6], which makes the existing VNT control mechanisms insufficient to accommodate the traffic demand. Koizumi et. al [7] 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. Therefore, VNT control methods that are adaptive to the traffic changes become important to avoid traffic congestions and to use network resources efficiently.

Recently, the dynamic VNT control that dynamically reconfigures VNTs based on their detection of degraded performance or periodic measurements of the network status without a priori knowledge of future traffic demand has been proposed [8,9]. In Ref. [8], the authors propose VNT control by assuming that traffic demand is changing gradually with a period of more than several hours. The method rely on the traffic demand matrices, and therefore the method cannot apply to VNT controls with short intervals of reconfigurations since traffic demand matrices is difficult to obtain with in a short period of time. In Ref. [9], the authors consider an hour-order traffic change and propose a VNT control method to adapt to the change. The method measures the traffic volume on each lightpath for short period and reconfigures VNT by using traffic demand matrices estimated from the measurement. The VNT control method again relies on the traffic demand matrices and the authors therefore try to estimate the traffic demand matrices more accurately. However, it requires several traffic measurements to estimate the traffic demand matrix. Thus the method cannot estimate traffic demand matrices correctly with a short period of time, and cannot be applied when the traffic demand is highly fluctuated.

We therefore developed a VNT control method that is adaptive against changes in network environment without using traffic demand matrices [10, 11]. 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. Our method measures only the traffic load on each lightpath (hereafter, we call the traffic load as link utilization). The quantity of information on the link utilization is less than that obtained from traffic demand matrices, but information about the link utilization is retrieved directly using, for example, SNMP (Simple Network Management Protocol).

Koizumi et al. [10,11] demonstrated that the VNT control based on attractor selection could reconfigure VNT with fast reaction and adaptation against changes in traffic demand. However, the simulation conditions are limited. In their simulation, they used a 19-node physical topology and evaluate with the randomly changing traffic demand. In the paper, only the concept of VNT control based on attractor selection was demonstrated, and did not understand well for the benefit of the method against the existing heuristic VNT control methods. In this paper, we evaluate the adaptability of the VNT control method against unknown and/or unexpected changes in surrounding environments and the range of network resource amount the method needs. We conduct simulations with various changes in traffic demand and physical topologies, and quantitatively show that the VNT control method can adapt to more various traffic changes than the existing heuristic methods.

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

II. Network model and related works

In this section, we describe the network model that we will use for the VNT configuration. Each node in the physical topology has IP routers and OXCs (Figure 1) and nodes are connected with optical fibers (Figure 2). The OXCs consist of three main blocks: input section, non-blocking optical switches, and output section. In the input section, optical signals are demultiplexed into W fixed wavelengths. Then, each wavelength is transferred to an appropriate output port by the non-blocking optical switch. Finally, at the output

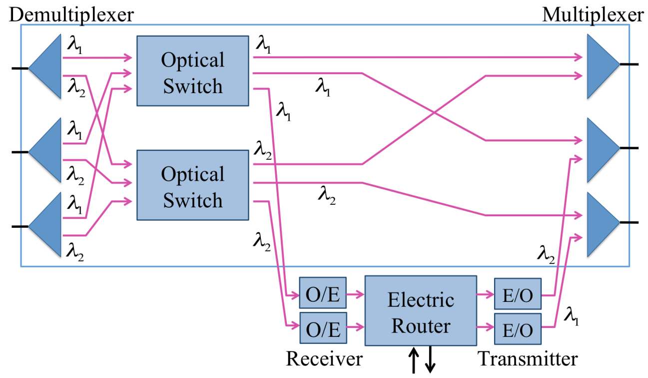

Figure 1. Node architecture

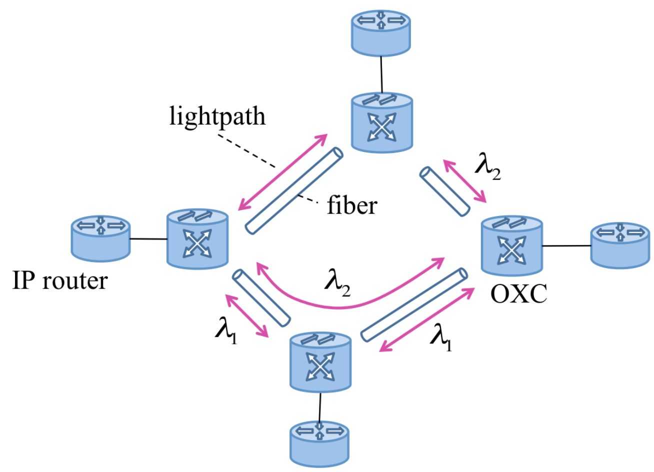

Figure 2. WDM network

section, each wavelength is multiplexed again and sent to the next node. By configuring the switches along a path, a lightpath is configured and a particular wavelength is carried from a transmitter at a node to a receiver at the other node without any electronic processing.

VNT is then constituted by setting up lightpaths on top of the physical topology (Figure 3). The actual traffic of the upper layer protocol, such as the IP, is carried on the constructed VNT. When a lightpath terminates at this node, the IP packets on the lightpath are converted to electrical signals and forwarded to the electronic router. When a lightpath begins at this node, IP packets from the electronic router are transmitted over the lightpath after being converted to optical signals. If lightpath is configured between all node-pairs, we do not need IP's packet processing in the VNTs. However, since the number of transmitters/receivers is limited, we should properly configure and reconfigure VNT.

In recent years, GMPLS (Generalized Multi-Protocol Label Switching), that is the technology to set and release lightpaths constructing VNT, is standardizing [12]. While international standard is being developed, advances in op-

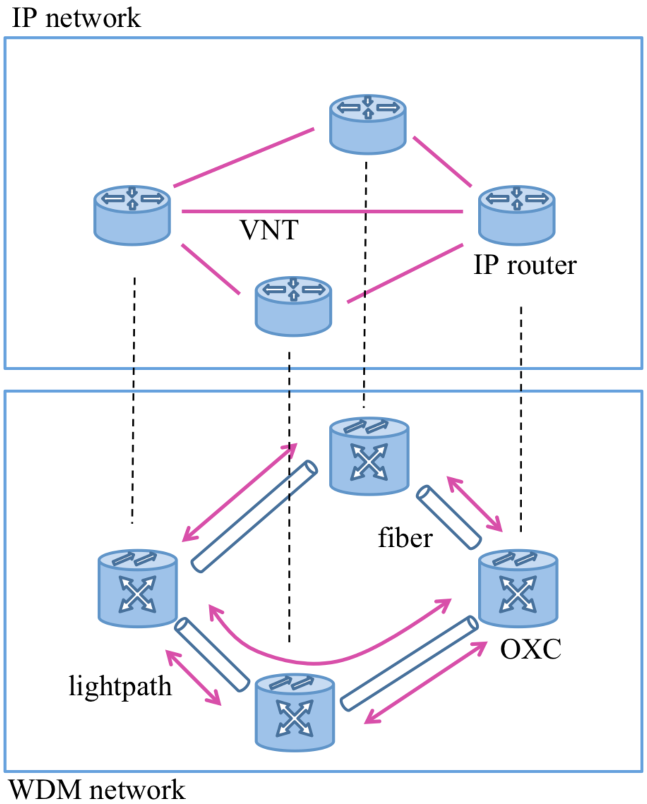

Figure 3. VNT configuration in IP-over-WDM network

tical technologies, such as optical switch with fast switching time, adaptability against changes of traffic demand becomes one of the important characteristics for the VNT controls. For example, in Ref. [8], authors try to keep the link utilizations between an upper limit and a lower limit against the traffic that grows during peak hours and falls during off-peak hours. The approach is different from previous studies that redesign the virtual topology according to an obtained traffic demand matrix through traffic measurements [4]. Ohsita et al. developed a VNT control method with an estimation of traffic demand matrices, and show that the method works with an hour-order traffic change [9]. More recently, Koizumi et al. demonstrated a VNT control based on the attractor selection model, which does not use the traffic demand matrix for VNT controls and thus achieves more shorter intervals of VNT reconfigurations [10, 11].

III. Attractor Selection

We first explain an attractor selection model that describes biological activities in a cell. The model is developed for a cell biology and please refer to Ref. [13] to understand the biological context of the model. This section explains an overview of attractor selection model, which will be use to explain the VNT control based on the attractor selection model in Section IV.

A. *Outline of Attractor Selection*

The attractor selection model represents metabolic reactions controlled by gene regulatory networks in a cell. Figure 4 illustrates a schematic representation in a cell. 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.

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.

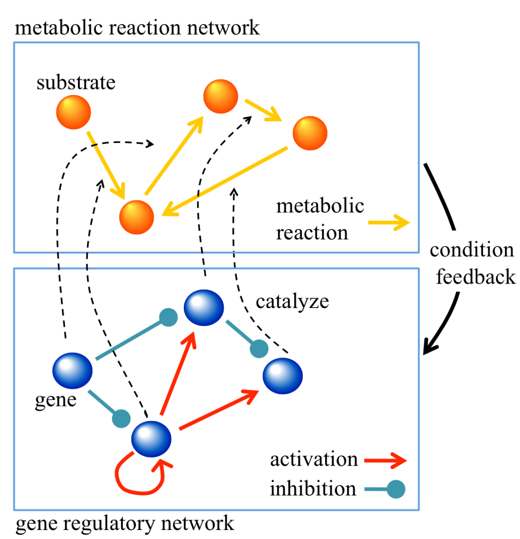

Figure 4. Networks in a cell

B. Mathematical Model of Attractor Selection

The internal state of a cell is represented by a set of expression levels of proteins on n genes, $(x_1, x_2, ..., x_n)$, and concentrations of m metabolic substrates, $(y_1, y_2, ..., y_m)$. The dynamics of the expression level of the protein of the i-th gene, x_i, is described as

$$\frac{dx_i}{dt} = f\left(\sum_{j=1}^{n} W_{ij} x_j - \theta\right) \cdot v_g - \cdot x_i v_g + \eta \tag{1}$$

The first and second terms at the right hand side represent the deterministic behavior of gene i, and the third term represents stochastic behavior.

In the first term, the regulation of protein expression levels on gene i by other genes are indicated by regulatory matrix W_{ij}, which takes 1, 0, or − 1, corresponding to activation, no regulatory interaction, and inhibition of the i-th gene by the j-th gene. The rate of increase in the expression level is given by the sigmoidal regulation function, $f(z) = 1/(1 + e - \mu z)$, where $z = \Sigma W_{ij} x_j - \theta$ is the total regulatory input with threshold θ for increasing x_i, and μ indicates the gain parameter of the sigmoid function.

The second term represents the rate of decrease in the expression level on gene i. This term means that the expression level decreases depending on the current expression level. The last term, η, represents molecular fluctuations, which is Gaussian white noise. Noise η is independent of production and consumption terms and its amplitude is constant. The change in expression level x_i is determined by deterministic behavior and stochastic behavior η. The deterministic and stochastic behaviors are controlled by growth rate v_g, which represents the conditions of the metabolic reaction network. In the metabolic reaction network, metabolic reactions, which are internal influences, and the transportation of substrates from the outside of the cell, which is an external influence, determine the changes in concentrations of metabolic substrates y_i. The metabolic reactions are catalyzed by proteins on corresponding genes. The expression level decides the strength of catalysis. A large expression level accelerates the metabolic reaction and a small expression level suppresses it. In other words, the gene regulatory network controls the metabolic reaction network through catalyses. Some metabolic substrates are necessary for cellular growth. Growth rate v_g is determined as an increasing function of the concentrations of these vital substrates. The gene regulatory network uses v_g as the feedback of the conditions on the metabolic reaction network and controls deterministic and stochastic behaviors. If the concentrations of the required substrates decrease due to changes in the concentrations of nutrient substrates outside the cell, v_g also decreases. By decreasing v_g, the effects that the first and second terms have on the dynamics of x_i decrease, and the effects of η increase relatively. Thus, x_i fluctuates randomly and the gene regulatory network searches for a new attractor. The fluctuations in x_i lead to changes in the rate of metabolic reactions via the catalyses of proteins.

When the concentrations of the required substrates again increase, v_g also increases. Then, the first and second terms again dominate the dynamics of x_i over stochastic behavior, and the system converges to the state of the attractor. In next section, we describe our VNT control method based on attractor selection.

IV. VNT Control Based on Attractor Selection

In this section, we briefly explain VNT control methods based on attractor selection. 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. 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 5).

Outline of our VNT control method is as follows:

Step. 1 Measure the link utilization via SNMP (Simple Network Management Protocol).

Step. 2 Determine growth rate from the link utilization. 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.

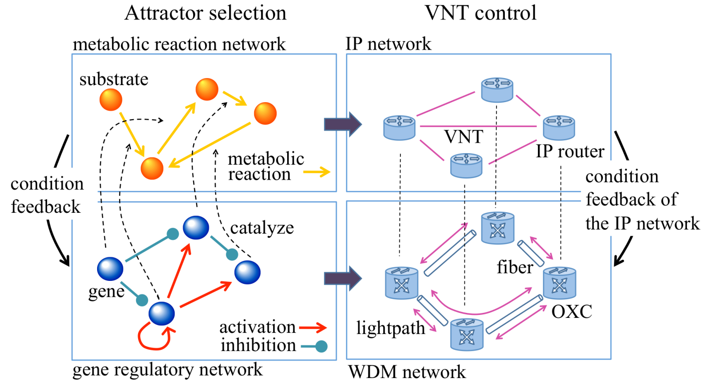

Figure 5. VNT control based on the attractor selection

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 link utilization changes again, so we repeat these steps again.

B. 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,

$$\frac{dx_{p_{ij}}}{dt} = v_g \cdot f\left(\sum_{p_{sd}} W(p_{ij}, p_{sd}) \cdot x_{p_{sd}} - \theta_{p_{ij}}\right) - v_g \cdot x_{p_{ij}} + \eta \quad (2)$$

where η represents Gaussian white noise, f is the sigmoidal regulation function, and v_g is the growth rate. v_g indicates the 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.

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 6 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.

$$v_g = \begin{cases} \frac{\gamma}{1+\exp(\delta\cdot(u_{\max}-\zeta))} & \text{if } u_{\max} \geq \zeta \\ \frac{\gamma}{1+\exp(\delta'\cdot(u_{\max}-\zeta))} & \text{if } u_{\max} < \zeta \end{cases} \quad (3)$$

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

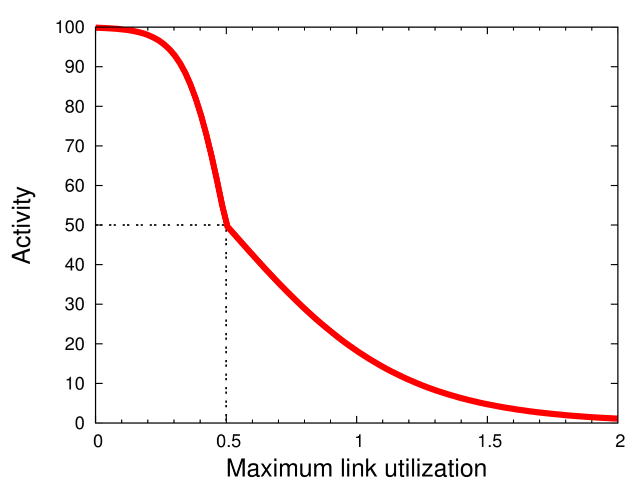

Figure 6. Activity function

than ζ, we increase the activity. Then the system is driven by deterministic behavior and the system will be stable.

C. 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

$$G_{p_{ij}} = \min\left(\lfloor P_R \cdot \frac{x_{p_{ij}}}{\sum_s x_{p_{sj}}} \rfloor, \lfloor P_T \cdot \frac{x_{p_{ij}}}{\sum_d x_{p_{id}}} \rfloor\right) \qquad (4)$$

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.

V. Performance Evaluation

We next evaluate the adaptability of our VNT control method against changes of traffic demand via computer simulations. For comparison purpose, we first introduce an existing heuristic method in Section V-A and then present some simulation results.

A. Existing Heuristic Method

Ref. [8] proposed a heuristic VNT control method, which we will refer to "ADAPTATION". ADAPTATION aims at achieving adaptability against changes in traffic demand. This method reconfigures VNTs according to the link utilization and the traffic demand matrix. ADAPTATION has a lower limit and an upper limit for link utilization and reconfigure VNT to put link utilization in the region. ADAPTATION measures the actual link utilization 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 [14] 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 7. 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 demand matrix is normalized such that the total amount of traffic, $\sum_{p_{ij}} d_{p_{ij}}$, is the same and is set to 10 in a unit of bandwidth of lightpaths.

In the simulation, Our VNT control method collects information about the link utilization every 5 minutes by SNMP. The parameter settings of our VNT control method are shown in Table I. η used in Equation 2 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 link utilization every 5 minutes and control VNT in the simulation.

C. Simulation Results

We first show the maximum link utilization dependent on time in Figure 8. In obtaining the figure, we set σ^2 to

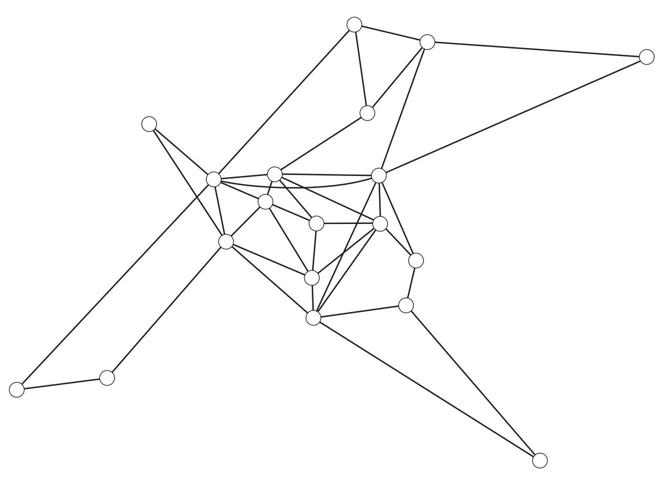

Figure 7. EON topology

Table I
PARAMETER SETTINGS OF OUR VNT CONTROL METHOD.

Name	Values
γ	100
δ	13
δ'	3
ζ	0.5
μ	1

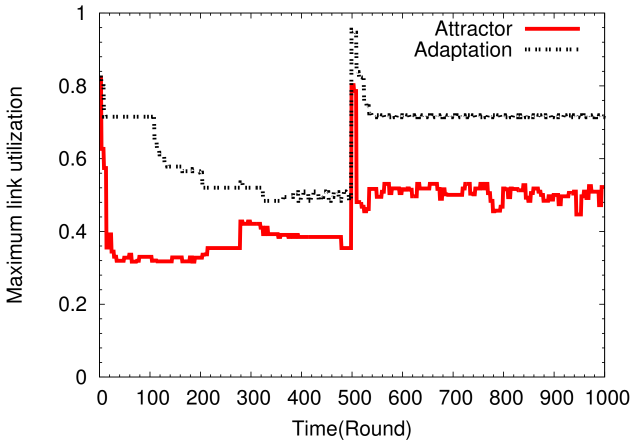

Figure 8. Changes of maximum link utilization

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 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 9 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

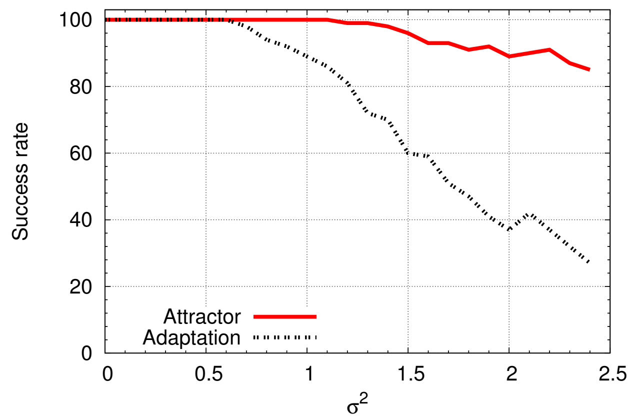

Figure 9. Success rate of VNT reconfigurations in EON topology

10 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 11. The figure shows the maximum value of control durations. When σ^2 is 1.1 and 1.5, the control duration of our method

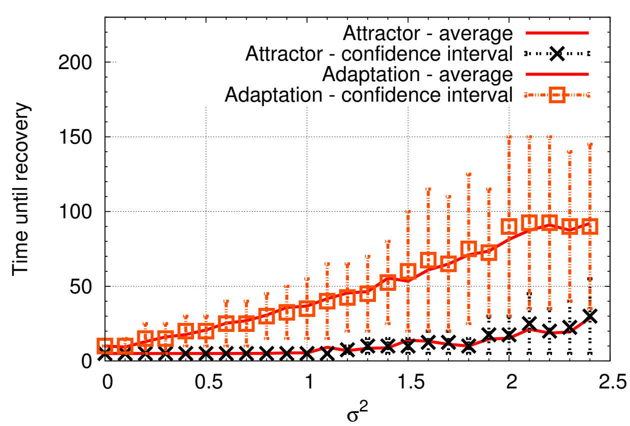

Figure 10. Average and 90% confidence interval of control duration in EON topology

is larger than that of the ADAPTATION method because of the stochastic behavior of our method; the noise term in Equation 2 does not work well in some cases. Note however that the success rate of our method is higher than that of the ADAPTATION method when σ^2 is 1.1 and 1.5.

We next show the results of our method in the Abilene topology (Figure 12). Figure 13 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 14 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 larger physical topology having 100 node and 200 bidirectional fibers that are connected randomly. Results are summarized in Table II. In the simulation, the total traffic volume is set to 30 in a unit of bandwidth of lightpaths. We also set the number of transmitters/receivers on each node to be 24. With these parameter settings, our method decreases the maximum link utilization as shown in Figure 15 and the success rate is higher than 90% as shown in Table II. Note that when the number of transmitters/receivers is too small for the physical topology, the number of attractors, i.e., the number of VNT candidates, is also small. In this case, the VNT control based on the attractor selection is difficult to search for a new attractor through a noise term in Equation 2.

To see the effect of number of transmitters/receivers more clearly, we conduct a set of simulations for the EON topology by changing the number of transmitters and receivers and evaluate the success rate for each VNT control method. We prepare three traffic scenarios shown in Table III by changing traffic volume and σ^2. In scenario 1, we set the traffic volume to the same as above simulation and σ^2 to 1.0. In scenario 2, we set the traffic volume to 1.5 times larger than scenario 1, but use the same value for σ^2. For scenario 3, we increase both the traffic volume and the σ^2. We generate a traffic demand matrix based on the parameters for each traffic scenario and then evaluate whether VNT control methods successfully adapt to the traffic demand. The other simulation conditions are the same as the simulation conditions of the EON topology (See Section V-B).

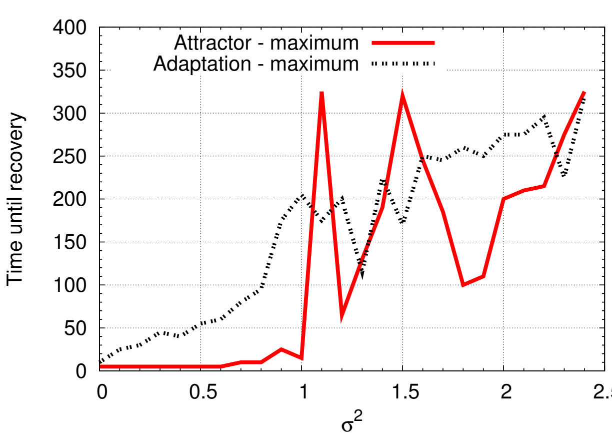

Figure 11. The maximum control duration in EON topology

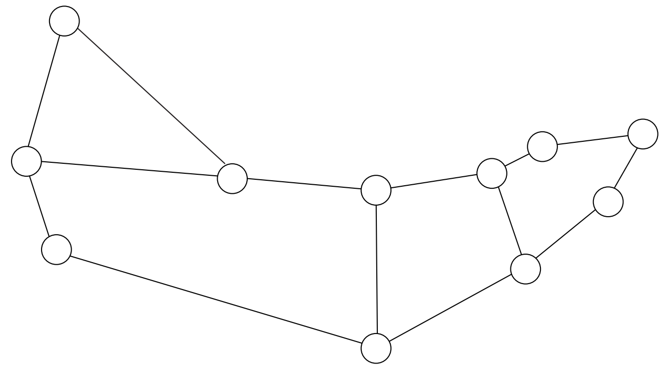

Figure 12. Abilene topology

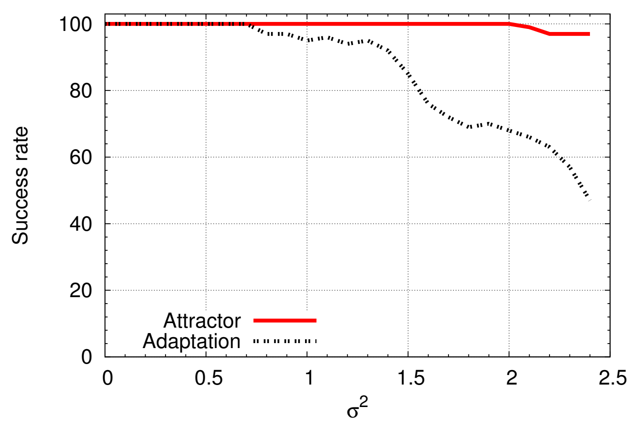

Figure 13. Success rate of VNT reconfigurations in Abilene topology

Table II
SUCCESS RATE OF VNT RECONFIGURATIONS IN 100-NODE TOPOLOGY

σ^2	Success Rate
1.3	100
1.4	100
1.5	100
1.6	100
1.7	100
1.8	100
1.9	100
2.0	100
2.1	100
2.2	98
2.3	98
2.4	97

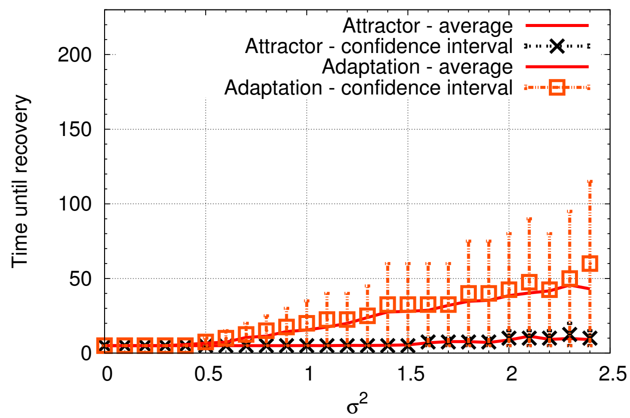

Figure 14. Average and 90% confidence interval of control duration in Abilene topology

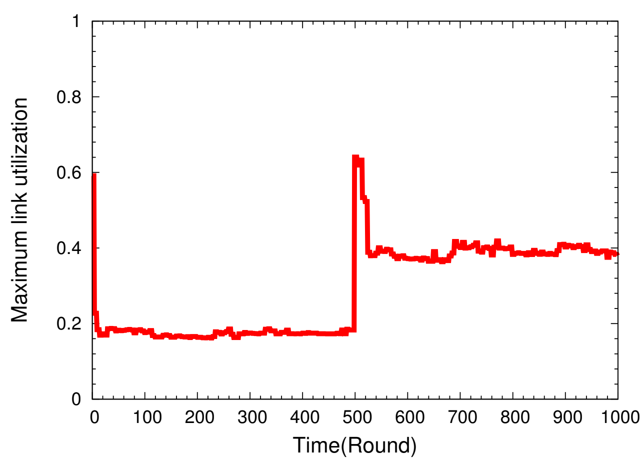

Figure 15. Attractor - Changes maximum link utilization in 100-nodes topology

Table IV summarizes the success rate of VNT reconfigurations. In the table, we introduce the results of MLDA (Minimum-delay Logical topology Design Algorithm) [4] which is a heuristic and centralized VNT control method on the basis of a given traffic demand matrix. MLDA simply places lightpaths between nodes in descending order of traffic demand. We show the results of MLDA with the actual traffic demand matrix to see how transmitters and receivers are effectively used in VNT control methods. From the table, we observe that each VNT control method

Table III
THREE TRAFFIC SCENARIOS IN THE EON TOPOLOGY

	Total traffic volume (relative to Figure 9)	σ^2
Scenario 1	1.0	2.0
Scenario 2	1.5	1.0
Scenario 3	1.5	2.0

have significantly low success rate with the small number of transmitters/receivers. This means that enough number of transmitters/receivers is crucial for VNT controls in changing network environments.

The benefit of heuristic VNT control methods appears with the small number of transmitters/receivers; ADAPTATION and MLDA have a higher success rate than ATTRACTOR when the number of transmitters/receivers is 5 or 6 for traffic scenario 1, but the differences are marginal. More importantly, the benefit of MLDA disappears as the number of transmitters/receivers increases; the success rate of ATTRACTOR and MLDA is mostly the same for traffic scenarios 1 and 2. Looking at the case of traffic scenario 3, we observe a disadvantage of MLDA. That is, the results of MLDA show poor success rate comparing with the results of ATTRACTOR. The reason is that when the variance of traffic demand matrix increases, the heuristic behind MLDA fails. ADAPTATION has a much lower success rate than the other VNT control methods due to the estimation error in obtaining the traffic demand matrix from the information of link utilization.

In summary, heuristic VNT control methods based on the traffic demand matrices have a capability to obtain good VNTs with the small number of transmitters/receivers. Therefore, the heuristic VNT control methods are useful for the network with gradual change in traffic demand matrices. However, for the network having large fluctuations on traffic demand, enough number of transmitters/receivers is crucial. With this case, our VNT control based on attractor selection achieves good adaptability to the traffic change and lower control durations.

VI. Conclusion

Adaptability against changes of traffic demand is one of the important characteristics. In this paper, we evaluated the adaptability of VNT control based on the attractor selection. Simulation results with various physical topologies and traffic demand matrices 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. We then evaluated the success rate with different number of transmitters/receivers for three traffic scenarios, and compared our VNT control methods with existing two heuristic VNT control methods. The results indicate that existing methods have a higher success rate than our VNT control method when the number of transmitters/receivers is small, but its differences are marginal. To achieve an adaptive VNT controls to the changes of network environments, enough number of transmitters/receivers is crucial. With this case, our VNT control based on attractor selection achieves good adaptability to the traffic change and lower control durations.

Table IV
SUCCESS RATE (IN PERCENTAGE)

	Number of transmitters/receivers								
	1	2	3	4	5	6	7	8	9
scenario 1 ATTRACTOR	0	0	0	0	6	12	52	89	96
scenario 1 ADAPTATION	0	0	0	0	7	23	30	37	51
scenario 1 MLDA	0	0	0	0	7	17	52	85	92
scenario 2 ATTRACTOR	0	0	0	0	0	0	17	82	100
scenario 2 ADAPTATION	0	0	0	0	0	2	8	18	32
scenario 2 MLDA	0	0	0	0	0	0	23	79	97
scenario 3 ATTRACTOR	0	0	0	0	0	0	5	44	96
scenario 3 ADAPTATION	0	0	0	0	0	0	0	2	7
scenario 3 MLDA	0	0	0	0	0	0	4	20	42

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