Robust Virtual Network Topology Control based on Attractor Selection

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Abstract— **The growth of the Internet and emerging application layer technologies causes numerous changes in network environments. Therefore, it becomes important to achieve robust methods of controlling networks in addition to optimizing their performance. In this paper, we propose a robust virtual network topology (VNT) control method based on *attractor selection*, which models behaviors where biological systems adapt to unknown changes in their surrounding environments and recover their conditions. The simulation results indicate that our proposed method adaptively responds to various changes in traffic demand and link failures.**

I. Introduction

Wavelength Division Multiplexing (WDM) networks offer a flexible network infrastructure by using wavelength-routing capabilities. In such wavelength-routed WDM networks, a set of lightpaths are established between nodes via optical cross-connects. Much research has been devoted to methods of carrying IP traffic, which is the majority of Internet traffic, over wavelength-routed WDM networks [1]–[3]. One approach to accommodating IP traffic on a WDM network is to configure a *virtual network topology* (VNT), which consists of lightpaths and IP routers. To achieve effective transport of traffic, *VNT control*, which configures a VNT on the basis of given traffic demand matrices, has been investigated [4], [5].

With the growth of the Internet, new application layer services such as peer-to-peer networks have emerged and these applications cause large fluctuations in network environments [6], [7]. Thus, it is important to achieve a VNT control method that is adaptive to changes in network environments.

Approaches to accommodating changing traffic demand on VNTs can be classified into offline and on-line approaches. In offline approaches, VNTs are statically constructed to accommodate one or multiple traffic demand matrices [8]. These approaches mainly assume that these traffic demand matrices will be available before the VNT is constructed. However, it is obvious that offline approaches cannot 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 [9], [10]. Therefore, on-line approaches adapt to changes in traffic demand. In [9], a VNT reconfiguration method that uses given traffic demand matrices and configures an optimal VNT for the new traffic demand matrix was proposed. In [10], the authors proposed an optimization-based and heuristic VNT reconfiguration method based on periodic measurements of the load on lightpaths. In this paper, we develop an on-line approach to achieve an adaptive VNT control method.

Existing on-line VNT control methods assume that traffic demand is changing gradually and periodically as observed in [11]. However, if 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 as has been pointed out [6], [7]. More importantly, environmental changes include not only changes in traffic demand but also various changes such as link failures. Therefore, an important objective is to develop a VNT control method that is robust against various environmental changes. To achieve this objective, we adopt a non-rule-based approach and not the rule-based approaches that are used by existing heuristic VNT control methods. A rule-based approach is defined as one that assumes a certain set of scenarios for changes in environments and prepares countermeasures to those changes as rules, i.e., algorithms for VNT reconfigurations. For these assumed environmental changes, these approaches may guarantee optimal performance or adaptability but they cannot guarantee if unexpected changes occur. In contrast with rule-based approaches, non-rule-based approaches do not use predefined algorithms for adapting to environmental changes. Instead of predefined algorithms, non-rule-based approaches mainly use stochastic behavior for adapting to changes in environments. Thus, they do not guarantee optimal performance but do have capabilities for adapting to unexpected environmental changes. Unlike most other rule-based VNT control methods, we aim at a VNT control method that will be robust against various changes in the environments by using a non rule-based approach. This paper focuses on mechanisms found in biological systems, which are adaptive against changes in their surrounding environments, as one of the non-rule-based approaches.

It is a well-known fact that mechanisms found in biological systems are robust against changes in environments [12]. In this paper, we focus on *attractor selection*, which models behaviors where living organisms adapt to unknown changes in their surrounding environments and recover their conditions. In [13], the authors show an attractor selection model for E. coli cells to adapt to changes in the availability of a nutrient. As another model of an attractor selection model, the mechanism for adaptability of a cell, which consists of a gene regulatory network and a metabolic network, is introduced in [14]. One successful proposal for adaptive network control based on attractor selection was presented in [15]. They proposed a path selection mechanism, which was robust against changes in the delay of paths, based on the attractor selection model introduced in [13]. The fundamental concept underlying attractor selection is that the system is driven by stochastic and deterministic behaviors, and these are controlled by simple feedback of current system conditions. While rule-based heuristic approaches cannot handle unexpected environmental changes, attractor selection has the capability of adapting to unknown changes since the system is driven by stochastic behavior and simple feedback of current system conditions. Therefore, we adopt attractor selection as the key mechanism in our VNT control method to attain robustness and adaptability against various changes in the environments.

In the previous work [16], we have discussed the applicability of attractor selection introduced in [14] to VNT control and shown the adaptability of our VNT control method based on attractor selection to changes in traffic demand. In this paper, we add extensions, hysteresis and smoothing mechanisms, to achieve stable VNT control and show that our proposed method is not only robust to changes in traffic demand but also link failures.

The rest of this paper is organized as follows. Section II briefly describes the attractor selection model introduced in [14]. We then propose an adaptive VNT control method based on attractor selection in Section III and show its behavior in Section IV. We conclude this paper in Section V.

II. Attractor Selection

The dynamic system that is driven by *attractor selection* uses noise to adapt to environmental changes. In attractor selection, *attractors* are a part of the equilibrium points in the solution space in which the system conditions are preferable. The basic mechanism consists of deterministic and stochastic behaviors. When the current system conditions are suitable for the environment, deterministic behavior drives the system to the attractor. Where the current system conditions are 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 system conditions have 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 conditions in the system. In this way, attractor selection adapts to environmental changes by selecting attractors using stochastic behavior, deterministic behavior, and simple feedback.

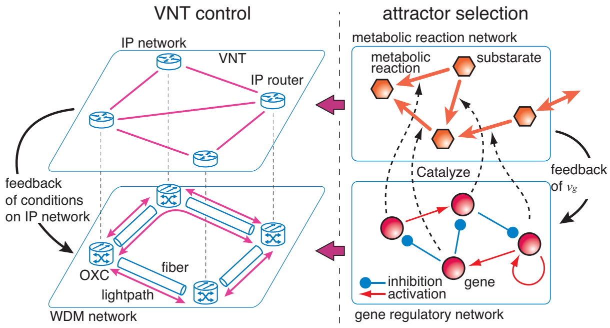


Fig. 1. Interpretation of attractor selection into VNT control

The right of Fig. 1 is a schematic of the cell model used in [14]. It consists of the gene regulatory network in the box at the bottom of Fig. 1 and the metabolic reaction network in the box at the top.

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. Deterministic behavior controls the expression level due to the effects of activation and inhibition from the other genes. In Fig. 1, those effects are indicated by the triangular-headed and circular-headed arrows, respectively. In stochastic behavior, inherent noise randomly changes the expression level.

In the metabolic reaction network, metabolic reactions consume several substrates and produce new substrates. These metabolic reactions are catalyzed by proteins on corresponding genes. In other words, the gene network controls the metabolic network through catalyses. In Fig. 1, metabolic reactions are illustrated as fluxes of substrates and catalyses of proteins are indicated by the dashed arrows.

The growth rate is determined by dynamics in the metabolic reactions. The gene regulatory network uses the growth rate as feedback of the conditions on the metabolic reaction network and controls deterministic and stochastic behaviors by using the growth rate. If the metabolic reaction network is in poor condition and the growth rate is small, the influence of stochastic behavior dominates deterministic behavior, triggering a search for a new attractor. During this phase, the expression levels are randomly changed by noise, and the gene regulatory network searches for a state that is suitable for the current environment. After the conditions of the metabolic reaction network have been recovered and the growth rate increases, deterministic behavior again drives the gene regulatory network to stable states.

Due to the space limitation, we have omitted a detailed description of attractor selection from this paper. Readers can refer to [14] for a detailed description of attractor selection. The next section explains the VNT control method based on this attractor selection model.

III. VNT Control Based on Attractor Selection

A. Overview of VNT Control Based on Attractor Selection

Our network consists of two layers: a WDM and an IP layer as shown in the left of Fig. 1. On the WDM layer, the WDM network consists of OXCs and optical fibers. VNT control configures lightpaths between IP routers via OXCs on the WDM network and these lightpaths and IP routers form a VNT. On the IP layer, packets are forwarded along the routes that are determined by IP routing on this VNT.

In attractor selection, 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. We interpret the gene regulatory network as a WDM network and the metabolic reaction network as an IP network, as shown in Fig. 1. The VNT control method drives the IP network by constructing VNTs and the performance of the IP network recovers after it has degraded due to environmental changes.

Our proposal works on the basis of periodic measurements of the link load, which is the volume of traffic on links, and it uses load information on links to know the conditions of the IP network. This information is converted to activity, which is the value to control deterministic and stochastic behaviors. Our method constructs a new VNT according to the system state of attractor selection, and the constructed VNT is applied as the new infrastructure for the IP network. By flowing traffic demand on this new VNT, the load on links in the IP network is changed, and our method retrieves this information to know the conditions of the IP network.

B. VNT Control Method Based on Attractor Selection

In the following sections, we use i, j, s, and d as indexes of nodes, and p_{ij} as an index of the source-destination pair from node i to j.

1) Dynamics of VNT Control: We place genes on every source-destination pair p_{ij} in the WDM network and the expression level $x_{p_{ij}}$ of each gene determines the number of lightpaths on p_{ij}. To avoid confusion, we refer to genes placed on the WDM network as *control units* and the expression levels of the control units as *control values*.

The dynamics of $x_{p_{ij}}$ is defined by the following equation,

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

where η represents white Gaussian noise, $\mathrm{f}(z) = 1/(1+\exp(-z))$ is the sigmoidal regulation function, and v_g is the value that indicates the condition of the IP network. We use the same formula as in [14] to determine the control values. According to the observation in [14], we use white Gaussian noise with a mean of 0 and a variance of 0.2 for η.

The number of lightpaths between p_{ij} is determined according to $x_{p_{ij}}$. We assign more lightpaths to a node pair with a high control value than one with a low control value. Function $\mathrm{f}(z_{p_{ij}} - \theta_{p_{ij}})$, where $z_{p_{ij}} = \sum_{p_{sd}} W(p_{ij}, p_{sd}) \cdot x_{p_{sd}}$, has its center at $z_{p_{ij}} = \theta_{p_i j}$ and exhibits rapid growth near $\theta_{p_{ij}}$. With smaller $\theta_{p_{ij}}$, the curve of $\mathrm{f}(z_{p_{ij}} - \theta_{p_{ij}})$ is shifted in the negative direction, and thus $\mathrm{f}(z_{p_{ij}} - \theta_{p_{ij}})$ increases. This increases $\mathrm{d}x_{p_{ij}}/\mathrm{d}t$, and this then leads to an increase in $x_{p_{ij}}$. This is equivalent to increasing the number of lightpaths between p_{ij} in our VNT control method. In the same way, a larger $\theta_{p_{ij}}$ leads to a decrease in the number of lightpaths between p_{ij}. Therefore, we control the number of lightpaths by adjusting $\theta_{p_{ij}}$ depending on the load on the link. To reduce the influence from fluctuations of the measured link load on VNT control, we use the exponential moving average of the link load, $y_{p_{ij}}$, with a smoothing factor of 0.5. To assign more lightpaths to a node pair with a highly loaded link, we decrease $\theta_{p_{ij}}$ for node pair p_{ij} that has high $y_{p_{ij}}$. We determine $\theta_{p_{ij}}$ by using $\theta_{p_{ij}} = -(y_{p_{ij}} - y_{\min})/(y_{\max} - y_{\min}) \times 2\theta^{\star} + \theta^{\star}$, where $\theta^{\star}$ is the constant value that represents the range of $\theta_{p_{ij}}$, and $y_{\max}$ and $y_{\min}$ correspond to the maximum and minimum load in the network. If p_{ij} has no links, we use $y_{\min}$ as $y_{p_{ij}}$ to gradually modify the VNT.

2) Regulatory Matrix: The regulatory matrix is an important parameter since the deterministic behavior of our method is dominated by this matrix. Each element in the regulatory matrix, which is denoted as $W(p_{ij}, p_{sd})$, represents the relation between node pair p_{ij} and p_{sd}. The value of $W(p_{ij}, p_{sd})$ is a positive number α_A, zero, or a negative number α_I, corresponding to activation, no relation, and inhibition of the control unit on p_{ij} by the control unit on p_{sd}. If the control unit on p_{ij} is activated by that on p_{sd}, increasing $x_{p_{sd}}$ leads to increasing p_{ij}. That is, node pair p_{sd} increases the number of lightpaths on p_{ij} in our VNT control method.

Let us consider three motivations for setting up or tearing down lightpaths for defining the regulatory matrix, i.e., establishing lightpaths for detouring traffic, increasing the number of lightpaths for the effective transport of traffic on the IP network, and decreasing the number of lightpaths due to a certain fiber being shared with other node pairs. First, for detouring traffic on the route from node i to j to other lightpaths, new lightpaths should be set up between node pair p_{ij}. We interpret this motivation as the activation of the control unit on p_{ij} by the control units on each node pair along the route of the lightpath between p_{ij}. Let us next consider the situation where a path on the IP network uses the lightpaths on p_{ij} and p_{sd}. In this case, a certain amount of 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 for IP traffic to be effectively transported. Therefore, the control units on p_{ij} and p_{sd} activate each other. Finally, let us consider the relation between node pairs that share a certain fiber. If the number of lightpaths on one node pair increases, that 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. To achieve a more effective VNT control method in terms of optimal performance, other motivations such as the relation between adjacent node pairs should be considered. Since the main purpose in this research is to achieve a robust VNT control method, we consider three motivations mentioned above.

The constant values, α_A and α_I, represent the strength of activation and inhibition. The total regulatory input to each control unit, $z_{p_{ij}} = \sum_{p_{sd}} W(p_{ij}, p_{sd}) x_{p_{sd}}$, is inherent in Eq. (1) and should be independent of the number of control units since the appropriate regulatory input is determined by the sigmoid function, $\mathrm{f}(z_{p_{ij}})$. To achieve a VNT control method that flexibly adapts to various environmental changes, Eq. (1) must have a sufficient number of equilibrium points, which are potential attractors depending on the surrounding environments. In this paper, we determine α_A and α_I to keep the total regulatory input to each gene the same strength as the result in [14]. We define α_A as $\alpha_A = 1.08N/\sum_{p_{ij}}\sum_{p_{sd}} W^A(p_{ij}, p_{sd})$ and α_I as $\alpha_I = 1.08N/\sum_{p_{ij}}\sum_{p_{sd}} W^I(p_{ij}, p_{sd})$, where N is the number of control units, and $W^A(p_{ij}, p_{sd})$ and $W^I(p_{ij}, p_{sd})$ are binary variables. The variable $W^A(p_{ij}, p_{sd})$ takes 1 if the control unit on p_{ij} is activated by that on p_{sd}, and otherwise 0. Due to the space limitation, we have omitted a detailed description from this paper. For a more detailed description, readers can refer to our previous work [16] and [14].

3) Activity: The growth rate is the value that indicates the conditions of the metabolic reaction network, and the gene regulatory network seeks to optimize the growth rate. In our VNT control method, we use the maximum link utilization, i.e., link load normalized by its capacity, on the IP network as a metric that indicates the conditions of the IP network. To avoid confusion, we will refer to the growth rate defined in our VNT control method as *activity* after this. This activity must be an increasing function for the goodness of the conditions of the target system, i.e., the IP network in our case, as mentioned in Section II. Therefore, we convert the maximum link utilization on the IP network, $u_{\max}$, into the activity, v_g, as

$$v_g = \begin{cases} \dfrac{\gamma}{1 + \exp(\delta \cdot (u_{\max} - \zeta))} & \text{if } u_{\max} \geq \zeta \\ \dfrac{\gamma}{1 + \exp(\delta/5 \cdot (u_{\max} - \zeta))} & \text{if } u_{\max} < \zeta \end{cases} \quad (2)$$

where 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 rapidly approaches 0 due to the poor conditions of the IP network. Then, the dynamics of our VNT control method is governed by noise and the search for a new attractor. Where the maximum link utilization is less than ζ, we increase the activity slowly with decaying gain in the activity to improve the maximum link utilization. Since improving the maximum link utilization from a higher value has a greater impact on the IP network than that from a lower value even if the degree of improvement is the same, we differentiate the gain of the activity as depending on the current maximum link utilization. Moreover, by retaining the incentive for improving maximum link utilization, our VNT control method continuously attempts to improve the conditions of the IP network. Parameter γ is set to 100, which is shown as the enough large value for the gene regulatory network to converge attractors despite the existence of noise in [14]. We set the target maximum link utilization, ζ, to 0.5 and the δ to 50 to achieve quick responses to changes in $u_{\max}$.

4) VNT Construction: The number of lightpaths between node pair p_{ij} is calculated on the basis of $x_{p_{ij}}$. However, since a fixed amount of noise has a constant influence on our VNT control method even when the IP network has good conditions and activity is high, $x_{p_{ij}}$ keep fluctuating. Thus, it leads to fluctuations in VNTs to construct VNTs by using $x_{p_{ij}}$ directly. To achieve stable VNT control, we introduce hysteresis, which is often used for avoiding routing fluctuations [17]. We use $x'_{p_{ij}}$ as the hysteresis applied on expression level. We set $x'_{p_{ij}}$ to $x_{p_{ij}}$ when $|x_{p_{ij}} - x'_{p_{ij}}| > \Delta$, and keep its current value otherwise. We determine the hysteresis threshold as $\Delta = v_g \cdot \varepsilon$, where ε is a constant value. Since low activity means a poor condition of the IP network, VNTs must be reconfigured to recover. Thus, in the case of low activity, we encourage reconfigurations of VNTs by using a small hysteresis threshold. In contrast, we use a large hysteresis threshold in the case of high activity to improve the stability of our VNT control method. To achieve stable VNT control in the case of high activity, we set ε to 0.0025, which makes Δ slightly larger than the variance of noise, η.

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 optical transmitters and receivers 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

$$G_{p_{ij}} = \min\left(\lfloor P_R \cdot \frac{x'_{p_{ij}}}{\sum_s x'_{p_{sj}}} \rfloor, \lfloor P_T \cdot \frac{x'_{p_{ij}}}{\sum_d x'_{p_{id}}} \rfloor\right). \quad (3)$$

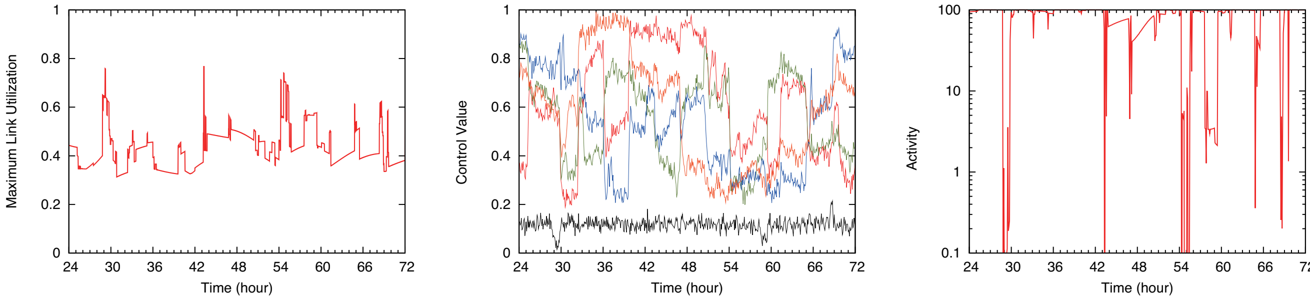
Since we adopt the floor function for converting real numbers to integers, each node has residual transmitters and receivers. We assign one lightpath in descending order of $x'_{p_{ij}}$ while the constraint on the number of transmitters and receivers is satisfied. Note that other constraints derived from physical resources such as the number of wavelengths on a fiber can easily be considered. For instance, restrictions on the number of wavelengths on a fiber are satisfied by adding $x'_{p_{ij}}$ normalized by the total control values for all the node pairs that use the same fiber to Eq. (3).

IV. Performance Evaluation

A. Simulation Conditions

We use the European Optical Network (EON) topology shown in Fig. 2 for the physical topology. The EON topology has 19 nodes and 39 bidirectional links. Each node has eight transmitters and eight receivers. We use the minimum hop routing of lightpaths on the WDM network. We use randomly generated traffic demand matrices in the evaluations that followed.

We focus on changes in traffic demand in the IP network and fiber failures as the environmental changes. We consider two types of traffic changes; the first included gradual and



(a) Maximum link utilization (b) Control values (c) Activity

Fig. 3. Basic behavior of VNT control based on attractor selection.

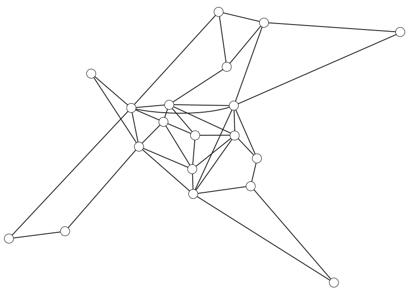


Fig. 2. European Optical Network topology

periodic changes and the second included sudden and sharp changes. By using Fourier series, traffic demand from node i to j at time t, $d_{ij}(t)$, changes gradually and periodically as $d_{ij}(t) = \beta_{ij}(a + \sum_{h=1}^{H}(b_{ij}^h \cos(2\pi th/T) + c_{ij}^h \sin(2\pi th/T)))$, where T is the cycle of changes in traffic demand; we use 24 hours as a cycle in this simulation. The constant parameters a, b_{ij}^h, and c_{ij}^h define the curve of $d_{ij}(t)$, and β_{ij} scales $d_{ij}(t)$. Since our main objective is to achieve adaptability against changes in traffic demand and not to optimize the performance of the VNT control method for realistic traffic patterns, we simply generate the parameters as follows. Parameters b_{ij}^h and c_{ij}^h are uniformly distributed random numbers in a range from 0 to 1. We set the constant value a to $\sqrt{2}$ to ensure that $d_{ij}(t)$ is non-negative. The scale factor of traffic demand β_{ij} follows a log-normal distribution with variance in the variable's logarithm, σ^2, according to the observation in [18]. We set H to 1. For abrupt changes in traffic demand, we randomly change β_{ij} at certain intervals while keeping the expected value of total traffic demand in the network constant. Shortest hop paths are used for forwarding traffic on the IP network.

B. Behaviors of VNT Control Based on Attractor Selection

This section explains the basic behaviors of our VNT control method. In the simulation experiments, we assume that our VNT control method will collect information about load on links every 5 minutes. We evaluate our VNT control method with the maximum link utilization in Fig. 3(a). The horizontal axis plots the time in hours and the vertical axis plots the maximum link utilization. The results for the first 24 hours have been omitted to disregard the transient phase during the simulation. In this section, we only focus on changes in traffic demand as environmental changes to highlight the basic behavior of our proposed method. Abrupt traffic changes occur every 3.6 hours and traffic demand continuously and gradually changes in the time between these abrupt traffic changes. Maximum link utilization degrades drastically every 3.6 hours due to the abrupt changes in traffic, but the maximum link utilization recovers shortly after this degradation.

To illustrate the adaptation mechanism of our VNT control method more clearly, we will present the control values, which determine the number of lightpaths between node pairs, and the activity, which is fed back to the our VNT control method and controls stochastic and deterministic behaviors, in Figs. 3(b) and 3(c), respectively. In Fig. 3(b), we selected five control units out of 342 on all node pairs and have plotted the control values for these control units. When there are only periodic and gradual changes in traffic demand, our proposed method adjusts the control values depending on the changes in traffic demand. When maximum link utilization is degraded due to sharp changes in traffic demand, this degradation is reflected as a decrease in activity as shown in Figs. 3(a) and 3(c). As the result of the decreases in activity, stochastic behavior dominates over deterministic behavior in our VNT control method. This is observed as fluctuations in the control values in Fig. 3(b). Our method searches for a new VNT that is suitable for the changed traffic demand while stochastic behavior dominates deterministic behavior. After the new VNT is constructed and the maximum link utilization is recovered, activity increases, and then deterministic behavior again dominates in the VNT control method. In this way, our method adapts to both abrupt and gradual changes in traffic demand by controlling deterministic and stochastic behavior with activity. In the previous work [16], we compared our method with other heuristic methods that aimed at accommodating changes in traffic demand and showed that our method achieves the higher adaptability and at least the same the same level of the efficiency in terms of the maximum link utilization. Due to the space limitation, we have omitted those results.

C. Adaptability to Environmental Changes

We next show the behavior of our VNT control method when link failures and abrupt changes in traffic demand occur

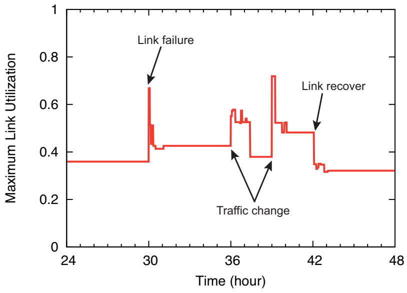


Fig. 4. Robustness against changes in traffic demand and link failures

simultaneously. We select 10 out of 78 optical fibers randomly, which fail at time 30 and recover at time 42. While fibers fail, two abrupt changes in traffic demand occur at time 36 and 39. The main purpose in this experiment is to investigate the adaptability of our proposed method, which is performed on the WDM network. To observe the adaptability of our proposed method more clearly, we assume that the IP network reroutes its traffic shortly after the occurrence of fiber failures.

The maximum link utilization over time is shown in Fig. 4. At time 30, it degrades due to fiber failures but recovers shortly after this degradation. Note that our proposed method has no mechanism to detect fiber failures and knows the condition of the IP network only through the activity. Therefore, the VNT control method based on attractor selection recovers from the degradation in the maximum link utilization due to fiber failures through the activity and the stochastic behavior as described in Section IV-B. Fiber failures and changes in traffic demand occur simultaneously at time 36 and 39, and this leads to the degradation in the maximum link utilization. However, our proposed method again recovers from this degradation in the same way as shown in Section IV-B.

V. Conclusion

We proposed a VNT control method that is robust to environmental changes. It is based on attractor selection, which models the behaviors of biological systems that adapt to environmental changes and recover their conditions. Our new approach is extremely adaptable to changes in traffic demand and fiber failures by appropriately controlling deterministic and stochastic behaviors depending on the activity, which is simple feedback of the conditions on the IP network. Our proposed method only uses load information on links to determine the activity. Since the load on links is directly retrieved within short intervals, our proposed method quickly and adaptively responds to changes in traffic demand and fiber failures. The simulation results indicated that our VNT control method quickly responds and adapts to changes in traffic demand and fiber failures. By using stochastic behavior and controlling it appropriately depending on the activity, our new approach adapts to various environmental changes.

In our approach, stochastic behavior, i.e., noise, plays an important role in achieving adaptability against environmental changes. In this paper, we defined the noise according to the observation in [14]. A future direction is to investigate suitable noise amplitude for VNT control methods to achieve more efficient search for a new VNT.

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