A method for updating attractor sets in noise-induced virtual network topology control

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***Abstract*—Our research group has proposed a VNT control method based on attractor selection. Since the number of attractors composing an attractor set is limited, it is important to decide what kind of attractors should be prepared. The existing method prepares attractors such that their topological characteristics are different from each other. However, since the existing method does not incorporate current traffic information for designing attractors, it is likely that VNT control needs additional time to find a good VNT. In this paper, we examine several strategies for updating attractors and evaluate the effectiveness of the strategies in terms of the number of steps to find a solution. Our basic approach is to check each attractor to see whether it is adaptive under the current traffic demand or not through offline simulations. Evaluation results show that removal of inappropriate attractors is most effective; the strategy reduces the number of steps to find a solution by 60 %.**

***Index Terms*—VNT Control, Wavelength Routing, Attractor, Attractor Selection, Attractor Update, Noise-induced Control**

I. Introduction

As smartphones and tablet-type devices become popular, many people are connected to the Internet. The volume of Internet traffic has increased approximately 10 times during the last decade and is predicted to increase even faster for the next decade [1], [2]. Nowadays, many people enjoy various Internet services such as video streaming or cloud services and expect new Internet services to further improve our Internet life. Such the situation leads to the large fluctuations of traffic demand on the Internet.

One of the approaches to adapt to fluctuations of traffic demands and effectively accommodate IP traffic is to deploy a flexible infrastructure, such as software-defined network (SDN) or networks based on wavelength division multiplexing (WDM). Then, the network operator constructs a virtual network and controls virtual network topologies (VNTs) in a dynamical manner. That is, network operators conduct traffic engineering over the flexible infrastructure so that the virtual network can adapt to the large fluctuations of traffic demands. VNT control in IP over WDM network is one of the examples to adapt to fluctuations of traffic demands. IP over WDM network consists of two layers, IP network and WDM network (Fig.1). In the WDM network, optical cross connects (OXCs) are interconnected by optical fibers. A set of optical channels, called lightpaths, are established between IP routers via OXCs. IP packets as electric signals are converted into optical signals and OXCs switch optical signals in the WDM network. Lightpaths and IP routers form a virtual network topology (VNT) and it accommodates IP traffic on the WDM network.

Many researches have investigated methods to accommodate the virtual network (see [3] and references therein). For example, a method proposed in [4] creates an optimal virtual network in terms of embedding costs, i.e., resources needed to respond to virtual network requests, by solving a mixed integer linear program (MILP). Ref. [5] investigates a method to reconfigure a VNT for IP over WDM networks, which aims to minimize the average hop distance or the maximum link utilization for time-varying traffic by solving a MILP. However, such the MILP approach requires traffic demand matrices and are available in advance since the optimal solution depends on the situation that the network faces. Since it requires some effort to obtain the traffic demand, it is difficult to quickly configure a VNT following traffic changes when traffic demands fluctuate largely. Therefore, it is important to achieve a method of controlling a VNT that is adaptive to changing traffic demands in a shorter period.

Our research group has proposed a VNT control method that is adaptive to fluctuations of traffic demands [6]. The method is based on a dynamical system called the attractor selection model which models a behavior where living organisms adapt to unknown changes in their surrounding environment and recover their conditions. The behavior of the system driven by attractor selection is described as

$$\frac{d\mathbf{x}}{dt} = \alpha \ \cdot f(\mathbf{x}) + \eta, \tag{1}$$

where $\mathbf{x}$ represents a state of the system, α is the conditions of the system, $f(\mathbf{x})$ defines an attractor structure in which a set of attractors is embedded. The attractor is a part of equilibrium points in the solution space. η represents a noise term. Note that this method only uses the conditions of the IP network, such as the maximum link utilization, for VNT control while most VNT control methods need information on traffic matrices. We have shown in Refs. [6], [7] that this method can configure a VNT adaptively against the fluctuations in network environments such as traffic changes and node failures.

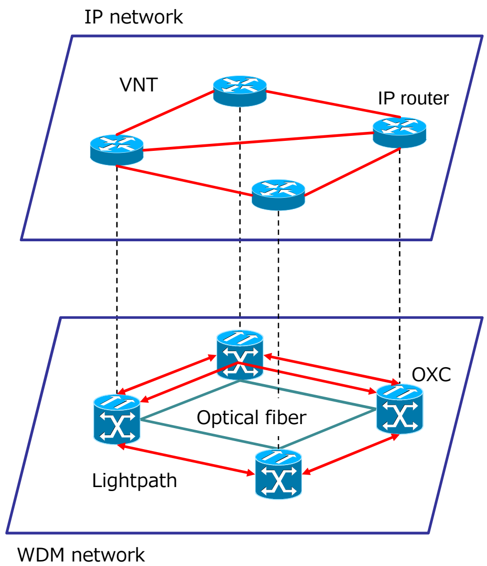


Fig. 1. IP over WDM network

In the VNT control method based on attractor selection, one of the important problems is how to set $f(\mathbf{x})$, i.e., what kinds of attractors are set to $f(\mathbf{x})$ since it determines the attractive state of the dynamical system. In Refs. [6], [7], the function $f(\mathbf{x})$ is prepared in a random manner. In Refs. [8], a design method for preparing attractors is proposed. The design method enumerates every pattern of VNTs and calculates the edge betweenness centrality [9] for each VNT. Then, the method prepares attractors whose bottleneck lightpaths are different from each other so that various kinds of VNTs are searched by the attractor selection. However, since the edge betweenness centrality is not dependent on traffic demand, some of the attractors in the attractor structure may be useless in a current traffic. More specifically, the state of the system takes a long time to reach a solution where its conditions are good.

In this paper, to prepare attractors adaptive to a current traffic, we investigate several approaches to updating a set of attractors based on the current traffic demand matrices. As mentioned above, a long time measurement is required to get the information of current traffic demand. However, we use the traffic demand information because intervals of updating a set of attractors can be longer than the interval of VNT control driven by Eq. (1). Our basic idea is to check whether or not each attractor is adaptive to current traffic demand via offline simulations. Using computer simulations, we evaluate several approaches for removal and addition of attractors to see the best approach to reducing the time to reach a solution.

The rest of this paper is organized as follows. In Section 2, we explain our VNT control method based on attractor selection. We then explain strategies for updating a set of attractors in Section 3. In Section 4, we evaluate the performance of VNT control with attractor update by a computer simulation. Finally, we conclude this paper in Section 5.

II. VNT Control Method Based on Attractor Selection

In this section, we explain our VNT control method based on attractor selection.

A. *Overview of VNT Control Based on Attractor Selection*

The behavior of VNT control based on attractor selection is described in Eq. (1). The state of the system is represented by $\mathbf{x} = (x_1, x_2, ..., x_n)$ (where n is the number of state variables). The basic mechanism of VNT control consists of deterministic behavior ($f(\mathbf{x})$) and stochastic behavior (η). The behavior is controlled by α, which indicates the conditions of the IP network. When the current conditions of the IP network are poor, α becomes small. Then, the stochastic behavior is dominant in controlling the system. When the current conditions of the IP network are good, α becomes large. Then, the influence of the stochastic behavior becomes a little and the state of the system converges on an attractor defined by $f(\mathbf{x})$. When an environmental change occurs and the system condition gets worse, α becomes low. The stochastic behavior dominates the system and system searches for a solution with a little effect of $f(\mathbf{x})$. During the search for a solution, when the system condition becomes moderate, the effect of $f(\mathbf{x})$ becomes large. Then, the system state is moved to the equilibrium points defined by $f(\mathbf{x})$.

Our VNT control method regards the on-off state of lightpaths as the state of the system and uses the conditions of the IP network as activity α. Our VNT control method then configures VNTs so that the comfort of the IP network gets improved when the conditions of the IP network become uncomfortable due to fluctuations of traffic demands.

B. *Activity*

Our VNT control method uses maximum link utilization on the IP network as a performance metrics. Although it is necessary to collect load information on all links (lightpaths) in the IP network, this can be retrieved in a much shorter time than the traffic demand matrices used by existing VNT control methods. We convert the maximum link utilization on the IP network, u_{max}, into the activity α as

$$\alpha = \frac{\gamma}{1 + \exp(\delta \cdot (u_{max} - \theta))}. \tag{2}$$

The activity is in a range of $[0, \gamma]$. The constant number θ is a threshold for VNT control. When the maximum link utilization is more than the threshold θ, the activity rapidly approaches to zero and our VNT control method searches for a new attractor so that the condition of the IP network gets improved. δ is also a constant number, which determines an inclination of the function.

C. Dynamics of VNT Control

Our VNT control method decides whether or not to set up a lightpath l_i according to a state variable $x_i (\in \mathbf{x})$. Dynamics of the state x_i is defined as

$$\frac{dx_i}{dt} = \alpha \cdot \left[\varsigma \left(\sum_j W_{ij} x_j \right) - x_i \right] + \eta. \quad (3)$$

α indicates the conditions of IP networks. The term $\varsigma\left(\sum_j W_{ij} x_j\right) - x_i$ represents the deterministic behavior. $\varsigma(z) = \tanh(\frac{\mu}{2} z)$ is a sigmoidal regulation function. The first term is calculated with a regulatory matrix W_{ij}, which defines an attractor structure. The second term η represents the stochastic behavior and is white Gaussian noise. After x_i is updated on the basis of Eq. (3), we decide whether or not to set up the lightpath l_i. Specifically, we set a threshold to 0 and if x_i is equal to or more than the threshold, we set up the lightpath l_i and otherwise tear down the lightpath l_i.

D. Attractors

Although the solution space is 2^{n^2} (n is the number of nodes), the number of attractors that can be kept as attractors is limited to 10 - 15% of the number of lightpath candidates n^2. Thus, it is important for attractor selection model to obtain "good" attractors for VNT control. In Refs. [6], [7], the function $f(\mathbf{x})$ is prepared in a random manner. Ref. [8] proposes a method for designing attractors to make VNT control method more adaptive against traffic changes. The basic idea is to classify attractor candidates that have different bottleneck links each other into different groups, as shown in Fig. 2. A bottleneck link is a link that has the largest value of edge betweenness centrality among links that form an attractor candidate. By preparing attractors with diverse characteristics, various kinds of VNTs are searched by attractor selection. Numerical results show that VNT control method with the designed attractors reduces the number of steps to find a solution.

E. Construction of Attractor Structure

The regulatory matrix W_{ij} that the first term of Eq. (3) has determines an attractor structure. We set the regulatory matrix so that pre-specified system state can be an attractor. Assuming that we set m attractors and one of the attractors is represented as $\mathbf{x}^{(k)} = (x_1^{(k)}, x_2^{(k)}, \ldots, x_n^{(k)})$ $(1 \le k \le m)$, the regulatory matrix that has m attractors is calculated as

$$\mathbf{W} = \mathbf{X}^{+}\mathbf{X}, \quad (4)$$

where $\mathbf{X}$ is a matrix that has $\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \ldots, \mathbf{x}^{(m)})$ in each row and $\mathbf{X}^{+}$ is the pseudo inverse matrix of $\mathbf{X}$.

III. Strategies for Updating Attractors

A. Necessity of Updating Attractors

In our VNT control method, it is important to decide what kinds of attractors are set to $f(\mathbf{x})$ since it determines the attractive state of the dynamical system. In the biological system, the attractor structure may be prepared based on an experience along with a long evolutionary history. In the engineering system, however, the attractor structure should be designed since, if we do not design the attractor structure properly, the state of the system takes a long time to reach a solution where its conditions are good. This fact is observed from the results of Ref. [8] which proposes a design method for the attractor structure. However, as we have explained in Sec. II-D, the design method considers topological characteristic and does not adjust the attractor structure to the traffic demand that the network faces.

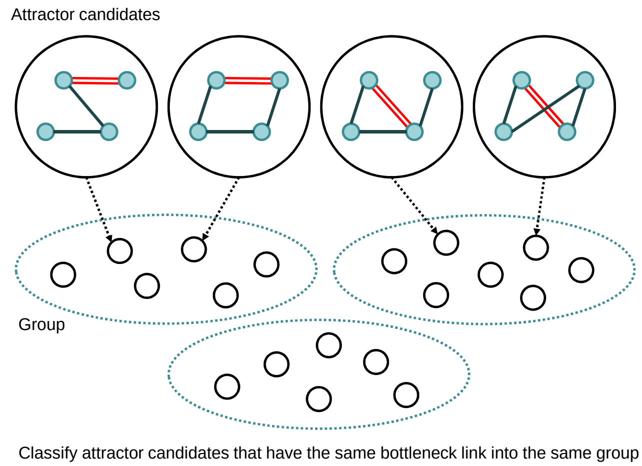


Fig. 2. Classification of attractor candidates.

What happens if the attractor structure or a part of attractors is not suitable for the current traffic demand? It is easily imagined from Eq. (1) that the system state may be attracted at first to an inappropriate attractor, but because the attractor is not inappropriate, the system state is next attracted to other attractors. That is, the inappropriate attractors will increase the number of steps to find a solution which can accommodate the traffic demand. Note that this is a rather worse scenario because the system state may also be attracted at first to inappropriate attractors. Thus, updating attractors, more specifically, removing inappropriate attractors is important to reduce the number of steps to find a solution when we apply the attractor selection to the engineering system.

We can take several strategies for updating the attractor structure over a dynamically changing environment. For example, new attractors can be added into $f(\mathbf{x})$ after the removal of inappropriate attractors. We will examine several strategies and evaluate their performance in Sec. 4.

B. Framework for Updating Attractors

The goodness and badness of attractors depend on the environment that the network faces. In the case of VNT control, the environment is the traffic demand. This suggests that the attractor structure should be updated based on the traffic demand. However, one of the advantages of our VNT control method is that the method does not need the information on the current traffic demand. To overcome this contradiction, we

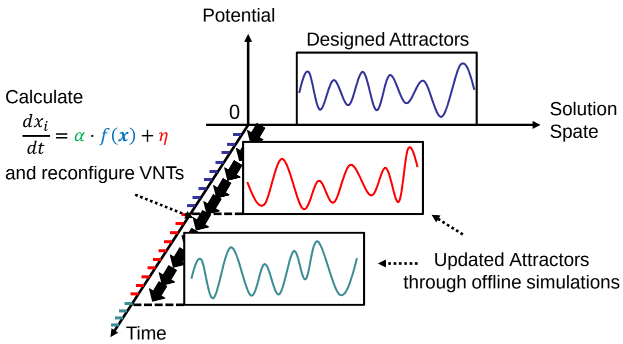


Fig. 3. Relation among attractor update, attractor selection, and attractor design

consider a framework that the interval of updating the attractor structure takes longer than the interval of reconfiguring a VNT.

Fig. 3 depicts the relation among the attractor update, the attractor selection, and the attractor design. Y-axis represents the actual time that the network is under spending. X-axis represents the system state, and its potential is plotted in Z-axis. The potential function $U(\mathbf{x})$ is derived from a relation $-dU(\mathbf{x})/dx = f(\mathbf{x})$, which means that $U(\mathbf{x})$ takes a lowest value when the system state is located at the attractor.

Before the initial time, $f(\mathbf{x})$ is designed by the method in Ref. [8] with an exhaustive calculation of topological characteristics of VNTs. At the initial time, VNT control method based on attractor selection starts to work. VNT control is carried out within a short period of time (black and fat arrows). Meanwhile, the traffic demand is measured by network operators through other network equipment. After the several steps of VNT control, the network operator acquires the current traffic demand. Then, the network operator updates the attractor structure to reduce the steps to find a solution in VNT control for the near future. The attractor structure can be updated at every time that the network operator acquires the current traffic demand.

With this framework, we can spend more time than the interval of VNT control for updating attractors. So, our basic idea for updating attractors is to utilize offline simulations to examine the effectiveness of each attractor and selects attractors which can reduce the number of steps to find a solution for VNT control. For the offline simulations, the information of the current traffic demand can be used. We prepare a virtual traffic environment that is the same as actual traffic environment and identify attractors that are adaptive to the environment without reconstructing an actual VNT.

C. Strategies for Updating Attractors

We explain the procedure of the method for updating a set of attractors. Meanings of notations are summaraized below.

- ϕ_i $(1 \leq i \leq N_{att})$: the i-th attractor
- η_s $(1 \leq s \leq N_{noise})$: noise with a seed s
- c_i: the number of successful configurations when VNT control with attractor ϕ_i is carried out. c_i is accumulated over η_s $(1 \leq s \leq N_{noise})$.
- $\mathbf{W}^{\{\phi_i\}}$: The regularity matrix whose attractor is ϕ_i. $\mathbf{W}^{\{\phi_i\}}$ is calculated by Eq. (4).

This method needs both the current traffic demand matrix T_{cur} and N_{att} attractors designed according to the algorithm in Ref. [8]. Although VNT control based on attractor selection is originally carried out through online calculations, our method verifies the effectiveness of attractors through offline calculations with T_{cur}. Specifically, we change traffic demands based on T_{cur}, control VNTs with each attractor, calculate the success rate and verify the effectiveness of attractors. During offline calculations, a state variable x_i, which decides whether or not to establish a lightpath l_i, is derived not from Eq. (3) but from Eq. (5). The success rate of VNT control using each attractor by the step S_{th} is calculated, and one or more attractors whose success rate is more than C_{th} are chosen. Finally, the regulatory matrix is updated according to the attractor set consisting of chosen attractors. The procedure of updating the attractor structure is described below.

Step 1. Initialize the variable $i \leftarrow 1, c_1, c_2..., c_{N_{atr}} \leftarrow 0$, go to Step 2.

Step 2. Calculate $\mathbf{W}^{\{\phi_i\}}$ based on Eq. (4) with the attractor $\{\phi_i\}$, go to Step 3.

Step 3. Execute following procedures for every seed of noise s $(1, 2, ..., N_{noise})$. Then, go to Step 4.

Step 3.1. Control VNTs based on T_{cur} by

$$\frac{dx_k}{dt} = \alpha \cdot \left[\varsigma \left(\sum_k W_{kl}^{\{\phi_i\}} x_l \right) - x_k \right] + \eta_s. \quad (5)$$

Then go to Step 3.2.

Step 3.2. Calculate $c_i \leftarrow c_i + 1$ when the goal of VNT control is achieved by the step S_{th}.

Step 4. When the calculation of the success rate of all attractors is finished, go to Step 5. Otherwise calculate $i \leftarrow i + 1$ and go to Step 2.

Step 5. Select attractors, ϕ_i, whose success rate, c_i, is greater than C_{th} and set them to the attractor set $\mathbf{\Phi}_{adaptive}$, go to Step 6.

Step 6. Calculate $\mathbf{W}^{\mathbf{\Phi}_{adaptive}}$ with $\mathbf{\Phi}_{adaptive}$ and update the regulatory matrix $\mathbf{W}$ with $\mathbf{W}^{\mathbf{\Phi}_{adaptive}}$.

IV. Evaluation of the Method for Updating Attractor Sets

A. Evaluation Environment

Physical Topology: A physical network for evaluation is shown in Fig. 4. USNET consists of 24 nodes and 86 links. Each node is composed of an OXC and an IP router. Optical fibers interconnect OXCs. The number of transmitters or receivers of IP routers is 10.

VNT control based on attractor selection: The noise η in Eq. (3) is a normal random number whose mean is 0 and deviation is 0.3 and μ is 20 in the equation $\varsigma(z) = \tanh(\frac{\mu}{2}z)$. Each parameter are defined as follow: $\gamma = 1$, $\delta = 50$, $\theta = 0.5$. The initial VNT is a random topology. We judge VNT control succeeds when max link utilization is less than 0.5 during 10 steps of VNT control in a row.

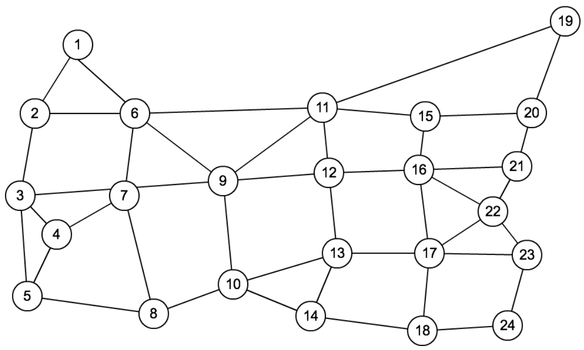


Fig. 4. USNET

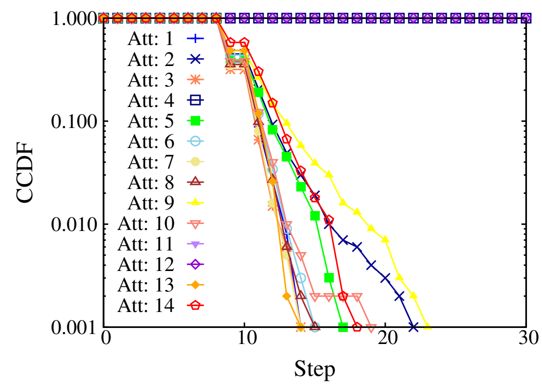


Fig. 5. The success rate of VNT control with each attractor

The parameters for updating attractors*:* In Eq. (5), the noise η_s is generated randomly with Gaussian distribution whose mean is 0 and deviation is 0.3. The parameters for updating attractors introduced in Sec. III-C is set as follows, $N_{att} = 7$, $N_{noise} = 1000$, $S_{th} = 14$, $C_{th} = 50$. We prepare 7 attractors designed based on the method in Ref. [8] before executing the algorithm in Sec. III-C.

Traffic Demand and Traffic Changes*:* The traffic demand $\mathbf{T}_{cur}$ is given by $\mathbf{T}_{cur} \leftarrow \mathbf{LN}(3.5,\ (0.1)^2)$. $\mathbf{LN}(\mu,\ \sigma^2)$ is a matrix whose components are lognormal random numbers. The numbers have the mean μ and the deviation σ.

Then, we change the traffic demand based on T_{cur} by following equation;

$$\mathbf{T}(0) \leftarrow \mathbf{T}_{cur} + \mathbf{N}(0,\ \sigma^2), \tag{6}$$

where $\mathbf{N}(\mu,\ \sigma^2)$ is a matrix whose components are normal random numbers that has the mean μ and the deviation σ. σ represents the scale of the traffic change, and we can evaluate how large scale VNT control with this method can adapt to. 1000 patterns of traffic changes are different from their seeds of $\mathbf{N}(0,\ \sigma^2)$.

Goal of VNT control*:* The goal of VNT control is to achieve max link utilization less than 0.5.

Attractor Sets*:* We prepare attractor sets $\mathbf{\Phi}_{static}$, $\mathbf{\Phi}_{adaptive}$ and $\mathbf{\Phi}_{add}$. $\mathbf{\Phi}_{static}$ is constructed by the method in Ref. [8]. $\mathbf{\Phi}_{adaptive}$ is the attractor set designed by removing non-adaptive attractors from $\mathbf{\Phi}_{static}$, and $\mathbf{\Phi}_{add}$ is the attractor set constructed by adding other adaptive attractors into $\mathbf{\Phi}_{adaptive}$, where other adaptive attractors is selected from 7 additional attractors prepared by the method in Ref. [8] and the number of attractors in $\mathbf{\Phi}_{add}$ is equal to the number of attractors in $\mathbf{\Phi}_{static}$.

B. Evaluation Result

1) Calculation of the Attractor Set: Here, we remove non-adaptive attractors from the attractor set $\mathbf{\Phi}_{static}$. $\mathbf{\Phi}_{static}$ consists of 7 attractors (attractor: 1, 2, 3, 4, 5, 6, 7) based on the method in Ref. [8]. $\mathbf{\Phi}_{static}$ is described as follows:

$$\mathbf{\Phi}_{static} = \{\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \phi_7\}. \tag{7}$$

Then we produce the attractor set $\mathbf{\Phi}_{adaptive}$. We also select adaptive attractors from 7 additional attractors (attractor: 8, 9, 10, 11, 12, 13, 14), add them into $\mathbf{\Phi}_{adaptive}$ in descending order of success rate and construct the attractor set into $\mathbf{\Phi}_{add}$.

TABLE I
THE SUCCESS RATE AFTER RECONFIGURING VNTS 14 TIMES

Attractor	1	2	3	4	5	6	7
Success Rate (%)	100	97.1	100	0.0	97.8	99.8	100
Attractor	8	9	10	11	12	13	14
Success Rate (%)	99.9	96.3	99.6	0	0	100	96.8

The success rate of VNT control with each attractor is shown in Fig. 5. The value in X-axis represents the number of the steps to reconfigure VNTs and is expected to be smaller. In addition, The value in Y-axis means the success rate, and CCDF gets smaller as the success rate gets larger. Fig. 5 shows that the success rate is more than 90% at 14 steps when VNT control is carried out using adaptive attractors, in contrast, the success rate does not reach 5% even at 30 steps, using non-adaptive attractors. For the quantitive discussion, Table I shows the number of the success rate. We find that the success rate of attractor 4 is 0%. Therefore, we produce $\mathbf{\Phi}_{adaptive}$ as follows:

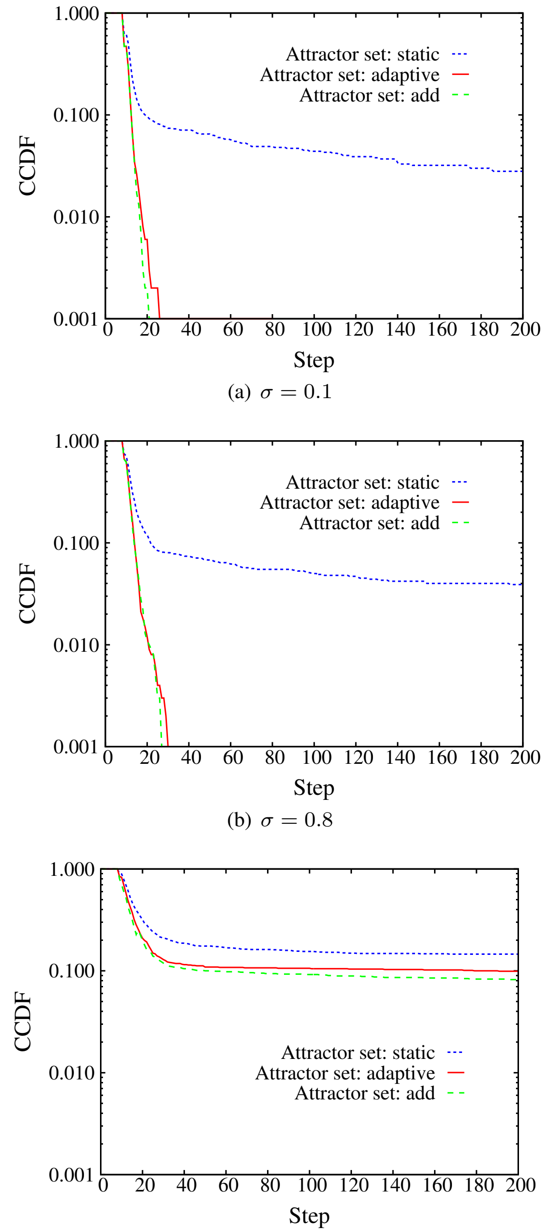
$$\mathbf{\Phi}_{adaptive} = \{\phi_1, \phi_2, \phi_3, \phi_5, \phi_6, \phi_7\}. \tag{8}$$

When we see the success rates of 7 additional attractors in Table I, we also find that the success rate of attractor 13 is 100%. Thus, we produce $\mathbf{\Phi}_{add}$ as follows:

$$\mathbf{\Phi}_{add} = \{\phi_1, \phi_2, \phi_3, \phi_5, \phi_6, \phi_7, \phi_{13}\}. \tag{9}$$

2) Evaluation of VNT Control after Fluctuations of Traffic Demands: Here, we evaluate several strategies and see the best strategy to reduce the time to find a solution. Specifically, we evaluate how many effects each attractor set prepared in Sec. IV-B1 has on the success rate and the number of steps of VNT control in the circumstances where traffic changes occur. Fig. 6 shows the success rate when σ in Eq. (6) is 0.1, 0.8 and 1.6. Even though traffic demands fluctuate, the success rate of VNT control with $\mathbf{\Phi}_{adaptive}$ is always higher than the one with $\mathbf{\Phi}_{static}$. In other words, this method can find a solution for VNT control quickly in comparison with the existing method. This result is due to the attractor 4. Since $\mathbf{\Phi}_{static}$ includes the attractor 4 while $\mathbf{\Phi}_{adaptive}$ does not, it is assumed that the attractor 4 has a bad effect on the success rate. By removing the attractor 4 from an attractor structure, this method achieves reduction of the number of steps to reach a solution. When $\mathbf{\Phi}_{adaptive}$ is compared with $\mathbf{\Phi}_{add}$, the success rate of attractor set "add" is slightly better than the success rate of attractor set "adaptive". We, however, do not consider $\mathbf{\Phi}_{add}$ is the best strategy because its effectiveness is limited in spite of the penalty of the amount of calculation for the success rate of VNT control with additional attractors.

When we see Fig. 6, the difference of the success rate among attractor sets is large in Fig. 6(a) and Fig. 6(b), but is small in Fig. 6(c). This means that the difference of the success rate among attractor sets gets smaller as the size of fluctuations gets bigger. Thus, attractor set "adaptive" and "add" are superior to attractor set "static" even if traffic demands change to some extent, but it is possible that they are not if fluctuations are too large. This method, however, is supposed to update an attractor structure periodically and dynamically with new $\mathbf{\Phi}_{adaptive}$, calculated using the information of traffic demands at the time. Our results show that removing inappropriate attractors effectively reduces the number of steps to find a VNT.



(a) $\sigma = 0.1$

(b) $\sigma = 0.8$

(c) $\sigma = 1.6$

Fig. 6. The success rate of VNT control when changing σ

V. Conclusion

The method in this paper is for updating attractor sets in VNT control based on attractor selection with an attractor set adaptive to traffic changes. The method in this paper utilizes attractors designed according to the method in Ref. [8] and the current traffic demand matrix, and constructs attractor sets by removing inappropriate attractors through offline calculations. We found that this method reduces the steps to find a solution for VNT control by approximately 60 % in comparison with the previous method.

In our simulations, we assume that the traffic demand matrix is available within several steps and it is always correct information. However, in the case of the large fluctuations of traffic demand, such the assumption may not be valid. Our future work is to consider strategies for updating the attractor structure in such the situation, and evaluate the performance of our method on various scale of network topologies.

Acknowledgment

This research was supported in part by Grant-in-Aid for Scientific Research (A) JP15H01682 of the Japan Society for the Promotion of Science (JSPS) in Japan.

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