A Distributed Control of Virtual Network Topologies by Using Attractor Selection Model

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Abstract—We propose a distributed VNT control method in IP over WDM networks. Our method is based on a dynamical system that models behavior where living organisms adapt to unknown changes in their surrounding environments and recover their conditions, and reduces computational overhead from previously proposed method. Evaluation results show that the method is as adaptive to traffic changes as previously proposed method.

1. Introduction

Optical networks offer a huge amount of bandwidth thanks to the wavelength-division multiplexing (WDM) technology that multiplexes optical signals operating on different wavelengths. Many researches have been devoted to investigates approaches to carry IP packets over the WDM-based optical networks (called IP over WDM networks) [1-3]. A most promising approach for the IP over WDM network is to set up an optical channel, called lightpath, between two IP routers through optical crossconnects (OXCs). OXCs that switch incoming wavelength signals are connected by fibers, which form a physical topology. A set of lightpaths offers a virtual network topology (VNT) to the IP network since no packet processing is required on lightpaths, and therefore, VNT is expected to reduce the processing overhead of IP routers.

To utilize the VNT, IP routers are equipped with optical transmitter and receiver devices that perform electro-optical signal conversion: a packet with electronic signal is converted to an optical signal and propagate the lightpath. Since the numbers of transmitter and receiver devices are limited due to a cost limitation of IP routers, it is not expected to prepare lightpaths between every pair of IP routers, which motivates us to control of VNTs under changing traffic demand.

In this paper, we present a distributed control method of VNT by using attractor selection. The attractor selection models a behavior where living organisms adapt to unknown changes in their surrounding environments and recover their conditions [4]. We have proposed a method that controls VNTs based on the attractor selection by a centralized manner and have shown that the method improves adaptability of VNT control against the changing traffic demand [5]. Our method presented in the current paper is an extension of the method in [5], and thereby our method inherits the adaptability as we will see the results in Section 3. At the same time, our method greatly reduces the calculation overhead thanks to the VNT control in a distributed manner.

2. A Distributed Control of VNT by Using Attractor Selection Model

2.1. Overview

Our basic idea for the distributed VNT control is to control a part of VNTs at each node[1]. More exactly, each node selects a set of lightpaths originating from the node by the attractor selection. Since a collection of lightpaths forms a VNT, a collection of the sets of lightpaths originating from each node also forms the VNT. Thus, our concern is how to select a set of lightpaths at each node by attractor selection.

In our approach, each node has controller that selects a set of lightpaths originating from the corresponding node. Hereafter, we denote a set of lightpaths originating from a node as *lightpath-tree*. The controller prepares the lightpath-tree candidates and set them as attractors which are used in the attractor selection. Figure 1 illustrates our control model. In the figure, the physical topology consists

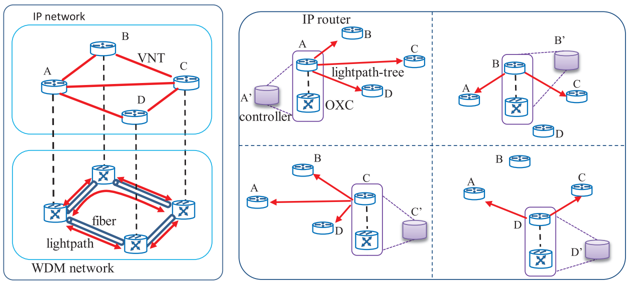

Figure 1: A Distributed Control of VNT

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[1] Here, a node consists of IP router and OXC as shown in Figure 1.

of 4 nodes (A, B, C, D) and each node has controller (A', B', C', D'). Then, attractor selection at each node selects a lightpath-tree, which in turn forms the VNT.

We next explain details of our lightpath-tree control conducted by each controller.

2.2. Lightpath-tree Control

2.2.1. *Concept of Attractor Selection*

Here, we briefly describe attractor selection, which is the key mechanism in our lightpath-tree control. The original model for attractor selection was introduced in [4]. 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 two behaviors, i.e., deterministic and stochastic behaviors, which are controlled by simple feedback of the conditions of the system. The system driven by attractor selection is expressed as the following expression.

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

The state of the system is represented by $\mathbf{x} = (x_1, \ldots, x_i, \ldots, x_n)$ (n is the number of state variables). α represents feedback of the system conditions, $f(\mathbf{x})$ represents deterministic term and η represents stochastic term. The state of the system is determined by $\alpha, f(\mathbf{x}), \eta$. α takes large value when the system conditions are suitable for the environment. When α takes large value, deterministic term $f(\mathbf{x})$ controls the system and drives the system to the attractor. When α takes small value, stochastic term η controls the system and the system state fluctuates randomly and searches for a new attractor. In this way, attractor selection adapts to environmental changes by selecting attractors using stochastic behavior, deterministic behavior, and simple feedback.

2.2.2. *Lightpath-tree Selection*

We next explain how to select the lightpath-tree by the attractor selection. Here, the main objective is to recover a performance of the IP network by appropriately selecting the lightpath-tree when the performance is degraded due to, e.g., the changes in traffic demand and the current VNT is no longer satisfactory.

Our method considers the state of the system as the state of all lightpaths originationg from the node. The information of condition or performance of IP network is interpreted as the feedback of conditions of the system. Figure 2 illustrates the control loop for our lightpath-tree control. Our method periodically measures link load which is defined as the traffic volume on lightpath divided by its capacity. In this paper, we use the maximum link load, which is the maximum of link load among every link, as the feedback information representing the condition of IP network.

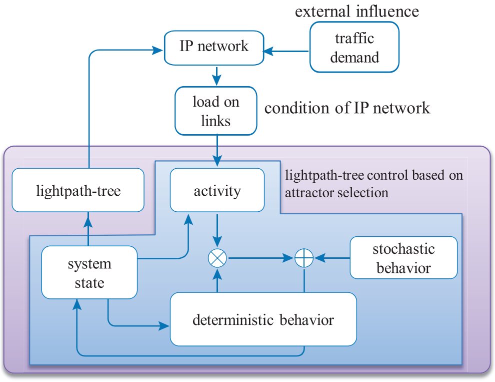

Figure 2: Control loop for lightpath-tree control based on attractor selection

The condition of IP network, that is, the maximum link load is converted to an activity value which is a control parameter to change the deterministic and stochastic behaviors. The detail of calculating the activity is presented in Section 2.2.3. Using the value of activity, the controller updates the system state based on Eq. 1. The controller selects a new lightpath-tree by converting from the updated system state. Finally, lightpaths are actually set up based on the lightpath-tree, and form a new VNT. IP network then uses the new VNT and accommodates the traffic demand, which may change the maximum link load of VNT. In our approach, the maximum link load is retrieved again, and is used as the information of the condition of IP network.

Formal description of our method is as follows. . We express the state of lightpath y_i by using the state variable x_i ($\in \mathbf{x}$). The dynamics of the state variable x_i is expressed as the following expression

$$\frac{dx_i}{dt} = \alpha \cdot \left(\zeta \left(\sum_j W_{ij} x_j \right) - x_i \right) + \eta \qquad (2)$$

α indicates the condition of the IP network. $\zeta\left(\sum_j W_{ij}x_j\right) - x_i$ represents deterministic term. $\zeta(z) = 1/(1 + exp(-\mu z))$ (μ is a parameter) is the sigmoidal regulation function. The first term of right of equation is the deterministic term and is calculated based on the interaction from all of lightpath-tree candidates where the interaction is defined by regulatory matrix W_{ij}. The second term, η, represents stochastic term and is white Gaussian noise. In this paper, the mean and variance of η is set to 0 and 0.15, respectively. After the x_i is updated based on Eq. 2, the controller decides whether or not to set up a lightpath based on a discrete value y_i. Note that x_i ranges from 0 to 1. We set a threshold to 0.5 and determine the value of y_i based on the threshold: y_i is set to 1 when x_i is 0.5 or greater than 0.5, otherwise y_i is set to 0.

When y_i is set to 1, the controller tries to set up the corresponding lightpath. However, because there is a limitation on the number of transmitters and receivers, the controller sometimes fails to set up the lightpath. In this case, the controller gives up setting up the corresponding lightpath.

When y_i is set to 0, the controller tears down the corresponding lightpath

2.2.3. Activity

In our control method, we use the maximum link load on the IP network as a metric that indicates the conditions of the IP network. This information is easily and directly retrieved by SNMP. This activity must be an increasing function for the goodness of the conditions of the target system. We convert the maximum link load on the IP network, u_{max}, into the activity, α by using the following expression. The constant number, θ, is the threshold for the activity. If the maximum link load is more than threshold θ, 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.

$$\alpha = \frac{\gamma}{1 + \exp(\delta \cdot (u_{max} - \theta))} \tag{3}$$

2.2.4. Construction of Attractor Structure of W_{ij}

The regulatory matrix W_{ij} is an important parameter since this matrix determines the deterministic behavior. Here, we describe how we set of W_{ij} that has an attractor structure consisting of lightpath-tree candidates as attractors. We construct regulatory matrix W_{ij} based on Hebbian theory in Hopfield network [6]. Assuming that we set K numbers of lightpath-tree candidates as attractors and $\mathbf{x^s}$ $(= (x_1^s, \ldots, x_i^s, \ldots, x_n^s))$ $(1 \leq s \leq K)$ represents one of the candidates, we define W_{ij} as the following expression.

$$W_{ij} = \begin{cases} \sum_{s=1}^{K}(2x_i^s - 1)(2x_j^s - 1) & \text{if } i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

x_i^s represents the state of i-th lightpath, l_i, of lightpath-tree candidate of s-th attractor. When we set $\mathbf{x^s}$ as attractor, we set x_i^s to 1 when l_i of s-th attractor is 1, and to 0 when l_i of s-th attractor is 0.

2.2.5. Dynamic Construction of Attractor Structure

Our dynamical system (Eq. 2) tries to change the system state to an attractor, but does not always converge to an attractor because of the stochastic term. Even when the system state is not an attractor, the controller tries to set up lightpaths based on the selected lightpath-tree. Note that, in our approach, the maximum link load is again retrieved after setting up the lightpaths, i.e., VNT is constructed. Thus, there is a case when the selected lightpath-tree is not an attractor, but the constructed VNT is satisfactory good for the current environment. In this case, the controller re-constructs the attractor structure including the attractor mapped from the constructed VNT.

Now we explain dynamic construction of attractor structure. We want to set a proper lightpaths subset for the current environment by renewing W_{ij} to achieve adaption to traffic changes and quick convergence on attractors. Here, we add a lightpaths subset to attractor structure and recalculate W_{ij} by Eq. 4 when the maximum link load get lower than θ (our goal). However, the number of attractors is limited by 15% of the number of lightpath-tree candidates according to the property of Hopfield network [7]. So we exclude the oldest attractor from the attractor structure when we add the new lightpath-tree that corresponds to the constructed VNT and is satisfactory good for the current environments.

3. Performance Evaluation

We use a random topology for the physical topology. The topology has 50 nodes and 100 bidirectional links. Each node has 16 transmitters and 16 receivers. The number of wavelengths on fibers is enough so that only the number of transmitters and receivers is a limiting factor to construct a VNT. The route of IP packets is determined based on the shortest-path routing over the constructed VNT. We assume that every two nodes have a possibility to set up a lightpath, and at most one lightpath is set up between nodes. We set γ to 1, δ to 50 and θ to 0.5 in Eq. 3. We set μ to 50 in the sigmoidal regulation function. At the beginning of simulations, we prepare five VNTs each of which is generated randomly, and set the initial attractor structure of each controller by pick up five lightpath-tree candidates from each VNT.

For comparison, we use previously proposed method based on attractor selection [5] and two heuristic VNT control methods: MLDA (Minimum delay Logical topology Design Algorithm) [2] and I-MLTDA(Increasing Multihop Logical topology Design Algorithm) [3]. Both of MLDA and I-MLTDA construct VNTs using the information of traffic demand between every two nodes.

We use the success rate of VNT control as evaluation metrics. The VNT control is succeed when the maximum link load is lower than $\theta(= 0.5)$ for 10 consecutive VNT constructions. Figure 3 shows the success rate when traffic demand between two nodes follows the lognormal distribution with mean 1 and variance σ^2 of the associated normal distribution. The simulation is finished when the number of steps of VNT control reaches 1000. In Figure 3, the x-axis represents the σ^2 and y-axis represents the success rate. For each value of σ^2, we first generate 100 patterns of traffic demand matrices and then exclude matrices each of which have the traffic demand that exceeds the threshold value $\theta(= 0.5)$. This is because we prepare one state variable between nodes and therefore there is no VNT whose maximum link load is lower than 0.5. In the figure, “Attractor Selection (distributed)” represents the result of our proposed method and “Attractor Selection (centralized)” represents the result of our previously proposed method. MLDA and I-MLTDA construct VNT assuming that the up-to-date and actual traffic demand matrix is available. With this assumption, heuristic algorithms work better than our method. Without this assumption, the heuristic

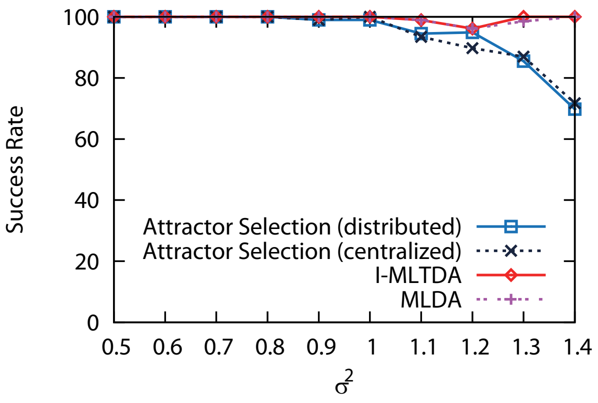

Figure 3: the success rate when traffic demand between two nodes follows the lognormal distribution with mean 1 and variance σ^2 of the associated normal distribution

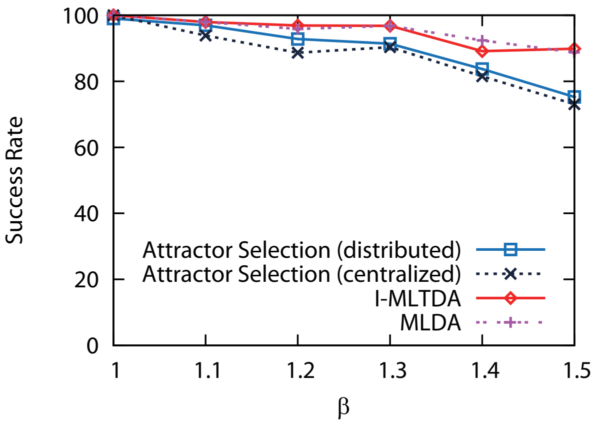

Figure 4: the success rate when the amount of traffic demand is changes from Figure 3

algorithms with the estimated traffic demand matrices do not work properly and lead to severe degradation on performance [5]. Not that our distributed control method does not use the information of traffic demand matrix for the VNT control, and therefore, our distributed control method will perform well if this assumption fails as we have revealed in [5].

Figure 3 shows that all of VNT methods achieve the success rate by 100% when σ^2 is less than 1.0. However the success rate of proposed VNT method decline when σ^2 is more than 1.0. The success rate of proposed method is lower than heuristic methods MLDA and I-MLTDA when σ^2 is more than 1.0. The reason why the VNT control based on attractor selection could not find the appropriate VNT comes from properties of initial attractor structure constructed from randomly generated VNTs. It is important for VNT control under the high variance traffic demand to appropriately construct and re-construct the attractor structure, which is one of our future research topics.

Figure 4 shows the success rate when the amount of traffic demand is changes from Figure 3. The distribution of traffic demand between nodes again follows the lognormal distribution with mean 1 and variance 1 of the associated normal distribution, but the amount of total traffic volume is scaled by β. In the figure, the success rate is plotted dependent on β. We observe that all of the results declines slightly as β increases. The success rate of our proposed method is almost similar to that of previously proposed method, but is again lower than MLDA and I-MLTDA.

4. Conclusion

In this paper, we proposed distributed VNT control method based on attractor selection and evaluated our method through computer simulations. The results showed that proposed method has the adaptability against traffic changes as previously proposed method has. The results also indicated that the success rate of our VNT control method can be improved by appropriately construct and reconstruct the attractor structure, which is left for our future research topics.

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