Adaptability of Virtual Network Topology Control Based on Attractor Selection against Multiple Node Failures

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Abstract

We propose a virtual network topology (VNT) control method that is adaptive to environmental changes in a network. It is based on *attractor selection*, which models the biological systems that behave adaptively against changes in their surrounding environments. The simulation results indicate that our VNT control method adaptively responds to changes in network environments caused by node failure and constructs operational VNTs in more than 95% of simulation trials when 20% of nodes in the physical network fail simultaneously.

I. Introduction

One approach for accommodating traffic on a wavelength-routed optical network is to configure a virtual network topology (VNT), which consists of lightpaths and IP routers [1]. Since emerging application services, e.g., video on-demand, cause large fluctuations in network environments, it is crucial to achieve an adaptive VNT control method against changes in network environments.

One of the best examples of adapting to various environmental changes is a biological system. Among several adaptive behaviors of biological systems, we focus on *attractor selection*, which models the behaviors of organisms when they adapt to unknown environmental changes and recover their conditions [2]. In [3], we developed a VNT control method based on attractor selection that is adaptive to changes in traffic. However, our previously proposed method requires elaborative design of its internal structure using information on an underlying physical topology in advance of its operation. Thus, it is difficult to keep its adaptability if its topological structure changes due to node failure. The method in this paper dynamically reconfigures its internal structure, i.e., *attractors*, according to changing network environments and achieves adaptability to network failures and to changes in traffic.

The rest of this paper is organized as follows. In Section II, we propose a VNT control method based on attractor selection. Then, we evaluate the adaptability of our method to network failures in Section III. We conclude this paper in Section IV.

II. VNT Control Based on Attractor Selection

A. Overview

In attractor selection, the gene regulatory network controls the metabolic reaction network, and the activity,

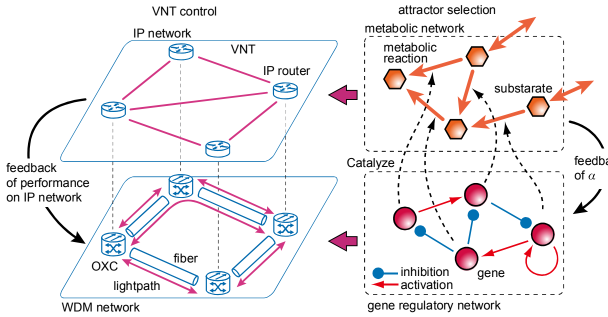

Fig. 1 Interpretation of attractor selection into VNT control

which is the status of the metabolic reaction network, is recovered when the growth rate is degraded due to changes in the environment [2]. In our VNT control method, the main objective is to recover the performance of the IP network by appropriately constructing VNTs when performance is degraded due to changes in network environments. Therefore, we interpret the gene regulatory network as a WDM network and the metabolic reaction network as an IP network, as shown in Fig. 1. Our VNT control method adapts to various changes in network environments by selecting suitable attractors, which correspond to VNTs in our method, for the current network environment.

B. Dynamics of VNT Control

We place genes on all the candidates of possible lightpaths. Each gene has an expression level of proteins x_i and the i-th lightpath is controlled by x_i. The dynamics of x_i is described as,

$$\frac{dx_i}{dt} = \alpha \cdot \left(\varsigma\left(\sum_j W_{ij} \cdot x_j\right) - x_i \right) + \eta, \qquad (1)$$

where η represents white Gaussian noise, $\varsigma(z)$ is the sigmoidal regulation function, and the activity, α, indicates the condition of the IP network. The definition of α has been described in [3]. In our method, we establish i-th lightpath if $x_i > 0.5$; otherwise, we do not establish. Therefore, our method interprets x_i as the VNT and x_i converges to the state of attractors. Attractors are a part of the equilibrium points in the phase space. The definition of attractors is a challenging and important aspect of our proposed method.

In the following section, we describe the definition of attractors.

C. Attractor Structure

Since our method selects one of the attractors and constructs the VNT corresponding to the selected attractor, defining attractors is a challenge. From the perspective of dynamical systems, α is regarded as a constant value that determines the convergence speed. The noise η is Gaussian white noise with mean 0. These values do not affect equilibrium points, that is, attractors in our method, in the phase space. Therefore, the equilibrium points are determined by the differential equation $\frac{dx_i}{dt} = \varsigma\left(\sum_j W_{ij} \cdot x_j\right) - x_i$. This is the same formula as a continuous Hopfield network [4]. Therefore, we use the knowledge of associative memory to store arbitrary attractors in the phase space [4].

Suppose we store a set of VNTs $g_k \in G$ in the phase space defined by Eq. (1). Let $\boldsymbol{x}^k = (x_1^k, \ldots, x_i^k)$ be the vector of the expression levels corresponding to VNT g_k. To store $\boldsymbol{x}^k$ in the phase space, we adopt the method introduced in [4], which stores patterns in the phase space by orthogonalizing them. Due to space limitations, we omitted detailed description of this method. We store m VNTs, $\boldsymbol{x}^1,\ldots, \boldsymbol{x}^m$, in the phase space. Let $\boldsymbol{X}$ be the matrix whose rows are $\boldsymbol{x}^1,\ldots, \boldsymbol{x}^m$. The regulatory matrix $\boldsymbol{W}=\{W_{ij}\}$, whose attractors are $\boldsymbol{x}^1,\ldots, \boldsymbol{x}^m$, is defined as $\boldsymbol{W}=\boldsymbol{X}^+\boldsymbol{X}$, where $\boldsymbol{X}^+$ is a pseudo inverse matrix of $\boldsymbol{X}$.

III. Performance Evaluation

A. Simulation Conditions

We use a randomly generated physical topology that has 100 nodes and 496 optical fibers. Each node has 16 transmitters and 16 receivers. We use randomly generated traffic demand matrices having elements that follow a log-normal distribution. In this evaluation, we store 30 attractors in the attractor structure. For each evaluation, we conduct 1000 simulation trials by using 10 randomly generated traffic demand matrices and 100 randomly selected node failure patterns. We focus on node failure as environmental changes in a network. When a node fails, incoming and outgoing optical fibers to the node also fail at the same time. All lightpaths that are routed on those failed nodes or optical fibers become unavailable. In our simulation, the failed lightpaths are always unavailable during node failure. For purposes of comparison, we use an existing heuristic VNT control method, the increasing multi-hop logical topology design algorithm (I-MLTDA) [5].

B. Adaptability against Multiple Node Failures

To visualize the overall performance of our proposed method, Fig. 2 is histograms of the maximum link utilization. The histograms summarize the results of 1000 simulation trials by using 10 randomly generated traffic demand matrices and 100 randomly selected node failure patterns. As shown in Fig. 2(a), our method constructs VNTs, having the maximum link utilization less than the target maximum link utilization, 0.5, in 955 out of 1000 simulation trials, whereas the maximum link utilization on the VNTs constructed using I-MLTDA are widely distributed. This result indicates that the performance of I-MLTDA depends on traffic or node failure patterns, but

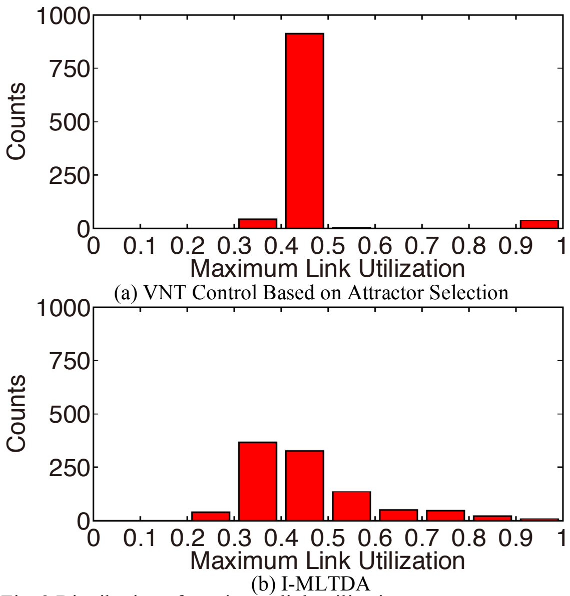

Fig. 2 Distribution of maximum link utilization

our proposed method achieves almost the same level of performance regardless of traffic or node failure patterns.

IV. Conclusions

We proposed a VNT control method that is adaptive to node failure. It is based on attractor selection, which models the behaviors of biological systems that adapt to environmental changes and recover their conditions. Unlike most engineering-based VNT control methods, our method does not rely on pre-defined algorithms and uses stochastic behaviors for adapting to changes in network environments. Our method dynamically reconfigures its attractor structure according to changing network environments and becomes adaptable to network failure in addition to changes in traffic demand achieved in [3]. Extending our approach for virtualization-based networks, such as network virtualization or OpenFlow, and achieving adaptability in such networks is one of our future research directions.

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