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A biological approach to physical topology design for plasticity in optical networks

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ABSTRACT

We previously proposed a virtual network topology (VNT) control method that is adaptive to traffic changes. However, the performance of VNTs is fundamentally determined by the physical infrastructure, and the physical network therefore needs to be designed so that it is capable of utilizing the adaptiveness of the VNT control method. In this paper, we propose a design method for optical networks, e.g., wavelength division multiplexing (WDM) networks. This method is based on a biological evolution model and provides adaptability under various patterns of traffic fluctuation and traffic growth. Our method determines the set of nodes to which transceivers should be added in order to give *plasticity* to the designed network, where plasticity represents changeability of VNT against environmental variation. Evaluation results show that our method accommodates more patterns of traffic fluctuation with lower link utilization than ad-hoc design methods do.

1. Introduction

In wavelength division multiplexing (WDM) networks, optical cross connects (OXCs) switch optical signals without optical-electrical-optical (OEO) conversion by using wavelength routing. A wavelength channel, called a lightpath, is established between nodes. Since the upper-layer's traffic, such as IP traffic, can change its nature, much research has examined the construction of a virtual network topology (VNT) on top of a WDM network [1,2]. A VNT is a logical network composed of lightpaths, and the connectivity among routers can be easily reconfigured by establishing or tearing down lightpaths. When the traffic demand changes and certain performance metrics degrade to the point where they are no longer acceptable, the VNT is changed to a new VNT that exhibits optimal or near-optimal performance under the network environment as it exists at that time.

The environment of the Internet is rapidly changing. With the appearance of new web services such as video streaming and cloud computing, traffic volumes have increased rapidly and fluctuate drastically. Some VNT control methods have been studied for countering traffic fluctuations, showing good performance on metrics such as keeping link utilization lower by adaptively reconfiguring the VNT in accordance with traffic changes [3,4]. However, when the traffic volume increases, VNT control methods may fail to find a suitable VNT. That is, there may be no solution that can provide good performance because of a lack of network resources or because of other problems. In such situations, network operators must reinforce the physical network resources. Much consideration has gone into physical network design [5–8]. In Ref. [5], the authors consider designing a physical topology in which logical rings can be established for survivability while minimizing the number of physical links. In Ref. [6], the authors address both physical and logical topology design, and formulate the problem as an integer linear programming problem of minimizing the number of wavelengths used. In Ref. [7], the authors consider a routing and wavelength assignment problem in optical networks with the aim of minimizing the cost over the long term under a restricted budget. In Ref. [8], the authors consider designing a mixed-line-rates network with minimum cost. Most of these works solve optimization problems against predicted traffic demand. However, when the environment changes drastically, it is natural that future traffic demand cannot be estimated accurately. Even if we are able to 'specify' future traffic demand by incorporating environmental uncertainty and use it in the design method, the designed network is specialized to the pre-specified situation, which may lose adaptability against unexpected traffic changes. Therefore, a new design approach that can accommodate various patterns of future traffic in conjunction with the VNT control method is needed.

In order to develop a new design approach, we consider biological evolution, which allows species to survive environmental changes over the long term. One important characteristic of biological evolution is *plasticity*, which describes the changeability against environmental changes [9]. In Ref. [9], the authors develop a gene expression dynamics model to explain how organisms can obtain both short-term

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(on the order of hours) robustness and long-term (on the order of days to years) plasticity. Following the gene expression dynamics model, we propose a method for designing physical networks and develop a design method for adding transceivers to IP routers in optical networks, e.g., IP-over-WDM networks. The number of transceivers is equal to the degree of virtual links, i.e., lightpaths, connected to the node. Our method determines a set of nodes to which transceivers should be added in order to give plasticity to the optical network. In an optical network capable of plasticity, it is expected that adaptive VNT control can enjoy plasticity of the physical infrastructure, and so network performance can avoid being degraded under various patterns of future traffic fluctuation, even unknown patterns. Through computational simulation, we confirm that our design method offers plasticity.

A preliminary version of this work has been presented in [10]. In our previous paper, we have introduced a concept of plasticity in designing optical networks and have compared with a heuristic method on the European optical network (EON) [11]. In the current paper, we introduce a mixed integer linear programming (MILP) solution for comparison and show the effects of the plasticity on the EON, the US nationwide network (USNET) and the Japan backbone network (JBN).

The rest of this paper is organized as follows. In Section 2, we describe the purpose of our research. We then propose a method of optical network design capable of plasticity in Section 3 and show evaluation results in Section 4. We finally conclude this paper and mention future work in Section 5.

2. Adaptive VNT control and physical network design method

When traffic changes drastically, a dynamic VNT control method that can adapt to various changes in traffic is needed. We previously proposed a VNT control method based on attractor selection that exhibits high adaptability to unexpected changes in traffic demand [4]. In this VNT control method, lightpath reconfiguration is driven by the following expression:

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

where x_i is a variable indicating that a lightpath between the node-pair i is configured when it exceeds a certain threshold. The function $f(\mathbf{x})$ represents deterministic behavior that causes the VNT to converge to one of the equilibrium point, that is, to an attractor. The activity α represents feedback of the network condition. When α is high, the system stays at an attractor that offers good conditions. When the network condition worsens due to traffic fluctuations, α decreases towards zero until stochastic behavior dominates the system. That is, lightpaths are reconfigured at random in the search for another attractor. After a while, the VNT again converges on a new attractor thereby adapting to the traffic fluctuation.

Although our VNT control method is more successful in terms of obtaining robustness against traffic changes than other existing methods are, it fails to obtain a good VNT when the network resources are insufficient for the increased traffic. This is a fundamental limit that also applies to other methods. The aim of this paper is therefore to consider a physical network design method for accommodating future unknown traffic demand as much as possible while keeping the adaptability of the attractor-based VNT control method. Fig. 1 illustrates the relation between VNT reconfiguration and our physical network design method. VNT control reconfigures the VNT over the physical network and adapts to traffic fluctuations. When traffic volume increases, we might not able to find a good VNT because of a shortage of network resources. We then need to add network resources such as physical links, IP routers, optical switches, and transceivers. Since the adaptability of VNT control depends on the underlying physical network, an improperly designed physical network may reduce the

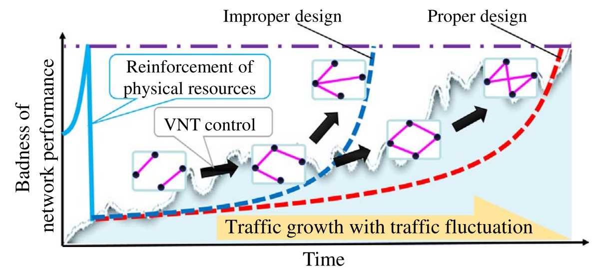

Fig. 1. VNT control and network design to prepare for traffic growth.

ability of VNT control to adapt to traffic fluctuations. We also note that our proposed design method is easily extended to incorporate other network resources. This proposal is applicable to not only our VNT control methods but also other existing dynamic VNT control methods.

3. Method for designing optical networks to have plasticity

In this paper, we apply a biological evolution model that mimics the robustness and plasticity of biological systems. This is introduced in the next subsection. Note that while we understand it is a rather lengthy explanation, it is necessary for readers to understand how biological plasticity can be applied to our case.

3.1. Biological model

Organisms adapt to the environment through the evolution of a genetic network. Robustness and plasticity are thought to be basic characteristics in evolutionary biology. Robustness is the capacity of an organism to maintain its own state and function against disturbances. In contrast, plasticity is changeability or flexibility in response to environmental fluctuations [9]. Organisms are able to adapt to new and/or unexperienced environments by greatly changing state as the external environment changes. Plasticity expresses sensitivity to external perturbations, and is an important characteristic for adaptive evolution.

In Ref. [9], the author formulates a model of the evolution process by taking account both biological robustness and plasticity. In the model, an organism optimizes the value of fitness against various kinds of environmental changes by changing gene expression (phenotype), in which the dynamics are governed by activation/inhibition between genes (genotype). The model consists of several elements (Fig. 2), each of which is explained below.

Gene: There are M genes. Each gene i has its own expression level $x_i(-1 \le x_i \le 1)$. When x_i exceeds some threshold θ_i, gene i is expressed. Otherwise, gene i is not expressed.

Input gene: k_{inp} genes among the M genes are input genes, and their gene expression levels are given initially and do not change regardless of the gene expression dynamics. Without loss of generality, we regard genes $x_i(1 \le i \le k_{inp})$ as the input genes. Changes in the expression levels of these input genes represents a change in the environment.

Phenotype: As a result of the gene expression dynamics, the gene expression levels $x_i(k_{inp} < i \le M)$ converge to some set of values. Note that the input gene expression levels are independent of the gene expression dynamics. Some genes are expressed and others are not expressed, thus forming a pattern of expressed genes. This pattern is called a phenotype. In Fig. 2, expressed genes are represented by filled circles and have a phenotypic value of 1, while non-expressed genes are represented by open circles and have a phenotypic value of 0.

Genotype: Genes are related to each other. These mutual relations are defined by a gene regulatory network. In Fig. 2 each solid

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