Achieving Plasticity in WDM networks: Application of Biological Evolutionary Model to Network Design

Koki Inoue, Shin'ichi Arakawa and Masayuki Murata
Graduate School of Information Science and Technology, Osaka University
1–5 Yamadaoka, Suita, Osaka 565–0871, Japan
Email: {k-inoue, arakawa, murata}@ist.osaka-u.ac.jp

***Abstract*—Our previous VNT control method is adaptive to traffic changes. However, performance of VNT is fundamentally decided by the physical infrastructure, and a physical network should be designed so that the adaptiveness of VNT control method can be enjoyed. In this paper, we propose a design method of WDM networks based on a biological evolution model to have adaptability under various traffic fluctuation and traffic growth. Our method determines a set of nodes where transceivers should be added so that the designed network can obtain a *plasticity*, which represents changeability against the environmental change. Evaluation results for a topology with 19 nodes show that our method accommodates more patterns of traffic fluctuation comparing with an ad-hoc design method.**

I. Introduction

In the WDM (Wavelength Division Multiplexing) network, OXCs (Optical Cross Connects) switch optical signals without OEO (Optical-Electrical-Optical) conversion by wavelength routing. Then, wavelength channel, called lightpath, is established between nodes. Since the upper-layer's traffic, such as IP traffic, changes in nature, many works have been considered to construct a VNT (Virtual Network Topology) on top of WDM networks [1], [2]. 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 degradations of some performance metrics are no longer acceptable, VNT is changed to new VNT that exhibits optimal or near-optimal performance under the current network environment.

Environments surrounding the Internet is rapidly changing. Because of the appearances of new web services such as video streaming and cloud computing, traffic volume rapidly increases and/or drastically fluctuates. Against the traffic fluctuation, some VNT control methods have been studied and they show good performance, such as keeping link utilization lower, by adaptively reconfiguring the VNT in accordance with traffic changes [3], [4]. However, when traffic volume increases, VNT control methods may fail to find suitable VNT. That is, there may be no solution to obtain good performance due to, e.g., lack of network resources. In such a situation, network operators must reinforce physical network resources. There has been much consideration about physical network design [5]–[8]. In Ref. [5], the authors consider designing a physical topology on which logical rings can be established for survivability, and minimizing the number of physical links. In Ref. [6], the authors address both physical and logical topology design, and they formulate the problem as an integer linear programming problem to minimize the number of wavelengths used. In Ref. [7], the authors consider a routing and wavelength assignment problem in the optical network. They aim to minimize cost in the long term with a restricted budget. In Ref. [8], the authors consider designing a mixed line rates network with minimum cost. Most of them solve optimization problems against predicted traffic demands. However, when the environments change drastically, it is quite natural that it is impossible to estimate the future traffic exactly. Even when we can 'specify' future traffic demand by incorporating environmental uncertainty and use it into design methods, 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 VNT control method is needed.

For developing the new design approach, we consider the biological evolution, in which organisms survive environmental changes for a long term. One of important characteristics in biological evolutions is *plasticity*, which is explained as changeability against environmental change [9]. In Ref. [9], the authors develop gene expression dynamics model to explain how organism can obtain both short-term (say, one through hour order) robustness and long-term (day through year order) plasticity. Following the gene expression dynamics model, we propose a method for designing a physical network and develop a design method for adding transceivers to IP routers in IP over WDM networks. Our method determines a set of nodes to which transceivers should be added so that the WDM network can obtain plasticity. In the WDM network having a capability of plasticity, it is expected that adaptive VNT control can enjoy the plasticity of physical infrastructure, thereby the network performance will not be degraded against various patterns of future traffic fluctuation, even though which are unknown. Through the computational simulation, we confirm that our design method can have the plasticity.

The rest of this paper is organized as follows. In Sec. II, we mention the purpose of our research. Then, we propose a method of WDM network design being capable of plasticity in Sec. III, and show evaluating result in Sec. IV. We finally conclude this paper and note the future work in Sec. V.

II. Adaptive VNT control and physical network design method

When the traffic changes drastically, a dynamic VNT control method that can adapt various traffic changes is needed. We proposed a VNT control method based on attractor selection, which shows high adaptability to unexpected traffic demand changes [4]. In the VNT control method, lightpath reconfiguration is driven by the following expression (1),

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

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 a deterministic behavior, which make the VNT converged to one of the equilibrium points, i.e., attractor. Activity α represents feedback of the network condition. When α is high, the system stays in the attractor with good condition. When the network condition gets worse by traffic fluctuation, α gets close to zero and then a stochastic behavior dominates the system. That is, lightpaths are reconfigured at random to search for another attractor. After a while, the VNT again converges to a novel attractor and adapts against traffic fluctuation.

Our VNT control method succeeds in obtaining robustness against the traffic changes than other existing methods, but of course, it fails to obtain the good VNT when network resources are not sufficient against the traffic increase. It is just same as other methods and a fundamental limit. Our purpose in this paper is therefore to consider a physical network design method to accommodate the future unknown traffic demand as much as possible while keeping the adaptability of the VNT control method based on attractor selection. Figure 1 illustrates the relation of VNT reconfigurations and our physical network design method. VNT control reconfigures the VNT over the physical network and adapts to traffic fluctuation. Against traffic volume increase, we may not able to find the good VNT because of shortage of network resources. Then, we need to add network facilities such as physical links, IP routers, optical switches, transceivers. Since the adaptability of VNT control depends on the underlying physical network, an improper design of physical network might suppress the ability of VNT control to adapt traffic fluctuation. We last note that our proposed design method is easily extended in order to incorporate other network resources. Also, the proposal is not only for our VNT control method, but also applicable to other existing dynamic VNT control methods in nature.

III. Design method of WDM network to have a plasticity

In this paper, we apply a biological evolution model, which explains the robustness and the plasticity of biological systems. It will be introduced in the next subsection. Note that we understand it is rather lengthy, but it is necessary for the

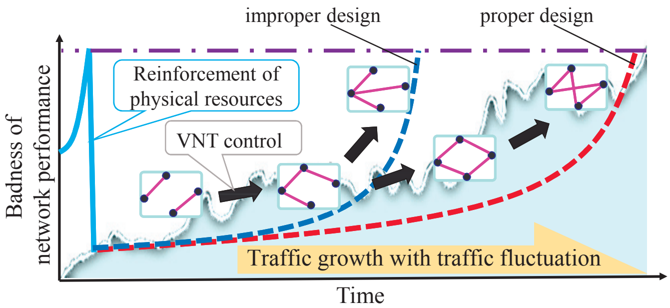


Fig. 1. VNT control and network design against traffic growth

readers to understand how the biological plasticity can be applied to our case. Then we will explain our proposed method by applying biological plasticity.

A. Biological model

Organisms adapt to the environment through evolution of its genetic network. A robustness and a plasticity are considered as the basic characteristics in the evolutional biology. Robustness is a capability to keep the state of own and function against disturbances. On the other hand, plasticity is a changeability or flexibility to the environmental fluctuation [9]. The organism can fit to the novel and/or inexperienced environment by greatly changing its state along with the external changes. Especially, the changeability against genetic changes is called evolvability in the evolutional process. Plasticity and evolvability express the sensitivity to the external perturbations, and they are important characteristics for an adaptable evolution.

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

gene: There are M genes. Each gene i has its own expression level $x_i(-1 \leq x_i \leq 1)$. In case x_i exceeds a threshold θ_i, gene i is expressed. Otherwise, the gene i is not expressed.

input gene:
k_{inp} genes among M genes are input genes, and their gene expression levels are given initially and unchanged regardless of the gene expression dynamics. Without loss of generality, we regard gene $x_i(1 \leq i \leq k_{inp})$ as the input gene. The change of these expression levels represents an environmental change.

phenotype:
As a result of the gene expression dynamics, the gene expression levels $x_i(k_{inp} < i \leq M)$ are converged to some values. Note that the input gene expression

levels are independent of the gene expression dynamics. Some genes are expressed and the others are not expressed. Then, there forms a pattern of the expressed genes. The pattern is a phenotype. In Figure 2, we depict an expressed gene with filled circle, and set its phenotypic value to '1', while a non-expressed gene with non-filled circle and set to '0'.

genotype:
Genes are related to each other. The mutual relationship is defined as gene regulatory networks. In Figure 2, a solid arrow represents an activating relation from a gene to another, and a dashed arrow represents an inhibiting relation. $J_{ij}(=\{-1,0,1\})$ represents the activation/inhibition relationship between gene i and gene j. When $J_{ij}=1$, gene i gets an effect of activation from gene j. When $J_{ij}=-1$, gene i gets that of inhibition from gene j. When $J_{ij}=0$, there is no relationship between gene i and j. A matrix J with element J_{ij} is the gene regulatory networks and is called genotype. J determines the gene expression dynamics.

fitness:
Fitness is an adaptability to the present environment or a condition of the system, which is calculated by a function $F(phenotype)$. That is, the gene's expression patterns, which are governed by genotype, determine fitness value. For the biological perspective, a typical example of function F is the number of expressed target genes. Here, the target genes are picked from biological context of view. $F(phenotype)$ becomes the highest when the expression pattern of target genes is all '1'. From the network design perspective, introducing target genes is not necessary. We just use traditional performance metric to calculate the fitness value. In this paper, we will use the average link utilization of VNT for calculating the fitness.

The dynamics of the gene expression levels is then described by the following equation,

$$dx_i/dt=\gamma\left\{f\left(\sum_j^M J_{ij}x_j\right)-x_i\right\}+\sigma\eta_i, \quad (2)$$

where the 1st term represents a deterministic behavior driven by the gene regulatory network J_{ij} (γ is a constant). $f(z)$ is a sigmoid function defined as,

$$f(z)=\frac{1}{1+\exp^{-\beta(z-\theta_i)}}+\delta, \quad (3)$$

where β is a parameter which determines the gradient in the neighborhood of the threshold θ_i, and δ is a small positive number which represents a spontaneous expression level. The 2nd term in Eq. (2) represents the stochastic behavior caused by noise from the environment. η_i is a random value following normal distribution with mean 0 and variance σ^2.

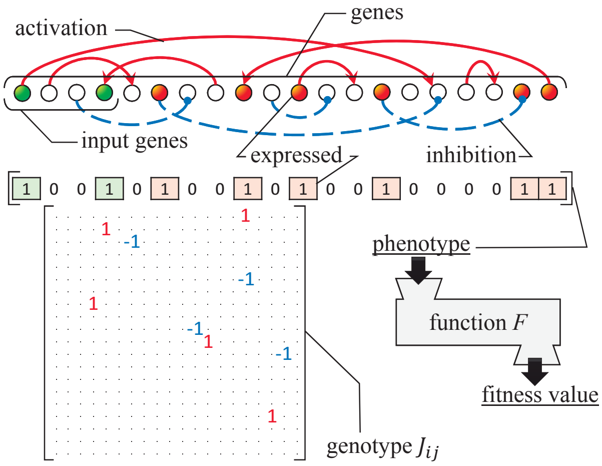


Fig. 2. The genetic model: $M=20, k_{inp}=4$

The evolution model repeats a selection-mutation process for each generation. There are N individuals, each of which has slightly different gene regulatory networks $\{J_{ij}^1,\ldots,J_{ij}^N\}$. Then, at a generation, each of individuals updates the gene expression level, x_i, by calculating the differential equation (2) with its own J_{ij}. The pattern of the gene expression levels, i.e., phenotype, determines the value of fitness $F(phenotype)$. That is, we obtain N fitness value dependent on the gene regulatory networks. The selection-mutation process is then applied for the N gene regulatory networks. Among N gene regulatory networks, N_s gene regulatory networks that show higher fitness value are selected and left for the next generation. The unselected gene regulatory networks are excluded for further calculations. N_s is a tunable parameter, and we set to $N/4$ in following. Each of the selected N_s gene regulatory networks is then mutated to 4 individuals; a few components in the matrices are randomly chosen and the value are switched into a random value from $\{-1,0,1\}$. Such the calculation of gene expression dynamics and selection-mutation process are repeated over generations.

We can now explain how the biological system has both robustness and plasticity. When the environment changes, i.e., the expression level of input genes changes, the biological system first reacts through the increase of phenotypic variance. This reaction makes the biological system to have plasticity which represents the changeability against environmental change. The robustness is obtained through the selection-mutation processes. Once a genotype deriving a phenotype with higher fitness is found, its duplications will account for a large majority. Then, the phenotypic variances decrease again.

B. Applying a method to add transceivers

In this paper, we take an optical transceiver into account as a target device of reinforcement in the WDM network. Figure 3 shows a simple example of our application. A lightpath can be established only when there remain transceivers at the both end-nodes. Then, adding a transceiver may result in a new lightpath available. In that situation, the key is a

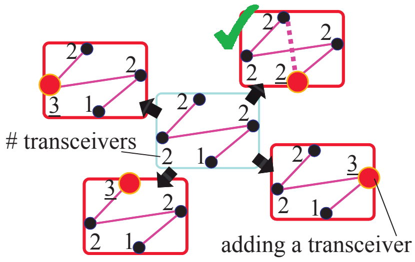


Fig. 3. a example of our applying in WDM network

TABLE I
CORRESPONDENCE BETWEEN EVOLUTION MODEL AND WDM NETWORK

biological evolution	WDM network
dynamics of gene expression level	VNT control
phenotype	VNT
genotype	regulatory matrix
fitness	average link utilization
environmental change	change of traffic demand

selection of nodes to which we should add transceivers. Our proposed method determines a set of nodes (IP routers) where transceivers should be added so that the network can obtain the plasticity by applying the biological evolution model.

1) Applying the biological evolution model to the WDM network design: Table I shows the correspondence between the genetic evolution model and the design method of WDM network. When the number of nodes in the WDM network topology is n, the number of candidates for lightpaths is equal to that of node-pairs, n^2. Each gene i corresponds lightpath l_i one to one, where $i = 1, 2, .., n^2$. In each generation, gene expression levels x_i are determined as a result of expression dynamics (2). The phenotype, i.e., a pattern of gene expression level determines VNT; lightpath l_i is to be "on" (established) if x_i exceeds the threshold θ_i. Otherwise, lightpath l_i is switched "off".

For the fitness, we use the average link utilization of VNT. In the biological model, fitness is calculated based on the expression pattern of a part of genes. Here, instead, we substitute the average link utilization for the value of fitness. Note that average link utilization is desired to take a low value. That is, the system condition is considered good when average link utilization is low. Therefore, we define fitness as an inverse of average link utilization.

We treat updating of the physical network as an environmental change. Input genes express the environment in the biological model, and the environmental change is given by modifying the value of input gene expression levels. In our WDM design method, we assign a progressing status of adding transceivers for the input genes. The number of input genes is equal to the number of WDM nodes, n. Therefore, there are n^2 ordinary genes ($i = 1, 2, .., n^2$) and n input genes ($i = n^2 + 1, n^2 + 2, .., n^2 + n$), therefore $n^2 + n$ genes in total. The gene $n^2 + i$ represents the node N_i. Initially, the expression levels of all input genes are 0. Every time when a transceiver is added to node N_i, the expression level of gene $n^2 + i$ is incremented by 1 to express effect of the physical network change even though the range of expression level may be violated. This is how to consider that a change of WDM network affects the expression dynamics, or the way to construct a VNT.

2) Evaluate the plasticity of WDM network: Our proposed method aims to determine a set of nodes (IP routers) where transceivers should be added so that the network can obtain a plasticity. For this purpose, we have to evaluate the degree of plasticity for physical networks. For this purpose, we examine the evolution process via following steps:

Step.1 Observe the traffic demand.

Step.2 Repeat the selection-mutation process over $T(= 15)$ generations. In each generation, a VNT is determined through Eq. (2). Then, fitness value is calculated under the observed traffic demand.

Step.3 Execute the following sub-steps S times.

- **Step.3.1** Change the traffic demands.
- **Step.3.2** Repeat the selection-mutation process over T generations. Then, fitness is calculated for changed traffic demand.

Step.4 Calculate a degree of plasticity by using S fitness values obtained in Step.3.

At the beginning of the reinforcement, we first obtain traffic demands (Step.1). At Step.2, we examine selection-mutational process for the observed traffic demand, and obtain a set of gene regulatory networks J_{ij} that are suitable for the observed traffic demand. In Step.3, we examine various patterns of traffic fluctuation with a random manner. Note that the single pattern of traffic fluctuation is not sufficient to estimate the plasticity. We obtain $S(= 16)$ fitness values as a result of Step.3. In this paper, the degree of plasticity is picked from the median value of fitness values.

3) Proposed design method: We aim that the WDM network will obtain a plasticity as a result of adding transceivers. We evaluate the plasticity by computational simulation in case some transceivers were added to a certain set of nodes. However, it is difficult to estimate the plasticity to determine the location of transceivers since the number of possible combinations for the location exponentially increases as the number of transceiver increases. So, we apply a simple heuristic, called ADD algorithm [10], to determine the location of transceivers. Given the number of transceivers to add, the ADD algorithm works as follows:

Step.1 Select a node to add a transceiver by calculating the plasticity when a transceiver is added to the node.

- **Step.1.1** Temporarily add a transceiver to each node.
- **Step.1.2** Evaluate the plasticity of the WDM network as explained in Sec. III-B2.
- **Step.1.3** Select the node which shows the highest value of plasticity at Step 1.2.

Step.2 Add a transceiver to the selected node. When there is another transceivers to add, Go back to Step.1. Otherwise finish the algorithm.

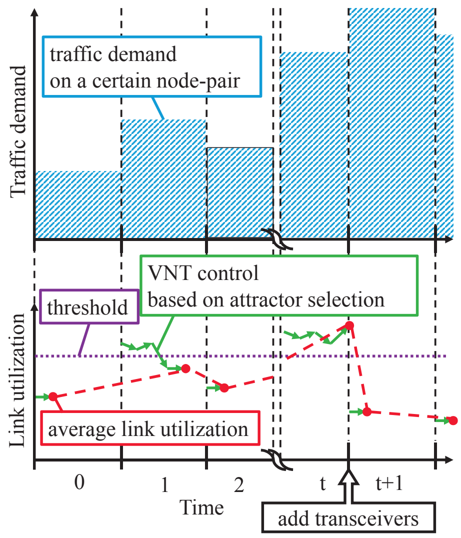


Fig. 4. Relation between VNT control and network reinforcement

C. Time scale of VNT control and network reinforcement

The biological evolution model explains how organism obtains the plasticity. When we apply the biological evolution model to network design method, a question arises: when transceivers should be added? Actually, the organisms may have their own cycle to apply the above-mentioned evolution process. In the case of our network design problem, we here consider that the network reinforcement is performed when VNT control method cannot find a good VNT. Note that we define the goodness of VNT as taking lower link utilization under the current traffic demand. Thus, the network reinforcement is performed when VNT control cannot achieves lower link utilization than a certain threshold.

Figure 4 illustrates the time-scale of VNT control, network reinforcement, and traffic changes. In the figure, horizontal axis represents the time-step of traffic changes, and the volume of traffic demand increases as the time-step increases. At each step, if necessary, VNT control method tries to find a good VNT under the traffic demand. When VNT control method find a good VNT, it keeps the VNT until the next time-step (see time-step 0, 1, 2 in the figure). When VNT control method cannot find a good VNT (say at time-step t), we regard that the VNT control failed. Then, the network reinforcement is performed just after we know the failure of VNT control, and the VNT control method is again applied at next time-step $t+1$.

D. Possible extension

In this paper, we take account of a transceiver in IP routers as a physical network resource. Our basic idea can be easily extend to deploy other network resources such as physical links and/or nodes. For example, when we consider deployment of physical link, we put input gene for a node-pair between which a link might be connected, instead of a node to which a transceiver might added.

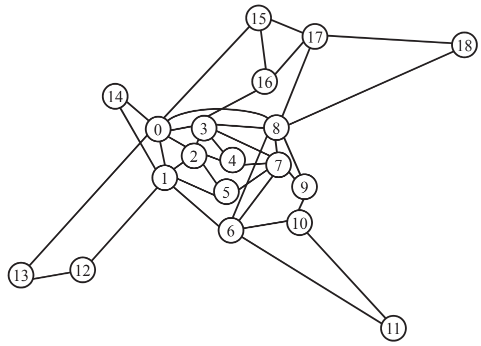


Fig. 5. Topology used in the computer simulation: EON

IV. Evaluation

In this section, we evaluate performance of the proposed method by computer simulation. The performance is measured by the adaptability of VNT control method based on attractor selection [4] on the WDM network which has been reinforced by the design method.

A. Simulation environment

Here we explain environments used in our simulation.

1) Topology: We have evaluated our proposed method on two physical topologies: EON (European Optical Network) model [11] and USNET model [12]. Both of results are similar, so we present the result of EON model hereafter. Figure 5 shows the EON model consisting of 19 nodes and 39 links. Each node is composed of an IP router and an OXC. An OXC is connected to another OXC by a link as shown in Figure 5. Each link is a single optical fiber. Establishing one lightpath between an IP router and another IP router uses one transceiver of the source node and one transceiver of the destination node. Then, a lightpath cannot be established when there is no available transceiver at either source or destination.

The initial number of transceivers of each node is set to 2 plus the number of degree of each node in the physical topology.

2) Traffic demand model: Each node-pair has its traffic demand. The initial values follows lognormal distribution, i.e., each traffic demand is set to a random number following $LN(\mu = 1, \sigma^2 = 0.5^2)$. Then, traffic demands increase or decrease every time-step. When $T^{i,j}_{act}(t)$ represents the traffic demand from node i to node j at the time-step t, a traffic demand model [13] is defined as the following expression,

$$T^{i,j}_{act}(t) = T^{i,j}_{exp}(t) + N(0, (\sigma_{noise} \times T^{i,j}_{exp}(t))^2), \quad (4)$$

where $T^{i,j}_{exp}(t)$ is an expected value of traffic demand from node i to node j at the time-step t. The second term represents an unexpected traffic fluctuation and is set to a random value following normal distribution $N(0, (\sigma_{noise} \times T^{i,j}_{exp}(t))^2)$. When σ_{noise} takes a higher value, the traffic demands change more drastically. By contrast, when σ_{noise} takes a lower value, the noise term has less effect, and $T^{i,j}_{act}(t)$ is close to $T^{i,j}_{exp}(t)$.

$T_{exp}^{i,j}(t)$ is calculated by following recurrence formula:

$$T_{exp}^{i,j}(t) = m + T_{act}^{i,j}(t-1). \quad (5)$$

The expected value increases by m at each time-step. Therefore, traffic demands continue to increase on average, whereas the trends of traffic fluctuation are different for each node-pair.

3) Method for comparison: We use an ad-hoc design approach for comparison purpose. The ad-hoc design method is based on I-MLTDA (Increasing Multi-hop Logical Topology Design Algorithm) [3], a heuristic method of designing a quasi-optimum VNT by using data of traffic demands and hop lengths. I-MLTDA establishes a lightpath between a node-pair (s, d) in an order from that shows the largest value of $\Delta^{sd} \times (H^{sd} - 1)$, where Δ^{sd} is a traffic demand from node s to node d and H^{sd} is a hop length in the shortest path from s to d. The detail of I-MLTDA is as follows:

Step.1 For each candidate, do the following sub-steps.

- **Step.1.1** Temporarily add transceivers to the node.
- **Step.1.2** Execute I-MLTDA against the traffic demands at the time of reinforcement.
- **Step.1.3** Evaluate the average link utilization for the VNT obtained in Step 1.2.

Step.2 Determine a node to add transceivers. We select the node that shows the lowest value of average link utilization. Then, add transceivers to the node. Go back to Step.1 if we try to add more transceivers.

In this paper, we use I-MLTDA for the ad-hoc design. Although there have been proposed various design methods, our purpose of introducing ad-hoc design method is to see the failure of design methods that are optimized and specialized to a temporal environment. We believe that our results in Sec. IV-B are valid with other heuristic algorithms.

4) VNT control method based on attractor selection: We use VNT control method based on attractor selection in the evaluating simulation. Of course we again apply I-MLTDA as the VNT control method. However, our primal purpose to design a WDM network is to maximize the adaptability of VNT control. So, we use VNT control method based on attractor selection for evaluation.

Our VNT control method is driven by activity, which is a feedback of network status. When activity is low, the random behavior tries to seek a better VNT. In this paper, the activity is given by the following equation,

$$activity = \frac{\gamma}{1 + e^{\delta(L_{average} - \theta)}}, \quad (6)$$

where $L_{average}$ is average link utilization and the other literals are parameters. With this definition, the activity rapidly approaches 0 when the average link utilization exceeds θ. That is, VNT control method tries to make the average link utilization to be smaller than the threshold. The activity value takes $(0, 1)$ as we set $\gamma = 1$. In this paper, we set the threshold θ to 0.25. That is, we assume that the condition of IP network is poor if the average link utilization is more than 0.25. The gradient δ of the activity function is set to 50 following [4].

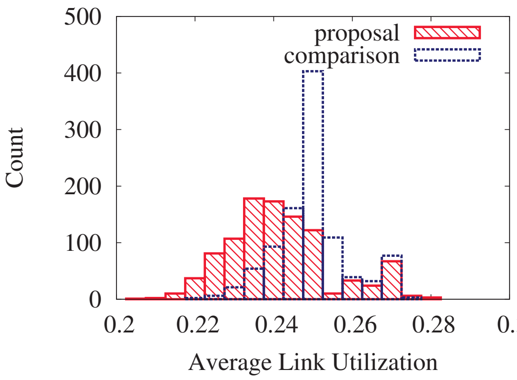
B. Simulation result

Here we explain the simulation result and discuss the performance of our proposed method. We set σ_{noise} in equation (4) to 0 at the beginning of the simulation, and conduct the VNT control based on attractor selection. Following Eq. (4) and (5), the traffic demand eventually increases as the time-step increases. Here we set m to 0.01. At time-step 140, the VNT control method fails to find a good VNT during 400 reconfigurations. Then, our design method and the ad-hoc design method calculate the node to add transceivers. The methods select three nodes to add transceivers, and 4 transceivers are added for each selected node. As the result of calculations, the proposed method adds transceivers to node $\{6, 6, 11\}$, and the ad-hoc design method adds to node $\{11, 12, 18\}$. The computational complexity of the proposed method is much larger than ad-hoc method, so it does take long time to execute the proposed simulation. However, the computational time is not a big issue here because physical network designs should not be executed at short intervals but should be in the long run.

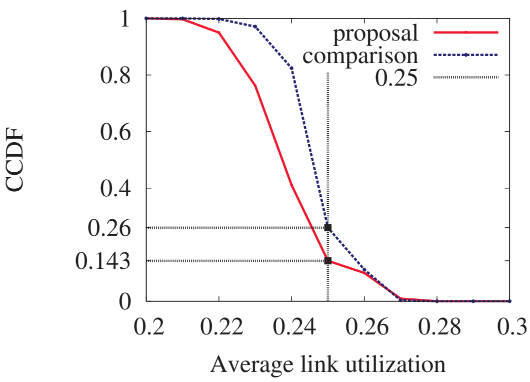
Then, we evaluate the adaptability of the reinforced WDM network against unexpected traffic increase. After the reinforcement, we set the parameter σ_{noise} to 0.10, and examine various patterns of traffic change to check whether VNT control method based on attractor selection can find a good VNT or not.

Figure 6(a) shows the distribution of average link utilization at the time-step 210 for 1000 patterns of traffic changes. Note that the traffic increases and fluctuates in different way from time-step 140 to 210. Therefore, Figure 6(a) shows the performance of the VNT control method against various patterns of traffic change. As we can see, more traffic patterns are accommodated with lower link utilization by the proposed method than that by the ad-hoc design method. We can conclude that the proposed method makes the WDM network more flexible, that is, our method improves the ability to accommodate various traffic fluctuations with lower network load. Figure 6(b) shows CCDF (Complementary Cumulative Distribution Function) of the same data, indicating that the proposed method accommodates 857 traffic fluctuation patterns and the ad-hoc design method accommodates 740. Consequently, the proposed method raises the success rate of VNT control based on attractor selection by more than 15% (because $0.857/0.740 \approx 1.158$) compared to the ad-hoc design method.

We change the noise strength σ_{noise} of traffic fluctuation to see the network by our design method can accommodate various patterns of traffic fluctuation. Figure 7 shows the VNT control success rate against σ_{noise}, and we observe the proposed design improves the success rate when traffic fluctuates strongly. When the noise level is low, both the proposed design and the ad-hoc design achieve almost 100% success rate. This is because that the network with ad-hoc design is optimized and specialized to the traffic demand matrix at the time of reinforcement, and the traffic demand



(a) Histogram



(b) CCDF

Fig. 6. Distribution of average link utilization

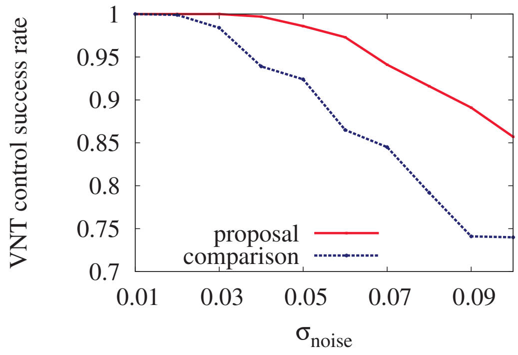


Fig. 7. VNT control success rate

matrix does not change drastically with lower σ_{noise}. As the noise level increases, the traffic changes more drastically. Thus, the ad-hoc design with VNT control cannot handle the traffic fluctuation. In comparison, the proposed design with VNT control can accommodate more traffic patterns even when σ_{noise} takes high.

V. Conclusion

We proposed a design method of WDM network, which determines a set of nodes where transceivers should be added, inspired from biological evolution so that the network can obtain the plasticity. Computer simulation for a topology with 19 nodes and 39 links showed that our method makes VNT control method based on attractor selection more adaptive against unexpected traffic fluctuations.

In the future work, we will evaluate on physical topologies other than EON and USNET and will investigate to extend our method so that it should add not only transceivers of a node but also links between nodes.

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