Virtual Network Reconfiguration in Elastic Optical Path Networks for Future Bandwidth Allocation

Toshihiko Ohba, Shin'ichi Arakawa, and Masayuki Murata

***Abstract*—Given the limited number of resources (i.e., frequency slots and transponders at optical switches) in elastic optical networks, one approach to accommodating traffic demand is for the network operator to offer a certain number of leased lightpaths in response to requests from service providers, while configuring a virtual network (VN) that accommodates the traffic demands of other consumers. It is essential to reconfigure the VN according to changes in traffic while setting aside resources for leased lightpaths and accommodating increased traffic demand on the VN. Our research group has proposed a VN reconfiguration method for traditional wavelength division multiplexing networks based on attractor selection, which is a model of the behavior by which living organisms adapt to unknown changes in their surrounding environment. However, simply adopting this method cannot make the best use of elastic optical networks since it assigns all wavelengths to accommodate the current traffic demand, which leads to a lack of resources for accommodating the future traffic demand. In this paper, we therefore propose a method for reconfiguring a VN over an elastic optical network. To set aside resources for future traffic demands, we newly define the potential bandwidth as a metric that reflects the bandwidth that can be additionally offered. Our method reconfigures a VN based on attractor selection using information about the service quality on the VN and the potential bandwidth, and it also adjusts the bandwidths of all the lightpaths that form the VN. The evaluation results show that our method can reconfigure a VN so the service quality on the VN is improved while keeping some resources unused.**

***Index Terms*—Attractor selection; Elastic optical network; Virtual network; VN reconfiguration.**

I. Introduction

Changes in the environment surrounding the Internet in recent years, such as advances in personal Internet-enabled devices and the emergence of new Internet services, have led to rapid growth in traffic demands. Thanks to the large bandwidth of optical fibers, optical networks have the potential to support this growing traffic demand. Recently, elastic optical networks based on orthogonal frequency division multiplexing technology have been shown to be a promising candidate for future cost-efficient optical networks [1–3].

In elastic optical networks, the spectrum resources are divided into narrow frequency slots such that a different number of frequency slots can be allocated to different optical connections (i.e., lightpaths). Elastic optical networks therefore offer higher spectrum utilization efficiency than traditional wavelength-routed networks based on wavelength division multiplexing (WDM) technology. This is because WDM networks require all of the wavelengths in a lightpath to be assigned, even when the traffic demand between the end nodes is not sufficient to fill the entire bandwidth, whereas elastic optical networks have the potential to assign spectrum resources to lightpaths based on traffic volumes or clients' bandwidth requirements through fine-grained frequency slots.

Many studies have been devoted to developing methods for accommodating traffic demand over an elastic optical network [4–10]. One approach to accommodating traffic demand over an elastic optical network is for the network operator to offer leased lightpaths in response to requests from service providers. In Ref. [4], routing and spectrum assignment (RSA) algorithms that offer lightpaths for each individual request are proposed. In this approach, the network operator can respond to a wide variety of requests from service providers with sufficient spectrum resources to provide the required bandwidth. Allocating sufficient frequency slots to lightpaths can lead to a reduction in power consumption. However, it is difficult to offer connections for all requests for end-to-end lightpaths since the number of transponders at each optical switch is limited. Therefore, a realistic approach for the network operator is not only to offer a certain number of leased lightpaths in response to requests, but also to configure a virtual network (VN) that accommodates other consumer traffic demand [5–10]. A VN consists of a set of lightpaths and client nodes (e.g., IP routers), with the traffic demand transferred over the VN in a multi-hop manner. When fluctuations in the traffic demand cause temporary traffic congestion, it is necessary to reconfigure the VN so the traffic congestion is resolved and the VN can accommodate the changing traffic demand. Furthermore, it is essential for the network operator to be able to configure the VN using a limited set of resources (i.e., frequency slots and transponders at optical switches) by using resources effectively

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in order to set aside resources for leased lightpaths and accommodate increased traffic demands on the VN.

References [5–10] propose methods for configuring a VN over an elastic optical network. These methods first collect traffic demand information and then configure the VN. However, it generally takes a long time to retrieve the traffic demand information matrix. Thus, when there are large fluctuations in the traffic demand, these methods have difficulty configuring the VN to follow the changes in traffic. It is therefore essential to develop a method for adaptively reconfiguring VNs in response to changes in traffic that occur over a short period of time. References [11] and [12] propose a VN reconfiguration method over traditional WDM networks that is adaptive to traffic changes and accommodates IP traffic effectively. This method is based on attractor selection [13], which is a model of the behavior by which living organisms adapt to unknown changes in their surrounding environment. This method can reconfigure a VN using a small amount of information about the service quality on the IP network, such as load information on all lightpaths, which can be retrieved in a much shorter time, typically 5 min or less, than traffic demand matrices. However, optimal utilization of elastic optical networks cannot be achieved by simply adopting this method because the method focuses on reducing traffic loads. That is, this approach assigns all of the wavelengths in order to accommodate the current traffic demand, which leads to a lack of resources for accommodating the future traffic demand. Therefore, applying this method to elastic optical networks results in missing the opportunity to accommodate the future traffic demand.

From the above discussion, the requirements for a VN configuration method for elastic optical networks are as follows:

- reconfigure the VN to accommodate the changing traffic demand,
- set aside resources to use for leased lightpaths and to accommodate increased traffic demand on the VN,
- reconfigure the VN in a shorter time period.

In this paper, we newly propose a VN reconfiguration method for elastic optical networks that can achieve these requirements. To achieve the second requirement, we newly define the potential bandwidth as a metric that reflects the bandwidth that can be offered for leased lightpaths and for increased traffic demand on the VN. Specifically, our method reconfigures the VN based on attractor selection using both information about the service quality on the VN and the potential bandwidth, and it adjusts the bandwidths of the lightpaths that form the VN. Our method is based on the observation of the service quality on the VN and the potential bandwidth. Therefore, measurement of traffic demand matrices is no longer necessary in our method. Note that, since the service quality on the VN depends on the traffic demand, the information on traffic demand is indirectly utilized in our method. This is the essential difference between our method and the previous methods.

The rest of this paper is organized as follows. In Section II, we first describe our target network model and related works. We then explain the concept of the attractor selection model and propose the VN reconfiguration method for elastic optical networks in Section III. In Section IV, we evaluate the performance of our method, and we conclude this paper in Section V.

II. Network Model and Related Work

In this section, we describe the network model that we use in this paper and also briefly describe existing VN reconfiguration methods for elastic optical networks.

A. Network Model

Figure 1 shows the network model considered in this study. Elastic optical networks can flexibly assign spectrum resources to lightpaths according to the changing traffic demand by introducing hardware components such as bandwidth-variable transponders (BVTs) and bandwidth-variable wavelength cross-connects (BV WXCs). Elastic optical networks employing these hardware components have been modeled as spectrum-sliced elastic optical path (SLICE) networks [3]. In SLICE networks, BV WXCs are interconnected by optical fibers. A BVT converts electric signals from a client node (e.g., an IP router) into optical signals by using sufficient spectrum resources (i.e., frequency slots). Every BV WXC on the route switches the optical signals to establish an end-to-end lightpath with the sufficient bandwidth. When the bandwidth utilization of the lightpath increases, the BVT can assign more spectrum resources to the lightpath in order to expand its bandwidth. In contrast, when the bandwidth utilization of the lightpath decreases, the BVT can release some spectrum resources to reduce the bandwidth. Adjusting the bandwidths of lightpaths according to the situation leads to reduction in the number of active frequency slots. As a result, SLICE networks have the potential to reduce the power consumption, since the power

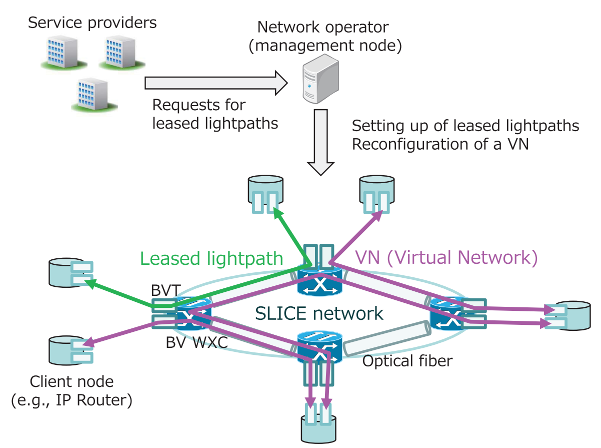

Fig. 1. SLICE network model and operation approach.

consumption depends on the number of active frequency slots [9,14].

The network operator accepts requests for lightpaths from service providers. When there are sufficient resources to provide a leased lightpath in response to a request, the network operator establishes a leased lightpath with the required bandwidth under the spectrum contiguity and continuity constraints. For example, when an event is held that spans more than one venue, a service provider may request dedicated lightpaths of the desired bandwidth between the venues. Furthermore, the network operator also constructs a VN to accommodate the traffic demands of other consumers. The network operator reconfigures the VN according to changes in traffic in order to maintain the service quality of network services accommodated by the VN while setting aside resources for the leased lightpaths. In this way, the network operator accepts various sources of traffic demand that are accommodated by the elastic optical network.

B. Related Works

There are many works for configuring a VN over an elastic optical network. Basically, they aim to solve the RSA problem for elastic optical networks using mixed integer linear programming (MILP) or using a heuristic algorithm.

Reference [5] proposes an approach to configuring a spectrum assignment of a VN over an elastic optical network. The topology of the VN is assumed to be a full-mesh topology, and the algorithm adjusts the bandwidth of lightpaths based on the traffic demand measurement. The method aims to minimize the packet delay and consumed capacity by MILP.

References [6–8] investigate VN configuration schemes over elastic optical networks. Reference [6] points out the advantage of BVT for total equipment costs, which include the costs of slot cards, transponders, and optical switches. The RSA problem is solved under static traffic demands. Reference [7] proposes a heuristic algorithm for configuring a couple of VNs over a multi-domain elastic optical network. Using the information of traffic demands for each VN, the algorithm minimizes the total network cost, including the costs of transponders, regenerators, and spectrum resources. Reference [8] considers the modulation level assignment problem in addition to the RSA problem. The heuristic algorithm in Ref. [8] jointly solves the routing, modulation level, and spectrum assignment problems. Using the traffic demand information, the algorithm tries to minimize the total network costs, such as the costs of transponders and routers.

Reference [9] presents minimal-power-consumption designs to minimize the total power consumption in elastic networks. The authors develop a MILP formulation and its heuristic algorithm. The traffic demand of each node pair is necessary to solve the problem. Reference [10] proposes a MILP formulation for several schemes of protection in cases where multiple VNs run over an elastic optical network.

These previous methods [5–10] aim to configure a VN over an elastic optical network that achieves some objective by MILP or using a heuristic algorithm, based on long-term measurement of traffic demand. However, when there are large fluctuations in the traffic demand, it is difficult for these methods to reconfigure the VN following the changes in traffic. It is therefore important to develop a method for adaptively reconfiguring VNs in response to changes in traffic that occur over a short period of time.

III. VN Reconfiguration Method in Elastic Optical Networks for Future Bandwidth Allocation

In this section, we first briefly explain the attractor selection model and then explain our VN reconfiguration method based on attractor selection for elastic optical networks.

A. Attractor Selection Model

Dynamic systems driven by the attractor selection model are able to adapt to unknown changes in their surrounding environments [13]. In the attractor selection model, attractors are a subset of the equilibrium points in the solution space where the system conditions are preferable. The basic mechanism of the attractor selection model consists of both deterministic behavior and stochastic behavior. The behavior of a dynamic system driven by attractor selection can be described as follows:

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

The state of the system is represented by $\mathbf{x} = (x_1, \ldots, x_i, \ldots, x_n)$, where n is the number of state variables. $f(\mathbf{x})$ represents the deterministic behavior, and η represents the stochastic behavior. The behavior is controlled by activity α, which is a simple feedback of the system conditions. When the current system conditions are suitable for the environment and the value of α is large, the deterministic behavior drives the system to the attractor. When the current system conditions are poor, that is, when the value of α is small, the stochastic behavior dominates the control of the system. While the stochastic behavior is dominant, the state of the system fluctuates randomly due to noise η, and the system searches for a solution where the system conditions are preferable. In this way, attractor selection adapts to environmental changes using both deterministic behavior and stochastic behavior based on the activity.

When we investigate a method for VN reconfiguration over an elastic optical network, the method is expected to reconfigure the VN to improve the service quality on it and/or to set aside resources by properly defining the state of the system $\mathbf{x}$ and the activity α.

B. Outline of the VN Reconfiguration Method

We have developed a method for reconfiguring VNs for elastic optical networks. Our method reconfigures the virtual topology and adjusts the bandwidth of the lightpaths that form the VN in order to improve service quality on the VN while keeping some resources unused. Given a current stage of VN configuration, i.e., the virtual topology and the configuration of frequency slots, our method observes the link utilization on the VN and determines the next stage of VN configuration. The method repeatedly executes these controls based on the measured link utilization on the VN, as shown in Fig. 2. Here, traffic is assumed to flow between client nodes via the shortest path in the VN. We refer to link utilization on the VN as simply link utilization. The following gives an outline of our method:

(Phase 1) Reconfigure the virtual topology.

(Phase 1-1) Calculate the activity based on both the service quality on the VN and information about resource utilization.

(Phase 1-2) Configure the virtual topology based on attractor selection.

(Phase 1-3) Allocate frequency slots to newly established lightpaths.

(Phase 2) Adjust the bandwidth of lightpaths that form the VN.

The method repeatedly reconfigures a VN in response to traffic changes. As inputs, the method uses the information of link utilization on all lightpaths, the current virtual topology, and the current configuration of frequency slots. Then, the method reconfigures a VN, i.e., reconfigures the virtual topology and reallocates frequency slots, as outputs. The outputs of an execution are used as inputs for the next execution.

Detail on the VN reconfiguration in each of these phases is given in the following sections.

C. *(Phase 1) Reconfiguration of the Virtual Topology*

1) (Phase 1-1) Calculation of the activity: We calculate the activity based on both the service quality on the VN and information about resource utilization. Specifically,

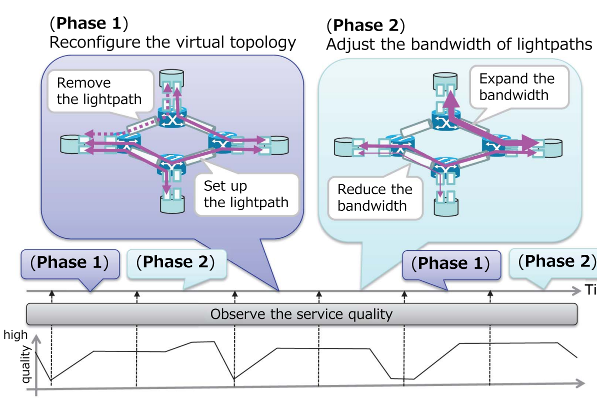

Fig. 2. Outline of the VN reconfiguration method.

we use the following two performance metrics to calculate the activity:

- $u_{\max}$: maximum link utilization,
- $B_{\text{potential}}$: potential bandwidth.

The maximum link utilization $u_{\max}$ represents the service quality on the VN. We then define the potential bandwidth $B_{\text{potential}}$ to reflect the bandwidth that can be offered for leased lightpaths and for accommodating increased traffic demands on the VN. Although our proposed method aims to set aside resources (i.e., frequency slots and BVTs) for requests for leased lightpaths and increased traffic demands, this approach to keeping as many unused resources as possible has the same goal as the approach of maximizing the traffic volume that can be accommodated in the future. Strategies for allocating resources for future demand have been discussed in Ref. [15]. In Ref. [15], the authors compare two approaches: one approach is to maximize the smallest value of the bandwidth that can be added to lightpaths between every node pair, while the other is to maximize the total volume of the bandwidth that can be added to end-to-end lightpaths. The latter approach was found to give lower blocking ratios for lightpath requests. That is, by introducing the latter approach, the network operator can accept more traffic demands to be accommodated in the network. We therefore also determine the potential bandwidth, which reflects the total volume of bandwidth that can be additionally offered to every node pair. We define the potential bandwidth as follows:

$$B_{\text{potential}} = \sum_{s,d \in V} B^{sd}_{\text{potential}}, \qquad (2)$$

where V represents the set of nodes in the network, and $B^{sd}_{\text{potential}}$ represents the potential bandwidth for the node pair (s, d). We introduce different definitions of $B^{sd}_{\text{potential}}$ depending on whether a lightpath is established between s and d or not:

- When a lightpath is established between s and d, we define $B^{sd}_{\text{potential}}$ as the bandwidth size that can be added to the lightpath (s, d). Figure 3 shows an example of $B^{sd}_{\text{potential}}$ in this case. The BVTs at nodes s and d can offer up to 40 Gbps of bandwidth, while the lightpath between s and d currently has a bandwidth of 20 Gbps. That is, the BVTs can offer an additional $40 - 20 = 20$ Gbps

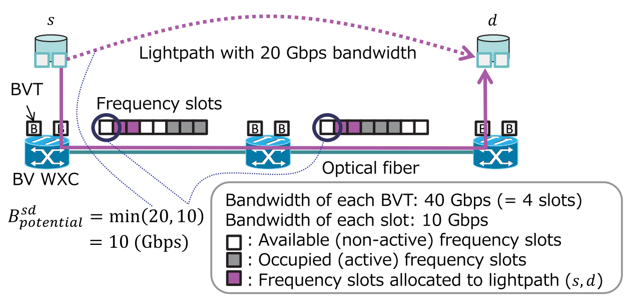

Fig. 3. Example of the potential bandwidth for a node pair (s, d): case where a lightpath is established between s and d.

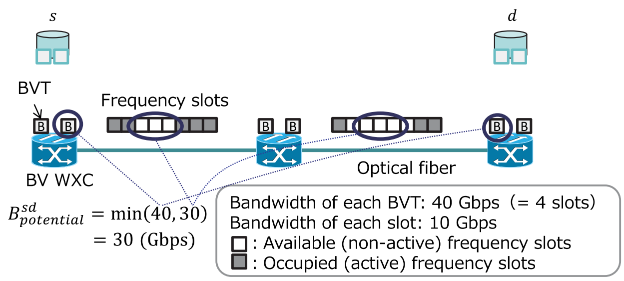

Fig. 4. Example of the potential bandwidth for a node pair (s, d): case where a lightpath is not established between s and d.

bandwidth. The number of frequency slots that can be allocated to the lightpath between s and d under the spectrum contiguity and continuity constraints is one, which gives a bandwidth of 10 Gbps. Therefore, we calculate the potential bandwidth for a node pair (s, d), $B^{sd}_{\text{potential}}$, as follows: $B^{sd}_{\text{potential}} = \min(20, 10) = 10$ Gbps.

- When a lightpath is *not* established between s and d, we define $B^{sd}_{\text{potential}}$ as the bandwidth size that can be offered if a lightpath is established between s and d. Figure 4 shows an example of $B^{sd}_{\text{potential}}$ in this case. The BVTs at nodes s and d can offer up to 40 Gbps of bandwidth. If we establish a lightpath between s and d, we can allocate three frequency slots to this lightpath under the spectrum contiguity and continuity constraints, giving $10 \times 3 = 30$ Gbps. We thus calculate the potential bandwidth for the node pair (s, d), $B^{sd}_{\text{potential}}$, as follows: $B^{sd}_{\text{potential}} = \min(40, 30) = 30$ Gbps.

We get activity α by calculating

$$\alpha = \alpha_{\text{mlu}} \cdot \alpha_{\text{pb}}, \tag{3}$$

where α_{mlu} indicates the condition of the VN in terms of the service quality on the VN, and α_{pb} indicates the condition in terms of preservation of resources. We convert the maximum link utilization on the VN $u_{\max}$ into α_{mlu} by using Eq. (4) below. The value of α_{mlu} is in the range [0, 1], and the constant value u_{maxth} is the target value of the maximum link utilization. When the maximum link utilization is less than the threshold u_{maxth}, α_{mlu} rapidly approaches 1. The constant number δ_{mlu} determines the gradient of the function. The conversion equation is

$$\alpha_{\text{mlu}} = \frac{1}{1 + \exp(\delta_{\text{mlu}} \cdot (u_{\max} - u_{\text{maxth}}))}. \tag{4}$$

We also convert the potential bandwidth $B_{\text{potential}}$ into α_{pb} by using Eq. (5) below. The value of α_{pb} is in the range [0, 1], and the constant number θ_{pb} is the target value of the potential bandwidth. When the potential bandwidth is more than the target value θ_{pb}, α_{pb} rapidly approaches 1. The constant value δ_{pb} determines the gradient of the function. The conversion equation is

$$\alpha_{\text{pb}} = \frac{1}{1 + \exp(\delta_{\text{pb}} \cdot (\theta_{\text{pb}} - B_{\text{potential}}))}. \tag{5}$$

The reason why we multiply α_{mlu} and α_{pb} together is that we aim to configure the VN to achieve the objectives for both the service quality on the VN and preservation of resources; in other words, we aim to configure a VN that can accommodate traffic demand on the VN while keeping some resources unused. The activity α takes a large value if and only if the both objectives are achieved; that is, α_{mlu} and α_{pb} take large values.

2) (Phase 1-2) Configuration of the virtual topology: We consider the state of the system $\mathbf{x}$ in the attractor selection model as the state of all possible lightpaths that form the VN. That is, we decide whether or not to set up a lightpath l_i based on a state variable $x_i (\in \mathbf{x})$. The dynamics of the state variable x_i are defined by

$$\frac{dx_i}{dt} = \alpha \cdot \left(\varsigma\left(\sum_j W_{ij} x_j \right) - x_i \right) + \eta. \tag{6}$$

The activity α indicates the condition of the VN, which is calculated in Phase 1-1. The term $\varsigma(\Sigma_j W_{ij} x_j) - x_i$ represents the deterministic behavior, where $\varsigma(z) = \tanh(\frac{\mu}{2} z)$ is a sigmoidal regulation function and μ is the parameter of the sigmoidal function. The first term is calculated using a regulatory matrix W_{ij}. The second term η represents the stochastic behavior and is white Gaussian noise with a mean value of zero. After x_i is updated based on Eq. (6), we decide whether or not to set up the lightpath l_i. Specifically, we set the threshold to zero, and if x_i is greater than or equal to the threshold, we set up the lightpath l_i and otherwise remove the lightpath l_i.

We set the regulatory matrix so it has a set of virtual topology candidates as attractors. That is, we set the regulatory matrix $\mathbf{W}$ so that $d\mathbf{x}/dt$ in Eq. (1) is equal to zero when the virtual topology reconfigured by our VN reconfiguration method $\mathbf{x} = (x_1, \cdots, x_n)$ is one of the attractors. For the attractors that are stored in the regulatory matrix, we use a method to decide the regulatory matrix using the pseudoinverse matrix, which is shown in Ref. [16]. Specifically, assuming that we have set m VN candidates as attractors and one of the candidates is represented by $\mathbf{x}^{(k)} = (x_1^{(k)}, \cdots, x_n^{(k)})$ $(1 \le k \le m)$, the regulatory matrix that has m attractors is

$$\mathbf{W} = \mathbf{X}^{+}\mathbf{X}, \tag{7}$$

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 pseudoinverse matrix of $\mathbf{X}$.

In these dynamics, the VN is reconfigured so activity α takes a large value. In other words, it is expected that our method is able to reconfigure the VN to maintain service quality on the VN while keeping some resources unused.

3) (Phase 1-3) Allocation of frequency slots: We now allocate frequency slots to the lightpaths we established in Phase 1-2. We set the bandwidth of these lightpaths to the maximum bandwidth a BVT can provide and allocate the number of frequency slots corresponding to that bandwidth. For example, assuming that the bandwidth a BVT can offer is 100 Gbps and the bandwidth per frequency slot is 10 Gbps, the number of frequency slots we allocate to the lightpath in this phase is 10. At this point, we introduce an

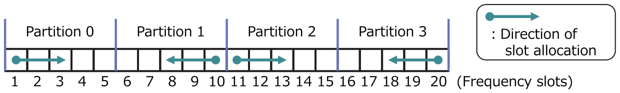

Fig. 5. First-last fit algorithm.

existing heuristic algorithm for allocating frequency slots for simplicity. We use the longest-path first-ordering algorithm [17] to determine the order of lightpaths to which frequency slots are allocated. We sort the lightpaths by the number of links on the shortest path in the physical topology (i.e., the number of physical hops) and allocate frequency slots first to the lightpath with the largest number of physical hops. We also use the first-last fit algorithm [18] for allocating frequency slots to the lightpath. An outline of this algorithm is shown in Fig. 5. In this algorithm, all frequency slots of each optical fiber are divided into a number of partitions, and we allocate a lightpath frequency slots from the partition that has the largest number of available frequency slots. In even-numbered partitions, we select the lowest indexed slots from the list of available frequency slots, and in odd-numbered partitions, we select the highest indexed slots from the list of available frequency slots.

D. (Phase 2) Adjustment of Lightpath Bandwidth

We adjust the bandwidth of each lightpath based on its link utilization. The link utilization of each lightpath is expected to be in the range $[u_{\mathrm{minth}}, u_{\mathrm{maxth}}]$, where u_{minth} is the lower limit of the target value of the link utilization and u_{maxth} is the upper limit of the target value of the link utilization. If the link utilization of a lightpath is lower than the lower limit value u_{minth}, it is considered that excessive allocation of frequency slots has caused reduced spectrum utilization efficiency. Poor spectrum utilization efficiency causes increased power consumption and decreases the amount of bandwidth that can be offered for leased lightpaths and for accommodating increased traffic demand on the VN. If the link utilization of a lightpath is higher than the upper limit u_{maxth}, it is considered that a high-loaded lightpath has caused the degradation of the service quality on the VN. Therefore, we adjust the bandwidth of each lightpath l_i as follows:

- If the link utilization of the lightpath l_i, denoted u_i, is less than u_{minth}, we reduce the number of frequency slots allocated to l_i so u_i is higher than u_{minth}.
- If u_i is greater than u_{maxth}, we increase the number of frequency slots allocated to l_i so u_i is lower than u_{maxth}. However, we consider spectrum contiguity and continuity constraints when adding frequency slots, and the number of frequency slots allocated to one lightpath does not exceed the number of slots corresponding to the maximum bandwidth the BVT can provide.

When we adjust the number of frequency slots, we fix the central frequency and symmetrically allocate or release the slots following the semi-elastic scheme proposed in Ref. [19].

IV. Performance Evaluation

In this section, we evaluate the performance of the VN reconfiguration method proposed in Section III.

A. Evaluation Using USNET

We first evaluate the performance of our method using the USNET topology shown in Fig. 6. Table I shows the parameters related to the physical network topology. The number of nodes (i.e., BV WXCs) is 24, and the number of links (i.e., bidirectional optical fibers) is 43. Each BV WXC has 10 BVTs that can offer up to 100 Gbps of bandwidth.

When we calculate the activity in Phase 1-1, we set δ_{mlu}, δ_{pb} to 50 in Eqs. (4) and (5). Table II shows the target values for VN reconfiguration. We set the target value of the link utilization to the range [0.2, 0.8] and the target value of the potential bandwidth θ_{pb} to $24 \times (24-1) \times 100 \times 0.2 = 11,040$, since we intend to set aside 20% of the bandwidth a BVT can offer between every node pair on average. When we reconfigure the virtual topology based on Eq. (6) in Phase 1-2, we set μ of the sigmoidal function $\varsigma(z)$ to 20. We also set the regulatory matrix W such that it contains virtual topology candidates designed by the method [12] as attractors. At the beginning of computer simulation, we configure one of the candidates as the initial virtual topology and allocate frequency slots by following the procedure in Phase 1-3. Table III shows the parameters related to frequency slot allocation. We assume that the available spectrum width of each optical fiber is 4.75 THz and set the spectrum width of each frequency slot to 12.5 GHz. That is, the number of available frequency slots per optical

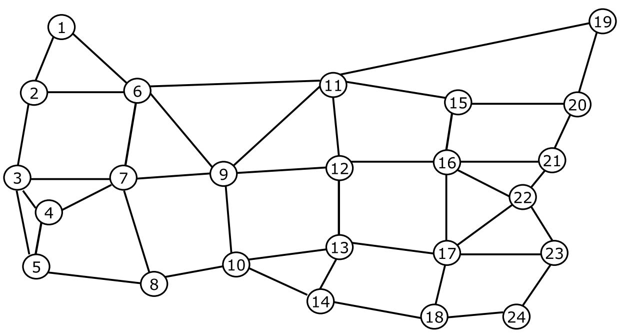

Fig. 6. USNET.

TABLE I
Physical Network Topology-Related Parameters (USNET)

Parameter	Value
Number of nodes	24
Number of links	43
Number of BVTs	10
Bandwidth of each BVT	100 Gbps

TABLE II
TARGET VALUES FOR VN RECONFIGURATION (USNET)

Parameter	Target value
u_{minth}	0.2
u_{maxth}	0.8
θ_{pb}	11,040

TABLE III
FREQUENCY SLOT ALLOCATION-RELATED PARAMETERS (USNET)

Parameter	Value
Spectrum width of each optical fiber	4.75 THz
Spectrum width of each frequency slot	12.5 GHz
Bandwidth of each frequency slot	10 Gbps
Number of partitions	4
Guard band	12.5 GHz

fiber is 380. Each frequency slot has a bandwidth of 10 Gbps. When we use the first-last fit algorithm in Phase 1-3, we divide the spectrum width of each optical fiber into 4 partitions, so each partition has 95 frequency slots. We set the guard band between occupied frequency slots of adjacent lightpaths to 12.5 GHz, which corresponds to one frequency slot.

For the evaluation, the initial traffic demand between each node pair is chosen in the range [0.0, 1.5] Gbps from a uniform random distribution. We then increase the demand of each channel by a capacity chosen in the range [0.0, 0.01] Gbps from a uniform random distribution at each step of VN reconfiguration. We compare our method to a method that configures the VN to accommodate only the current traffic demand using all the information about the traffic demand between every node pair. Specifically, we introduce the most subcarriers first (MSF) algorithm [17] in order to determine the virtual topology and the first-last fit algorithm in order to allocate frequency slots to the lightpaths that form the VN. The MSF algorithm establishes lightpaths between node pairs selected in ascending order of number of requested frequency slots. In this evaluation, the reference method collects information about the traffic demand between each node pair by long-term measurements. The method then sets up lightpaths and allocates frequency slots to lightpaths between node pairs in ascending order of traffic volume. The bandwidths of the lightpaths established by this reference method are the maximum bandwidth a BVT can provide. That is, this reference method does not adjust the bandwidths of the lightpaths.

Figure 7 shows the potential bandwidth at each step of VN reconfiguration. The horizontal axis shows the number of steps of the VN reconfiguration, and the vertical axis shows the potential bandwidth at each step. The dotted line indicates the target value of the potential bandwidth θ_{pb}. At each even-numbered step, our proposed method enters Phase 1 (i.e., reconfigures the virtual topology), and at each odd-numbered step, it enters Phase 2 (i.e., adjusts the bandwidths of the lightpaths). The reference method, which is denoted "MSF+First-last fit" in the figure, reconfigures the VN every 20 steps based on information about the traffic demand between every node pair. Figure 7 shows that the potential bandwidth in our method is kept higher than the target value until around step 900. The reason for the gradual decrease in the potential bandwidth is that our method expands the bandwidths of the lightpaths (i.e., adds frequency slots to lightpaths) in accordance with increases in traffic demand. In contrast, the potential bandwidth in the reference method takes a very small value. This is because the reference method establishes as many lightpaths as possible and does not adjust the bandwidths of the lightpaths in order to accommodate the current traffic demand. The above suggests that our method may be able to set aside resources for leased lightpaths and to accommodate increased traffic demand on the VN until around step 900.

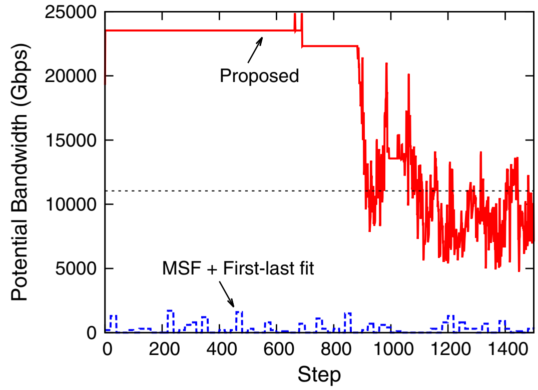

Fig. 7. Potential bandwidth (USNET).

In terms of the direct effects of the high potential bandwidth maintained by the proposed method, Fig. 8 shows the number of resources used (i.e., frequency slots and BVTs). Figure 8(a) shows the number of occupied (i.e., active) frequency slots at each step of VN reconfiguration. The horizontal axis shows the number of steps of the VN reconfiguration, and the vertical axis shows the total number of occupied frequency slots at each step. We can see that the number of occupied frequency slots with the proposed method is smaller than half that with the reference method until step 900. This is because the proposed method adjusts the bandwidth of each lightpath based on the link utilization in Phase 2 in order to accommodate the current traffic demand, whereas the reference method does not. The reason for the gradual increase in the number of occupied frequency slots with the proposed method is that additional frequency slots are allocated to the lightpaths adaptively in response to increases in the traffic demand. Figure 8(b) shows the number of lightpaths that form the VN (i.e., the number of used BVTs) at each step of VN reconfiguration. The horizontal axis shows the number of steps of the VN reconfiguration, and the vertical axis shows the total number of lightpaths at each step. The dotted line indicates the maximum number of lightpaths that can be established to configure the VN. Figure 8(b) shows that the number of lightpaths established by the proposed method

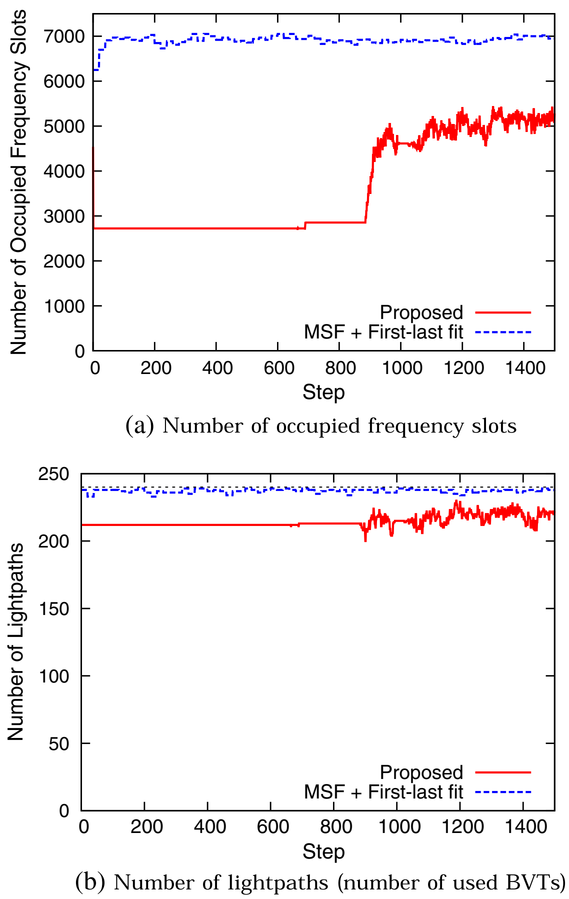

Fig. 8. Number of used resources (USNET).

is consistently lower than that by the reference method. In other words, the proposed method configures the VN by using fewer BVTs. This is because the proposed method reconfigures the virtual topology by using the potential bandwidth as the activity in Phase 1 in order to keep more resources unused. By keeping a high potential bandwidth, the proposed method can set aside resources for leased lightpaths and to accommodate increased traffic demands on the VN (i.e., reduce the number of resources used to configure the VN).

Figure 9 shows the maximum link utilization at each step of VN reconfiguration. The horizontal axis shows the number of steps of the VN reconfiguration, and the vertical axis shows the maximum link utilization of the VNs configured at each step. The upper dotted line indicates the upper limit value u_{maxth}, and the lower dotted line indicates the lower limit value u_{minth}. In Fig. 9, we can see that the maximum link utilization by our method rises at first, but it is kept below the upper limit value by VN reconfiguration. That is, our method can reconfigure the VN so that it can accommodate changing traffic demands. Note that the potential bandwidth takes a higher value than the target value θ_{pb}, as shown in Fig. 7, when our method reconfigures the VN to accommodate the traffic demand. The maximum link utilization by the reference method rises gradually as the traffic demand increases. At about step

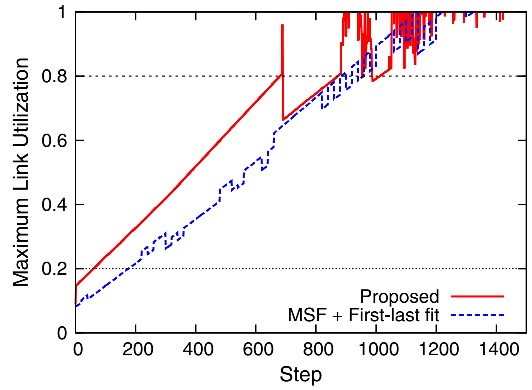

Fig. 9. Maximum link utilization (USNET).

900, the maximum link utilization by the reference method reaches almost the same value as the proposed method. That is, the VN configured by the proposed method is able to maintain the service quality on the VN to the same degree as the VN configured by the method that uses all the traffic demand information.

Figure 10 shows the distribution of the number of VN reconfiguration steps until convergence by the proposed method for 1000 patterns of traffic demand. We generated these traffic demand patterns by increasing the demand between each node pair until the maximum link utilization by the reference method rose above the upper limit value u_{maxth}. We consider the proposed VN reconfiguration method to have succeeded if the VN reconfiguration meets the target values for both maximum link utilization and potential bandwidth (i.e., the VN reconfiguration finds a solution) within 10 successive steps of the VN reconfiguration. We assume that the traffic demand is given at time zero and evaluate the number of steps of the VN reconfiguration required until the VN reconfiguration successfully converges. The horizontal axis shows the number of steps until convergence, and the vertical axis shows the frequency of the number of steps until convergence. From Fig. 10, we can see that our method can find a solution within 20 steps for 992 traffic patterns. Our method can thus achieve target values of both maximum link

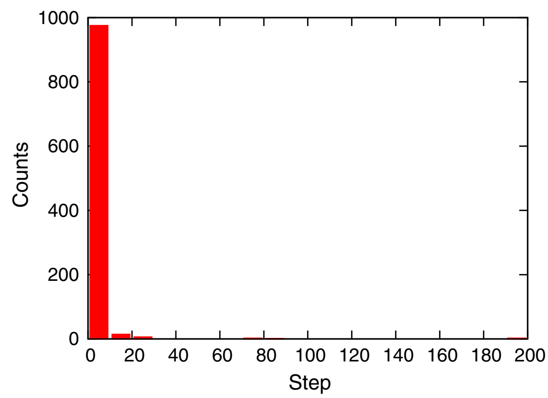

Fig. 10. Distribution of the number of steps until convergence (USNET).

utilization and potential bandwidth for a wide variety of traffic demands without all of the information from the traffic demand matrices.

The above evaluation shows that the proposed method is able to configure a VN that improves the service quality on the VN while setting aside resources for leased lightpaths and accommodating increased traffic demands on the VN.

B. Evaluation Using the Simple CAIS Internet

We next evaluate the performance of our method using the Simple CAIS Internet topology, shown in Fig. 11. This topology has bottleneck links in terms of the allocation of frequency slots, such as the link between nodes 2 and 5. Table IV shows the parameters of the physical network topology. The number of nodes is 16, and the number of links is 23. Each BV WXC has 8 BVTs that can offer up to 100 Gbps of bandwidth. Table V shows the target values for VN reconfiguration. We set the target value of the potential bandwidth θ_{pb} to $16 \times (16-1) \times 100 \times 0.2 = 4800$, with the intention of setting aside 20% of the bandwidth a BVT can offer between every node pair on average. The

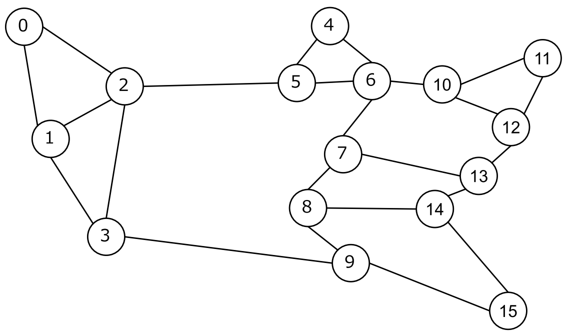

Fig. 11. Simple CAIS Internet.

TABLE IV
PHYSICAL NETWORK TOPOLOGY-RELATED PARAMETERS (SIMPLE CAIS INTERNET)

Parameter	Value
Number of nodes	16
Number of links	23
Number of BVTs	8
Bandwidth of each BVT	100 Gbps

TABLE V
TARGET VALUES FOR VN RECONFIGURATION (SIMPLE CAIS INTERNET)

Parameter	Target value
u_{minth}	0.2
u_{maxth}	0.8
θ_{pb}	4800

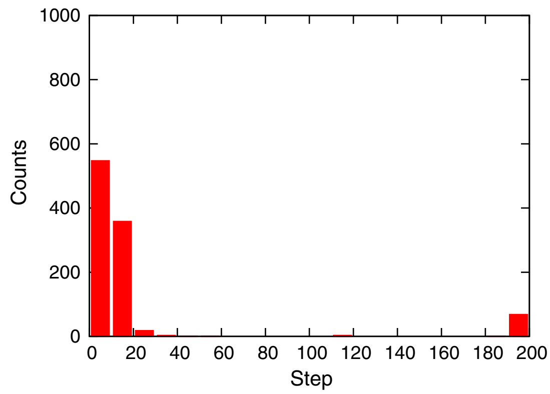

Fig. 12. Distribution of the number of steps until convergence (Simple CAIS Internet).

other target values and parameters for reconfiguring the VN in Phase 1 are the same as in Subsection IV.A. The parameters related to frequency slot allocation are also the same as in Subsection IV.A (shown in Table III). For the evaluation, we generated 1000 patterns of traffic demand in the same way as in Subsection IV.A and compared our method to the same method as in Subsection IV.A.

Figure 12 shows the distribution of the number of VN reconfiguration steps until convergence by the proposed method for 1000 patterns of traffic demand. The horizontal axis shows the number of steps required until the VN reconfiguration successfully converges, and the vertical axis shows the frequency of the number of steps. This figure shows that our method is able to find a solution within 20 steps for 910 traffic patterns. That is, our method can reconfigure the VN to improve the service quality on the VN while keeping unused resources for fewer traffic patterns than the evaluation in Subsection IV.A. This is because it is difficult for the proposed method to find a solution due to the bottleneck links in the allocation of frequency slots. When the proposed method removes some lightpaths and tries to newly establish lightpaths between other node pairs in Phase 1, it is likely that the method cannot set up new lightpaths because of the restrictions on the resources. Therefore, although our method reconfigures a VN to set aside resources, there are cases where it takes a long time to find a VN configuration that uses fewer resources. Note that our method can find a solution within 180 steps for a further 22 traffic patterns.

The above evaluation shows that our method is able to reconfigure the VN to improve the service quality on the VN while keeping unused resources for a wide variety of traffic demands. However, it is likely that it will take a long time for our method to find a solution when the physical network topology has bottleneck links in the allocation of frequency slots.

C. Effect of the Granularity of Frequency Slots

In this section, we evaluate the effect of the granularity of frequency slots. Specifically, we evaluate the

TABLE VI
FREQUENCY SLOT ALLOCATION-RELATED PARAMETERS (USNET: COARSE FREQUENCY SLOTS)

Parameter	Value
Spectrum width of each optical fiber	4.75 THz
Spectrum width of each frequency slot	25.0 GHz
Bandwidth of each frequency slot	20 Gbps
Number of partitions	4
Guard band	25.0 GHz

performance of our method using USNET when the granularity of the frequency slots is coarser.

Table VI shows the parameters related to frequency slot allocation. We assume that the available spectrum width of each optical fiber is 4.75 THz and set the spectrum width of each frequency slot to 25.0 GHz. That is, the number of available frequency slots per optical fiber is 190, which is half the number in Subsection IV.A. Each frequency slot has a bandwidth of 20 Gbps. We also set the guard band between occupied frequency slots to 25.0 GHz, which corresponds to one frequency slot. The other parameters related to the physical network topology and reconfiguration of the VN, and the target values, are similar to those in Subsection IV.A. For the evaluation, we use the same pattern of traffic demand and reference method as in Subsection IV.A.

Figure 13 shows the potential bandwidth at each step of the VN reconfiguration. The horizontal axis shows the number of steps of the VN reconfiguration, and the vertical axis shows the potential bandwidth at each step. The dotted line indicates the target value of the potential bandwidth θ_{pb}. At each even-numbered step, the proposed method enters Phase 1 (i.e., reconfigures the virtual topology), and at each odd-numbered step, it enters Phase 2 (i.e., adjusts the bandwidths of the lightpaths). The method for comparison, which is denoted "MSF+First-last fit" in the figure, reconfigures the VN every 20 steps based on the traffic demand information between every node pair. Figure 13 shows that the potential bandwidth by the proposed method is kept higher than the target value until around step 700. However, after around step 700, the potential bandwidth is lower than the values in Fig. 7, which shows the potential bandwidth in the case where the granularity of frequency slots is finer. In other words, when the granularity of the frequency slots is coarser, it is more difficult to keep a high potential bandwidth in cases where the traffic loads are large. Our method expands the bandwidths of the lightpaths (i.e., adds frequency slots to lightpaths) according to the increased traffic demand. However, since the granularity of frequency slots is coarse, the potential bandwidth that can be additionally offered is sharply reduced. That is, coarser granularity of frequency slots makes it more difficult to set aside resources for leased lightpaths and accommodating increased traffic demand on the VN in cases where the traffic loads are large.

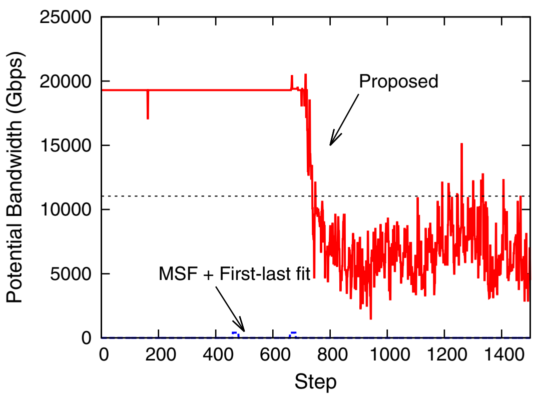

Fig. 13. Potential bandwidth (USNET: coarse frequency slots).

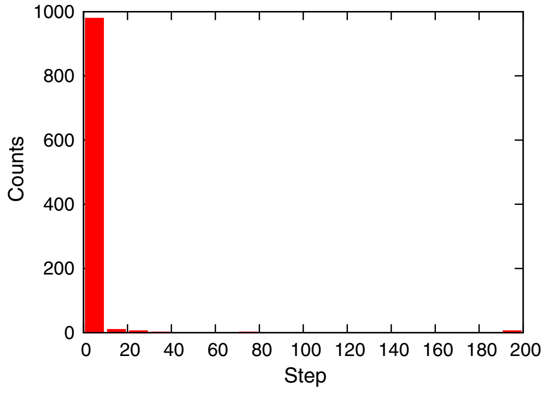

Fig. 14. Distribution of the number of steps until convergence (USNET: coarse frequency slots).

Figure 14 shows the distribution of the number of VN reconfiguration steps until convergence by the proposed method for 1000 patterns of traffic demand. We generated these traffic demand patterns by increasing the demand between each node pair until the maximum link utilization by the reference method rose above the upper limit value u_{maxth}. The horizontal axis shows the number of steps required until the VN reconfiguration successfully converges and the vertical axis shows the distribution of the number of steps. This shows our method is able to find a solution within 20 steps for 991 traffic patterns. That is, our method can reconfigure the VN to improve the service quality on the VN while keeping unused resources for slightly fewer traffic patterns than the evaluation in Subsection IV.A. This is because it is difficult for the proposed method to find a solution, particularly one that keeps the potential bandwidth high, because of the coarse granularity of the frequency slots.

From the above evaluation, we find that a coarser granularity of frequency slots makes it more difficult for the proposed method to keep a high potential bandwidth while maintaining service quality on the VN. In other words, it is easier for our method to achieve the objectives when the granularity of frequency slots is finer. Since there are efforts to break down the spectrum width of optical fiber into even more frequency slots [1,2], this tendency suits our method.

V. CONCLUSION

In this paper, we proposed a VN reconfiguration method for elastic optical networks. Our method reconfigures a virtual topology based on attractor selection using only information about the traffic loads on every lightpath and the potential bandwidth, which we define in this paper as a metric that reflects the bandwidth that can be additionally offered, and then the method adjusts the bandwidths of the lightpaths that form the VN. We showed that our method can configure a VN with fewer resources (i.e., frequency slots and BVTs) while maintaining the service quality on the VN to almost the same degree as a VN configured by using all the traffic demand information. By configuring a VN with fewer resources, the network operator can provide more bandwidth to meet future requests for leased lightpaths and accommodate increased traffic demand on the VN.

One future direction for this work is how to design the physical networks (i.e., elastic optical networks) and how to enhance the network equipment. As shown in Subsection IV.B, it is likely that bottleneck links in terms of allocation of frequency slots will make it difficult to rapidly configure a VN that can accommodate traffic demand while setting aside resources. It is therefore expected that our method will be able to find a solution in a shorter time period if the physical network is better designed.

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References

[1] G. Zhang, M. De Leenheer, A. Morea, and B. Mukherjee, “A survey on OFDM-based elastic core optical networking,” *IEEE Commun. Surv. Tutorials*, vol. 15, pp. 65–87, Feb. 2013.

[2] O. Gerstel, M. Jinno, A. Lord, and S. B. Yoo, “Elastic optical networking: A new dawn for the optical layer?” *IEEE Commun. Mag.*, vol. 50, no. 2, pp. s12–s20, Feb. 2012.

[3] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, “Spectrum-efficient and scalable elastic optical path network: Architecture, benefits, and enabling technologies,” *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 66–73, Nov. 2009.

[4] B. Chatterjee, N. Sarma, and E. Oki, “Routing and spectrum allocation in elastic optical networks: A tutorial,” *IEEE Commun. Surv. Tutorials*, vol. 17, pp. 1776–1800, May 2015.

[5] W. Wei, C. Wang, and X. Liu, “Adaptive IP/optical OFDM networking design,” in *Optical Fiber Communication Conf.*, Mar. 2010, paper OWR6.

[6] T. Tanaka, A. Hirano, and M. Jinno, “Advantages of IP over elastic optical networks using multi-flow transponders from cost and equipment count aspects,” *Opt. Express*, vol. 22, pp. 62–70, Jan. 2014.

[7] S. Hong, J. P. Jue, Q. Zhang, X. Wang, H. C. Cankaya, Q. She, W. Xie, and M. Sekiya, “Virtual optical network provisioning over flexible-grid multi-domain optical networks,” in *IEEE GLOBECOM*, Dec. 2015, pp. 1–6.

[8] V. Gkamas, K. Christodoulopoulos, and E. Varvarigos, “A joint multi-layer planning algorithm for IP over flexible optical networks,” *J. Opt. Commun. Netw.*, vol. 33, pp. 2965–2977, July 2015.

[9] J. Zhang, Y. Zhao, X. Yu, J. Zhang, M. Song, Y. Ji, and B. Mukherjee, “Energy-efficient traffic grooming in sliceable-transponder-equipped IP-over-elastic optical networks [Invited],” *J. Opt. Commun. Netw.*, vol. 7, pp. A142–A152, Jan. 2015.

[10] K. D. R. Assis, S. Peng, R. C. Almeida, H. Waldman, A. Hammad, A. F. Santos, and D. Simeonidou, “Network virtualization over elastic optical networks with different protection schemes,” *J. Opt. Commun. Netw.*, vol. 8, pp. 272–281, Apr. 2016.

[11] Y. Koizumi, T. Miyamura, S. Arakawa, E. Oki, K. Shiomoto, and M. Murata, “Adaptive virtual network topology control based on attractor selection,” *J. Lightwave Technol.*, vol. 28, pp. 1720–1731, June 2010.

[12] T. Ohba, S. Arakawa, Y. Koizumi, and M. Murata, “Scalable design method of attractors in noise-induced virtual network topology control,” *J. Opt. Commun. Netw.*, vol. 7, pp. 851–863, Sept. 2015.

[13] C. Furusawa and K. Kaneko, “A generic mechanism for adaptive growth rate regulation,” *PLoS Comput. Biol.*, vol. 4, e3, Jan. 2008.

[14] J. L. Vizcano, Y. Ye, and I. T. Monroy, “Energy efficiency analysis for flexible-grid OFDM-based optical networks,” *Comput. Networks*, vol. 56, pp. 2400–2419, July 2012.

[15] D. Leung, S. Arakawa, M. Murata, and W. D. Grover, “Re-optimization strategies to maximize traffic-carrying readiness in WDM survivable mesh networks,” in *Optical Fiber Communication Conf.*, Mar. 2005, paper OWG6.

[16] R. Rojas, *Neural Networks: A Systematic Introduction*. Springer, 1996.

[17] K. Christodoulopoulos, I. Tomkos, and E. Varvarigos, “Elastic bandwidth allocation in flexible OFDM-based optical networks,” *J. Lightwave Technol.*, vol. 29, pp. 1354–1366, Mar. 2011.

[18] R. Wang and B. Mukherjee, “Spectrum management in heterogeneous bandwidth networks,” in *IEEE GLOBECOM*, Dec. 2012, pp. 2907–2911.

[19] M. Klinkowski, M. Ruiz, L. Velasco, D. Careglio, V. Lopez, and J. Comellas, “Elastic spectrum allocation for time-varying traffic in flexgrid optical networks,” *IEEE J. Sel. Areas Commun.*, vol. 31, pp. 26–38, Jan. 2013.

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