Virtual Network Reconfiguration with Adaptability to Traffic Changes

Masahiro Yoshinari, Yuichi Ohsita, and Masayuki Murata

***Abstract*—One approach to accommodating time-varying traffic is to construct a virtual network over an optical backbone network by connecting nodes with optical paths. The virtual network is dynamically reconfigured by adding or deleting optical paths so as to suit the current traffic. However, a large number of optical paths have to be added when there are large traffic changes, and this may entail a large overhead. To avoid adding a large number of optical paths, we should construct a virtual network that is adaptive to traffic changes, wherein congestion caused by traffic changes can be mitigated by adding only a small number of optical paths. In this paper, we propose a method to control a virtual network that adapts to traffic changes. We propose a new index, called *flow inclusive relation modularity (FIRM)*, inspired by a model of lifeforms which survive and evolve under significant environmental changes. Through simulation, we clarify that the virtual network with high FIRM can handle traffic changes by adding a small number of optical paths. Moreover, we find that a virtual network embodying FIRM reduces the number of optical paths that have to be added when there are significant traffic changes compared with a virtual network configured only on the basis of the utilization of optical paths.**

***Index Terms*—Traffic Change; Traffic Engineering; Topology; Optical Network; Reconfiguration**

I. Introduction

Various new applications such as cloud storage services have been deployed over the Internet. Such applications increase the amount of traffic and cause unpredictable changes in traffic [2]. A network must accommodate such time-varying traffic efficiently. However, a backbone network suited to one traffic environment easily becomes unsuitable after the traffic changes.

One approach to accommodating such large time-varying traffic is to reconfigure the virtual network over an optical backbone network [3-11]. In this approach, a virtual network is constructed over the WDM optical network, which itself is composed of optical cross connects (OXCs) and optical fibers between OXCs. IP routers are connected to OXC ports. Lightpaths (hereafter called *optical paths*) are established between two IP routers by configuring OXCs along the route between the routers in the optical WDN network. The routers and optical paths between these routers form a virtual network. Traffic between two routers is thus carried over the virtual network, and the virtual network is reconfigured dynamically by adding or deleting optical paths so as to accommodate the current traffic.

Several approaches to reconfiguring virtual networks over WDM optical networks have been proposed [3-11]. In these method, optical paths are added so as to create a virtual network that can accommodate the current traffic without congestion, and unnecessary optical paths are deleted to be used in the future reconfiguration of the virtual network. If the traffic gradually changes, the addition of only a small number of optical paths at each time slot is sufficient to avoid congestions. However, the traffic may change suddenly [12, 13]. For example, the new application or the website which suddenly becomes popular may cause the sudden increase of the related traffic [12]. The changes of the routing table of the BGP also cause the sudden change in traffic pattern within an ISP [13]. In these cases, a large number of optical paths are required to be added to accommodate traffic without congestion. Adding a large number of optical paths may incur a large overhead, because OXCs have to be configured along the routes of each optical path, and routing tables of the routers at the both ends of the optical path have to be updated. As a result, it may take time to mitigate the detected congestion. To mitigate the congestion immediately after the detection even in the case of the sudden traffic changes, the virtual network that can accommodate any traffic change by adding only a small number of optical paths is required.

In this paper, we discuss a method to construct a virtual network that can accommodate any traffic change by adding only a small number of optical paths. We call such virtual networks *virtual networks adaptive to traffic changes*. By constructing a virtual network adaptive to traffic changes, we can avoid having to add a large number of optical paths even when there are significant traffic changes.

The construction of a virtual network adaptive to traffic changes requires an index of the adaptability of

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a network to changes in traffic. There are several indices of network topology. The betweenness centrality of a link [14] indicates the probability that traffic from a source node to a destination node passes through the link when the shortest paths are used. The link criticality [15], or the network criticality [16], indicates the probability of congestion occurring by considering all feasible paths. A link whose link criticality or betweenness centrality is high may handle a large amount of traffic and is an important link. A network whose network criticality is high may also be congested when traffic changes or network failures occur. However, these indices do not indicate the number of optical paths that should be added when congestion occurs.

Therefore, we proposed a new index of adaptability of virtual networks to changes in traffic [1]. In this paper, we first introduce our index. Our index is inspired by a model of lifeforms which survive and evolve under significant environmental changes. An important property of such lifeforms is modularity [17, 18]. Lipson *et al.* [17] studied the functions of lifeforms. They divided the functions of the lifeforms into modules so that closely related functions belong to the same module and they defined modularity as the number of modules. They showed that lifeforms with high modularity survive and evolve.

Inspired by this, we studied the relationship between the functions of the virtual network. A virtual network accommodates flows from the source nodes to the destination nodes. Thus, we studied the relation between the functions of the flow accommodation and the modularity of the functions on the basis of the routes of the flows. We call this sort of modularity *flow inclusive relation modularity (FIRM)*

In addition to the introduction of the FIRM proposed in our previous paper [1], this paper also applies the FIRM to a method to reconfigure a virtual network. When a problem such as congestion occurs, this method adds optical paths in a similar way to the existing methods so as to solve the current problem immediately. On the other hand, it deletes optical paths so as not to make the FIRM too large. As a result, the virtual network maintains high adaptability to traffic changes and requires only a small number of optical paths to be added to it even when there are significant traffic changes. In this paper, by comparing the reconfiguration method using the FIRM with other reconfiguration method, we demonstrate the impact of considering the FIRM.

This paper is organized as follows. In Section II, we explain the virtual network topology constructed over WDM optical networks and give an overview of virtual network reconfiguration. In Section III, we explain the characteristics of lifeforms which survive and evolve in response to significant environmental changes. Then, inspired by the characteristics of these natural lifeforms, we propose FIRM. In Section IV, we develop and evaluate a virtual network control considering FIRM. We conclude and mention future work in Section V.

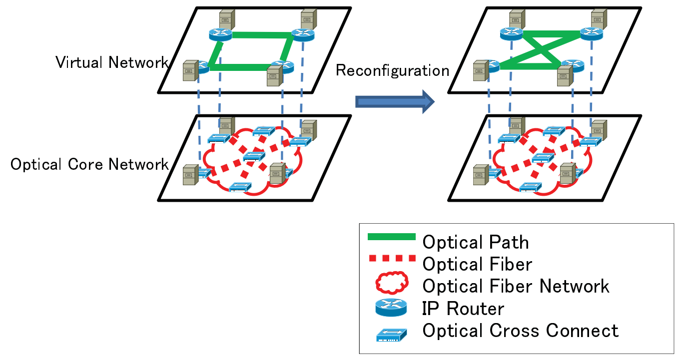


Fig. 1. Reconfiguration of a Virtual Network in an IP over WDM Optical Network

II. Overview of Virtual Network Reconfiguration

A. Virtual Networks over WDM Optical Networks

Wavelength division multiplexing (WDM) is a technology that carries multiple wavelength channels on a single fiber. WDM carries a large amount of traffic at a low cost.

A number of network architectures using WDM have been developed. The IP over WDM network shown in Figure 1 is one such architecture. The optical network is constructed from optical cross connects (OXCs) and optical fibers. IP routers are connected to this network by connecting their ports to one of the ports of the OXCs. Lightpaths (hereafter called *optical paths*) are established by configuring the OXC along the routes between routers. The intermediate OXC binds an input wavelength channel to a specified output wavelength channel. The IP routers at both ends of the optical path are connected in the IP layer. The IP routers and optical paths form a virtual network. Traffic between two routers is carried over the virtual network using IP layer routing.

The virtual network can be reconfigured by adding or deleting optical paths in order to efficiently utilize the bandwidth provided by the WDM network. Thus, this network architecture can handle significant traffic changes by reconfiguring the virtual network so as to suit the current traffic.

B. Reconfiguration of the Virtual Network based on the Current Traffic

Many methods to control the virtual network have been proposed. One approach is to construct an optimal virtual network based on the current traffic. Mukherjee *et al.* [3] formulated virtual network design problems as optimization problems and proposed heuristic algorithms based on the simulated annealing to find nearly optimal solutions. After the optimal virtual network is obtained, the optical paths are added and/or deleted so that the virtual network becomes the calculated optimum one. However, this method requires a large number of optical paths to be added or deleted, which causes a large overhead.

Another approach is to adapt the current virtual network so as to suit the current traffic [4-11]. The virtual network can be adapted by (1) adding optical paths and (2) deleting optical paths.

Optical paths are added when the virtual network cannot accommodate the current traffic. Such a situation is detected by monitoring the performance of the network. For example, the method in Gençata *et al.* [7] monitors the utilization of the optical paths. Congestion is detected when the utilization of an optical path becomes larger than a predefined threshold T_H, and optical paths are added so as to make the maximum utilization of optical paths less than T_H. Problems such as congestion should be solved as quickly as possible. Thus, the adaption of the virtual network should ideally be completed as soon as a problem occurs. Gençata *et al.* proposed a heuristic method to add optical paths to mitigate the congestion. This method adds an optical path to the node pair with the largest amount of traffic among the node pairs whose traffic passes the congested links.

Virtual network control methods delete as well as add optical paths. By deleting optical paths, resources such as ports of IP routers and wavelengths, can be reclaimed for future optical paths. Unlike the addition, it is permissible for the process of deleting an optical path to take a long time, because it can be performed when users do not face any immediate problems. This means that optical paths can be deleted periodically over a long interval measured in hours. The optical paths to be deleted are selected by referring to their current utilization. Gençata *et al.* [7] regard the optical paths whose utilizations are less than a predefined threshold T_L as the candidate optical paths to be deleted. They check whether the deletion of each of the candidate optical paths does not cause congestion. Then, the optical paths are deleted if the deletion does not cause congestion.

The above methods focus on the demands of the current traffic; optical paths are added to accommodate the current traffic, and unnecessary optical paths are deleted. However, if a significant traffic change occurs, the suitable virtual network to accommodate those changes may be significantly different from the current one. In this case, even if we use a method to adapt the virtual network, a large number of optical paths may have to be added if it considers only the current traffic. Adding a large number of optical paths may incur a large overhead and affect a large number of users. To combat this problem, we devised a method that adapts a virtual network to traffic changes by adding only a small number of optical paths.

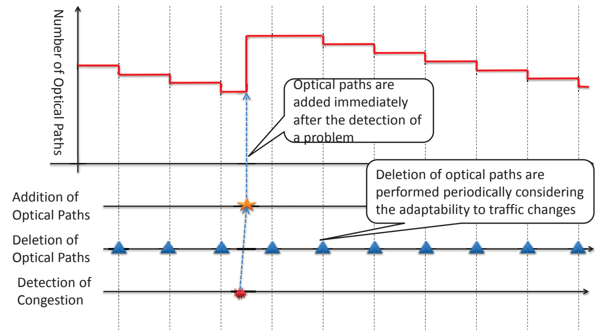


Fig. 2. Overview of Virtual Network Reconfiguration Considering Adaptability to Traffic Changes

C. Reconfiguration of the Virtual Network Considering the Adaptability to Traffic Changes

Figure 2 shows the overview of our virtual network reconfiguration. Similar to the existing virtual network reconfiguration methods, our method has two phases: addition of optical paths and deletion of optical paths.

Addition of optical paths aims to solve problems such as congestion. This objective is shared by the existing methods. Thus, we can use an existing method to add optical paths as required. As discussed in the previous subsection, optical paths should be added immediately so as to mitigate the current problem. Thus, as shown in Fig. 2, optical paths are added immediately after a problem is detected.

Optical paths are deleted in order to release resources. Although deletion frees up the resources that can be used in a future reconfiguration, it may inadvertently lead to an increase in the number of optical paths to be added when the traffic changes in the future, especially if the optical paths necessary to accommodate the future traffic are the ones deleted. Thus, in our method, we select the optical paths to be deleted in a way that will maintain the network's adaptability to changes in traffic. In so doing, the virtual network can handle a large traffic changes by adding only a small number of optical paths.

The process of deleting optical paths considering adaptability may take time. However, as discussed in the previous subsection, it can be performed periodically over intervals lasting hours.

Our method needs an index to measure the adaptability of the virtual network to the traffic changes; this is discussed in Section III.

III. Index of Adaptability to Environmental Changes

Here, we introduce an index that describes how well an adaptive virtual network can handle significant traffic changes by adding only a small number of optical paths. Our index is inspired by natural lifeforms that survive and evolve in response to significant environmental changes. Below, we explain the characteristics of such lifeforms. Then we explain our index and investigate its properties.

A. Functional Modularity and Environmental Changes in Lifeforms

Lipson *et al.* [17] clarified one of the characteristics of lifeforms that survive and evolve under significant environmental changes through simulations. They modeled individuals as a suite of functions, which synthesize products from environmental resources (see Figure 3(a)). In this model, an individual dies when there are not enough products for it to survive, and it duplicates itself and evolves if there are enough products for this to happen.

Among the characteristics of lifeforms, they focused on the relationship between functions. Each function consumes resources and generates products. A relationship between functions exists when those functions consume the same resources or when those functions carry out or block production of the same product. By using this relationship, they defined an index called *modularity*, which is defined as the number of groups had by dividing the functions into groups that include the related functions. According to the results of Lipson *et al.*, lifeforms with higher modularity survive and evolve. In addition, lifeforms evolve so as to have higher modularity.

When the modularity is high, functions belonging to different modules only have a small impact on each other. Thus, environmental changes affecting the functions in one module do not affect other functions in the other modules. As a result, individuals with high modularity are not significantly affected by environmental changes and survive.

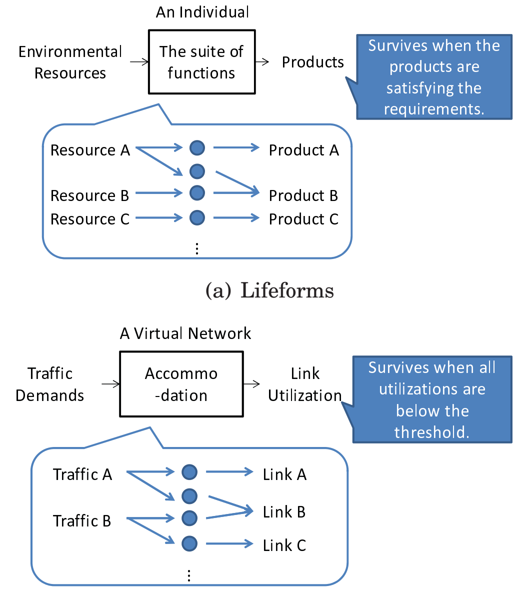
B. Flow Inclusive Relation Modularity and Traffic Changes in Virtual Networks

Inspired by the above study, we decided to model a virtual network incorporating an index that can identify virtual networks that can handle significant traffic changes by adding a small number of optical paths.

The function of the virtual network is to accommodate traffic. We model this function as shown in Figure 3(b). Here, a virtual network accommodates traffic by assigning optical paths to meet the demand. As long as the utilizations of all optical paths are less than a threshold, we regard the virtual network as being operated properly.

The model shown in Fig. 3(b) is similar to the one for lifeforms in Fig. 3(a). The traffic demands of the model in Fig. 3(b) correspond to the resources of the model in Fig. 3(a).

Therefore, by applying the results of the lifeform simulations discussed in the previous section, we can make a virtual network whose functions have high



(a) Lifeforms

(b) Virtual Network

Fig. 3. Model of Functions

modularity that will be adaptive to significant traffic changes. Thus, in this paper, we define the modularity of the functions of the virtual network and investigate the relationship between modularity and the number of optical paths to be added to accommodate significant traffic changes.

To define a modularity of a virtual network, we need to define the relationship among the functions in the virtual network. Here, we can model the virtual network as a suite of functions that accommodate flows passing between the source and destination nodes. We define the relationship between functions, but there are several approaches to doing so. For example, one can regard the functions related to the flows passing through the same optical path as related functions. Here, we will focus on close relationships between functions. We define such a relationship as follows: the functions for flow A and for flow B are regarded to be related if all links passed by flow A are passed by flow B. Hereafter, we call this relationship a *flow inclusive relation* (FIR).

As shown in Figure 4, an FIR is described as a graph in which a vertex is defined for each flow. The vertices are connected with edges if their corresponding functions have an FIR. Hereafter, we call this sort of graph a *flow inclusive relation graph* and call its vertices *flow nodes*.

In applying the results of Lipson *et al.* [17] to a virtual network, we can say that a virtual network with high modularity is one that has high adaptability to changes in traffic. In this paper, we shall define modularity as the modularity of the flow inclusive graph calculated by the method proposed by Newman [19]. Hereafter, we call it *flow inclusive relation modularity (FIRM)*.

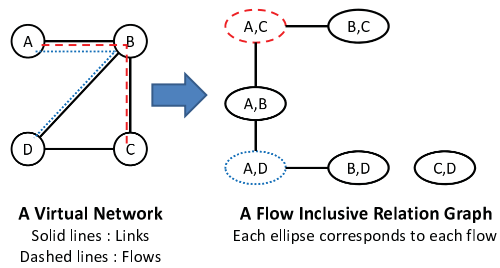


Fig. 4. Example of a Flow Inclusive Relation

The modularity of a graph is defined as

$$Q = \sum_{g \in G} \left[\frac{1}{2m} \sum_{i,j \in N_g} \left(A_{ij} - \frac{k_i k_j}{2m} \right) \right], \tag{1}$$

where A_{ij} is the number of edges between node i and node j, $k_i$is the degree of node i, $m = \frac{1}{2} \sum_i k_i$ is the total number of edges, G is the set of modules, and N_g is a set of nodes which satisfy $g \in G$.

In Eq. 1, $\frac{k_i k_j}{2m}$ indicates the expected value of the total number of edges in the group in a random network having the same number of nodes and the same number of edges. $\sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m} \right)$ indicates the difference between the total number of edges in the group and the expected value of the total number of edges in the corresponding group in a random network. The modularity Q is the value of $\sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m} \right)$ normalized by multiplying it with $\frac{1}{2m}$ so that the maximum value is 1. As Q approaches 1, the inner-module edges become denser and the inter-module edges become sparser.

Newman [19] proposed a method to divide a given network into modules so as to achieve higher modularity. This method recursively divides a network into two modules so as to maximize the modularity until the division no longer increases the modularity.

We obtain the FIRM value of a virtual network by applying Newman's method. The obtained value indicates whether the functions of the network are divided into groups so that each group includes the functions closely related to each other.

In the network with a high FIRM value, changes in the traffic of one flow do not have a large impact on the flows belonging to different modules in the flow inclusive relation graph. Thus, the addition of the optical paths and route changes related to the flows only within a module mitigate the congestion caused by the traffic changes. In addition, because the flows within a module share many optical paths, the changes to the routes of a small number of flows within the module can mitigate congestion affecting all flows within the module. In this way, a network with high FIRM can mitigate the congestion of all optical paths by adding only a small number of optical paths.

TABLE I
CHANGE IN FIRM AFTER ADDING AN OPTICAL PATH

Increase in FIRM	# of patterns
More than 0.04	5
More than 0.03 and less than or equal to 0.04	42
More than 0.02 and less than or equal to 0.03	113
More than 0.01 and less than or equal to 0.02	180
More than 0.00 and less than or equal to 0.01	121
0.00	4
Decrease	54

C. Properties of Flow Inclusive Relation Modularity

1) Relationship between FIRM and the Number of Links in a Network: First, we investigated the relationship between FIRM and the number of optical paths. Here, we compared FIRM values before and after adding an optical path. We used a 5×5 grid topology as an initial virtual network. After that, we added an optical path to a node pair where a direct optical path did not exist.

The number of node pairs between which a direct optical path does not exist is 520 in the 5×5 grid topology. Here, we determined whether the addition of an optical path increased FIRM or not for all patterns of adding an optical path.

Table I shows the results. As can be seen, adding an optical path increases FIRM in most cases. That is, the virtual network with more optical paths tends to have a larger FIRM. A control that maintains high FIRM avoids a situation where there are too few optical paths in the network. A virtual network with a small number of optical paths seems less adaptive to traffic changes, because it seems to require a large number of links to be added to it when the traffic changes.

This table also indicates that the increase in FIRM as a result of adding a link depends on which optical paths are added. There are even cases when the addition of an optical path does not increase FIRM. This means that we can avoid having a small FIRM value by carefully selecting the optical paths to be deleted.

2) Relationship between Number of Nodes in a Network and FIRM: We investigated the relationship between FIRM and the number of nodes in the virtual network by calculating the FIRMs of 2D grid topologies with various numbers of nodes. For this calculation, we used the shortest path for the routes between nodes.

Table II shows the FIRMs of 2D grid topologies with various numbers of nodes. Here, the FIRM value depends on the size of the network. It becomes larger the number of nodes increases. However, a network with more nodes cannot be regarded as one with high adaptability because additional paths may be required to accommodate the time-varying traffic of more node pairs. That is, FIRM cannot be used to compare the adaptability of virtual networks with different numbers of nodes.

3) FIRM of the Typical Network Topologies: Table III shows the FIRMs of the network topologies,

TABLE II
FIRM VS. NUMBER OF NODES IN A GRID TOPOLOGY

Grid size	# of nodes	FIRM
3×3	9	0.4319
3×5	15	0.4662
3×7	21	0.5068

TABLE III
FIRM OF THE TYPICAL TOPOLOGIES

Topology Name	# of nodes	FIRM
NSFnet	14	0.5826
EON(European Optical Network)	19	0.6042

which were used in the evaluation of many previous researches (e.g. [8, 11]); NSFnet and European Optical Network (EON). Comparing Table III with Table II, these typical network topologies have larger FIRMs than the grid topologies with a similar number of nodes. This is caused by the difference of the number of hops between nodes; the maximum numbers of hops of the 3×5 and 3×7 grid networks are 6 and 8 respectively, while the maximum numbers of hops of the NSFnet and EON are 4 and 5 respectively. The flows with a large number of hops share the links with a large number of other flows. Thus, a large number of flows are related to the flow, and the related flow inclusive relation graph cannot be divided into small modules. As a result, the FIRM in the grid topology becomes small.

4) Relation between FIRM and the number of added paths in response to traffic changes: We investigated the relation between FIRM and the number of added paths by using the following procedure.

1) Generate initial virtual networks and calculate their FIRM values
2) Generate traffic and reconfigure the virtual networks so as to accommodate it. Then, count the number of optical paths added during the reconfiguration.

We assumed that there were a sufficient number of ports in the IP routers and sufficient bandwidth, because insufficient resources would limit the number of optical paths that can be added. That is, we would not be able to conduct an investigation related to the number of added optical paths if we did not have sufficient resources to add optical paths.

a) Environments:

Initial Virtual Networks : We generated various initial virtual networks that have various FIRM values. We used the method of Hidaka [20] to generate the topologies. This method inputs the number of groups n and a probability parameter p and generates a topology as follows.

1) Generate n groups and locate one node in each group. The nodes are connected so as to form a ring.
2) Add the nodes. When adding a node, select the group of the node randomly. Connect the added node to one node randomly selected from the nodes in the group. Then add an edge between the additional node and the node which belongs to the other group with probability p or add an edge between the additional node and a node in the same group with probability $(1 - p)$.

This method generates various network structures depending on p. Setting p to a small value makes the nodes within a group closely connected and the connections between groups sparse. On the other hand, setting p to a large value generates a network that has no groups with closely connected nodes.

We generated 255 initial virtual networks by varying p from 0.00 to 1.00 in steps of 0.02. We set the number of nodes to 49 and the number of groups to 5.

Traffic Matrices : Antoniou et al. [21] monitored traffic in ISPs and found that traffic between source and destination router pairs follows a log normal distribution. Thus, we generated traffic matrices so as to follow a lognormal distribution; the parameters were set to the same values as the results of Antoniou et al. [21]. After that, we scaled the generated traffic matrices so that the average traffic between node pairs would be 0.05 times the bandwidth of each optical path.

We generated ten patterns of traffic matrices for each initial virtual network.

Method to Reconfigure Virtual Networks : Similar to the method proposed by Gençata *et al.* [7], we added optical paths so as to make the maximum utilization of optical paths lower than the threshold T_H. To compare the numbers of added optical paths, we used a method that accommodates traffic with a small number of optical paths. To make the number of added optical paths small, we added optical paths in a way that minimized their maximum utilization. Optical paths continued to be added until the utilizations of all paths became lower than T_H.

The virtual network was reconfigured as follows.

- Step 1 Calculate all utilizations of optical paths. Denote the maximum utilization of the optical paths as L.
- Step 2 If $L \leq T_H$, the reconfiguration is over. Otherwise go to 3.
- Step 3 For each node pair, calculate the maximum utilization of optical paths when the optical path between the pair is added and routes are changed.
- Step 4 Add the optical path between the node pair that minimizes the maximum utilization. Go back to Step 1.

In the above steps, we calculated the routes over the virtual network by using the constrained shortest path first (CSPF) algorithm so as to avoid the utilization of optical paths exceeding T_H. To avoid a large overhead when adding an optical path, we changed only the routes of the flows passing through links whose utilization exceeded T_H. We set T_H to 0.5.

b) Results: Figure 5(a) shows the relation between FIRM and the number of added paths. The horizontal axis indicates the FIRM value of each virtual network, and the vertical axis indicates the number of paths added to each virtual network. Each circle indicates the average number of added paths, and each error bar indicates the 68.27% confidence interval of the number of the added paths.

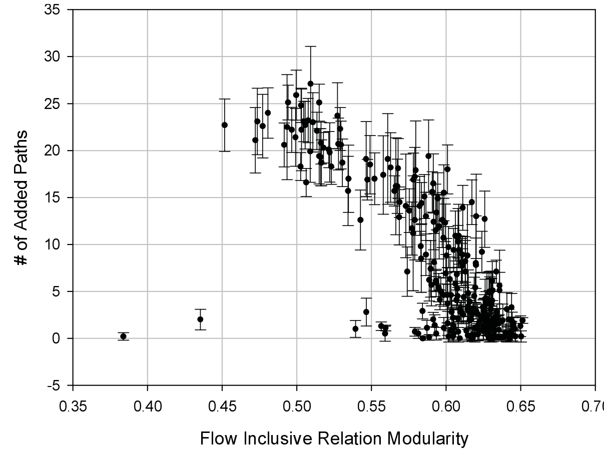
From this figure, we can see that there is a negative correlation between FIRM and the number of added paths except in the case of two virtual networks which do not contain optical paths with utilizations larger than T_H. This is because the functions to accommodate flows can be divided into multiple modules including flows which are closely related to each other in a network with high FIRM. As discussed above, a change in the traffic of a flow does not affect the flows belonging to other modules. In addition, congestion caused by increasing the traffic of multiple flows within the same module can be mitigated by changing a small number of optical paths, because the flows within the same module share many optical paths. On the other hand, if the FIRM value is low, a large number of optical paths have to be added because the flows are not closely related. In such case, an optical path has to be added to each flow causing the congestion.

We also compared FIRM with betweenness centrality. The betweenness centrality of an optical path is the probability that congestion occurs on it. We investigated the maximum betweenness centrality among all links. Figure 5(b) shows the relation between the maximum betweenness centrality and the number of optical paths to be added. The horizontal axis is the maximum betweenness centrality of each virtual network, and the vertical axis is the number of paths added to each virtual network.

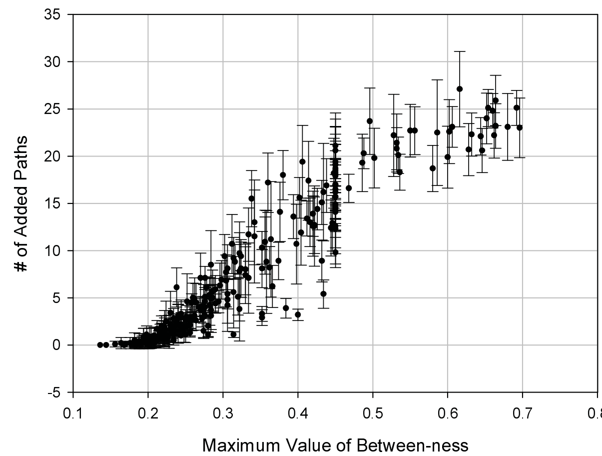
Figure 5(b) shows that there is a positive relation between maximum betweenness centrality and the number of optical paths to be added. This is because a virtual network with a smaller maximum betweenness centrality has less chance of becoming congested. Therefore, in a virtual network with a small maximum betweenness centrality, few links are congested, and the number of optical paths to be added is small.

However, the above discussion does not indicate that a virtual network with a smaller maximum betweenness centrality can adapt to any traffic change simply by adding only a small number of optical paths. If the traffic changes significantly, the number of the congested links may become large. Even in this case, though, the virtual network should be able to accommodate traffic by adding only a small number of optical paths.

Therefore, we focused on virtual networks having multiple congested links. In this comparison, we used virtual networks whose maximum betweenness centralities were from 0.4 to 0.5. We excluded from the comparison virtual networks with maximum betweenness centralities larger than 0.5, because a virtual network with a large betweenness centrality too easily becomes congested.



(a) Flow Inclusive Relation Modularity

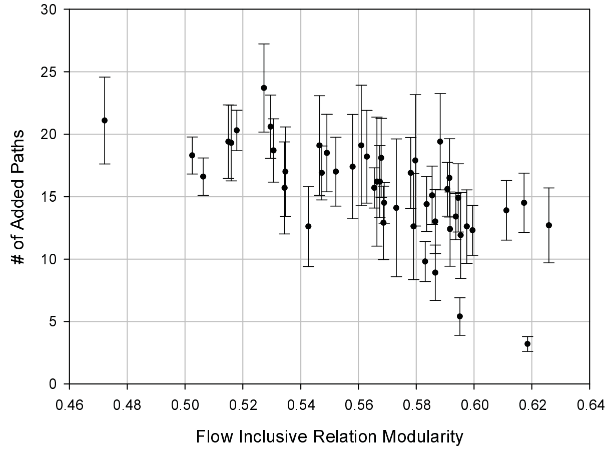


(b) Maximum Betweenness

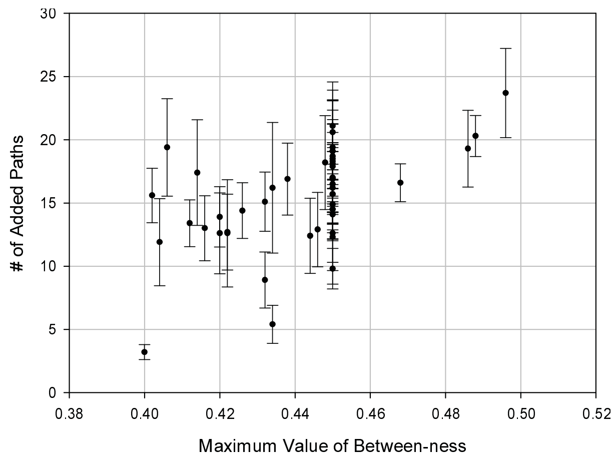
Fig. 5. Relation between Index and the Number of Added Optical Paths (All Virtual Networks)

Figure 6 shows the relation between FIRM or maximum betweenness centrality and the number of optical paths to be added for virtual networks whose maximum betweenness centralities range from 0.4 to 0.5. There is a clear negative correlation in the case of FIRM. On the other hand, several virtual networks have similar maximum betweenness centralities, but have widely varied numbers of added optical paths. This is because maximum betweenness centrality only identifies which virtual networks easily become congested and cannot identify virtual networks that can handle changes in traffic by adding only a small number of optical paths.

5) Accuracy of FIRM as an Index of Adaptability : We investigated the accuracy of FIRM as an index of a virtual network that requires only a small number of additional optical paths to handle traffic changes.



(a) Flow Inclusive Relation Modularity



(b) Maximum Betweenness

Fig. 6. Relation between Index and the Number of Added Optical Paths (Virtual Networks with Maximum Betweenness Values from 0.4 to 0.5)

To evaluate the accuracy of the index, we evaluated the accuracy of a simple identification method using FIRM. In this identification method, the virtual network with a FIRM value higher than a threshold T_F is identified as one that requires only a small number of additional optical paths.

The accuracy of the identification was evaluated with two metrics, the false negative rate (FNR) and the false positive rate (FPR). FNR is defined by

$$FNR = \frac{m_{fn}}{m_p}, \tag{2}$$

where m_p is the number of virtual networks whose average numbers of additional paths are less than a certain threshold R, and m_{fn} is the number of networks that are identified as virtual networks that require more than R additional optical paths but actually require less than R additional optical paths. Similarly, the false positive rate (FPR) is defined by

$$FPR = \frac{m_{fp}}{m_n}, \tag{3}$$

where m_n is the number of virtual networks whose

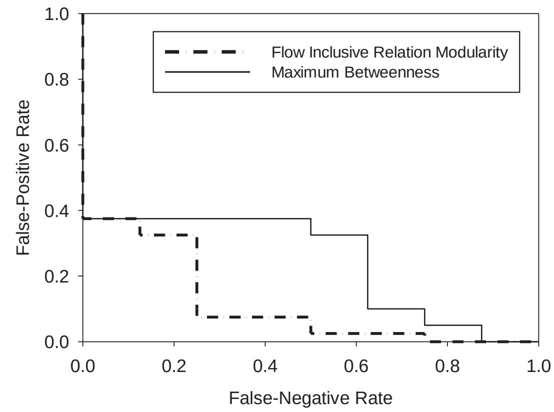


Fig. 7. Relationship between FNR and FPR

average numbers of additional paths are more than a certain threshold R_{th}, and m_{fp} is the number of virtual networks that are identified as networks that require less than R additional optical paths but actually require more than R additional optical paths.

FNR and FPR depend on R and T_F. Setting T_F to a large value or R to a small value, FNR becomes large while FPR becomes small. On the other hand, setting T_F to a large value or R to a small value, FNR becomes small while FPR becomes large.

Here, we set R to 10. We evaluated FNR and FPR by changing T_F. If a T_F that makes both FNR and FPR small exists, FIRM is regarded as an accurate index of virtual networks that require a large number of optical paths to be added when their traffic changes.

Figure 7 shows the relationship between FNR and FPR. In this figure, FNR and FPR are calculated by using the results of the virtual networks whose maximum betweenness centralities are from 0.4 to 0.5 (these are described in Subsection III-C4). The horizontal axis indicates FNR, and the vertical axis indicates FPR. This figure also plots the relation betweeen FNR and FPR when maximum betweenness centrality is used as an index to identify the virtual network requiring a large number of optical paths to be added to them.

From this figure, we can see that the method using FIRM simultaneously achieves a lower FNR and lower FPR compared with the method using maximum betweenness centrality. This means that FIRM identifies the virtual networks which can accommodate significant traffic changes with a small number of additional paths more accurately than maximum betweenness centrality. Therefore, to construct an adaptable virtual network that can handle significant traffic changes by adding only a small number of optical paths, we should construct the virtual network whose FIRM is high.

IV. Virtual Network Reconfiguration Considering Flow Inclusive Relation Modularity

A. Method to Reconfigure the Virtual Network Considering the FIRM

In this section, we describe a virtual network control considering FIRM. The control enables a virtual network to adapt to changes in traffic by maintaining a high FIRM value.

The virtual network control can add and delete optical paths. As discussed in Section II-C, optical paths are added immediately after a problem is detected, and they are periodically deleted with a long interval between deletions. The rest of this subsection explains the process of addition and deletion of the optical paths in our method.

1) Addition of Optical Paths : The aim of adding optical paths is to solve a detected problem such as congestion. Because the detected problem should be solved immediately, the method adds a small number of optical paths. Since the aim of our method is the same as the existing virtual network reconfiguration methods, we can use any of the existing methods to add the optical paths. In the evaluation described in Section IV-B, we used the method explained in Section III-C4a.

2) Deletion of Optical Paths : Optical paths are deleted in order to free up resources for future reconfigurations. However, we should carefully select the optical paths to be deleted in a way that does not degrade adaptability, as discussed in Section II-C.

In our method, we periodically check whether the optical paths can be deleted without degrading the adaptability or causing congestion. To do so, we calculate the FIRM of the virtual network where one of the optical paths is deleted. If the deletion reduces the FIRM significantly, the virtual network after the deletion is regarded as having insufficient adaptability.

Therefore, the optical paths can be deleted when both of the following conditions are satisfied; (1) The virtual network after the deletion of the optical path satisfies the requirements (e.g. the requirements of the link utilization); (2) FIRM does not becomes lower than a threshold T_f even when the optical path is deleted.

We delete only one optical path at each step of the virtual network control in order to make the impact of the deletion small. The virtual network control selects the optical path to be deleted by the following steps in which the current traffic matrix is known.

- Step I Calculate the candidate virtual networks and routes over the virtual network in which one of the optical paths has been deleted. Then, A virtual network that does not satisfy the requirements (e.g. the requirements of the link utilization) is eliminated from the candidate virtual networks.
- Step II Calculate the FIRM of each candidate virtual network.
- Step III Select the virtual network whose FIRM is the largest among the candidates.
- Step VI If the FIRM of the selected virtual network is larger than T_f, delete the optical path that does not included in the selected virtual network. Otherwise, no optical paths are deleted.

This method enables us to delete optical paths, while keeping a high FIRM value.

In the Step I of the above steps, we can use any method of selecting the candidate optical paths to be deleted; a process to delete optical paths in the existing virtual network reconfiguration method can be used to calculate the candidate virtual networks. One of the examples is to calculate the candidate virtual networks based on the link utilizations. In this approach, we obtain the candidate virtual networks where one of the optical paths whose utilizations are smaller than a threshold T_l is deleted. Then, a virtual network whose maximum link utilization becomes larger than a threshold T_h after the deletion of the optical path is eliminated from the candidates. By limiting the candidates, we can select the optical path to be deleted fast even in a large network.

In the evaluation described in Section IV-B, we use the above method based on the link utilization. However, to focus on the impact of considering the FIRM, we regard all optical paths as the candidate optical paths to be deleted by setting T_l to a sufficiently large value. In the method used in our evaluation, we calculated the routes over the virtual network by using the constrained shortest path first (CSPF) algorithm so as to avoid the utilization of optical paths exceeding T_h.

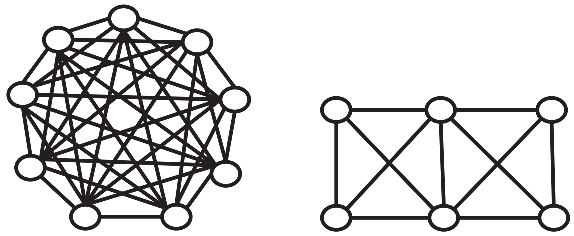
B. Evaluation

We evaluated the virtual network reconfiguration performance while focusing on the impact of FIRM. We compared virtual networks in which the same numbers of optical paths were deleted by our method and by the methods that do not use FIRM.

The evaluation was conducted as follows.

- Step i Generate an initial virtual network and initial traffic matrix.
- Step ii Delete optical paths by using our method or the other methods.
- Step iii Generate the traffic changes.
- Step iv Add optical paths to accommodate traffic after the change and count the number of added optical paths.

1) Compared Virtual Network Reconfiguration: In our evaluation, we apply the FIRM to the reconfiguration based on the link utilization as discussed above. In this method, we obtain the candidate virtual networks in which one of the optical paths is deleted without the link utilization larger than a threshold T_h. Then,



(a) Fully connected network (b) Grid base network

Fig. 8. Initial Virtual Network Used in Our Evaluation

among the candidate virtual networks, we select the virtual networks with the largest FIRM value. By this method, we keep the FIRM value as large as possible.

In our evaluation, we compare our method with the following two kinds of methods.

Link utilization based method: In this method, the optical paths to be deleted are selected based on the link utilization similar to the method proposed by Gençata *et al.* [7]. This method selects the virtual network with the smallest maximum link utilization among the same candidate virtual networks as our method. This method keeps the maximum link utilization as small as possible. By comparing our method with this method, we demonstrate the impact of considering the adaptability.

Betweenness based method: This method considers the betweenness centrality instead of the FIRM. This method selects the virtual network with the smallest maximum betweenness centrality among the same candidate virtual networks as our method. This method keeps the maximum betweenness centrality as small as possible. By comparing our method with this method, we demonstrate the impact of considering the FIRM instead of the betweenness centrality.

2) Environments Used in Our Evaluation:

a) Initial Virtual Network: In our evaluation, we use the initial networks that have a large number of optical paths that can be deleted, to investigate the impact of the process to delete the optical paths.

We use two kinds of the initial networks as shown in Figure 8. The first one is a fully connected network with nine nodes. The other one is the grid base network with six nodes where four bidirectional links (i.e., eight unidirectional optical paths) are added to the $2{\times}3$ grid network as shown in Figure 8(b).

b) Traffic: The initial traffic matrix was generated as the random values following a lognormal distribution similar to the evaluation described in Section III-C4a.

In our evaluation, we focus on the case that the large and sudden traffic change occurs. To generate such large traffic changes, we add the random value to the randomly selected node pairs. The node pairs whose traffic is increased are selected by using the uniform random values; (1) generate a uniform random value for each node pair, and (2) select the node pairs with the largest random values. Then, the increased amount of traffic is also generated as a uniform random value.

For the nine-node fully connected network, we selected 27 node pairs, and set the range of the added random value to 0-0.7 of the bandwidth of the optical paths. For the six-node grid base network, we selected 4 node pairs, and set the range of the added random value to the same value as the nine-node fully connected network.

We generate 5 initial traffic matrices, and generate 30 traffic changes for each initial traffic matrices by changing the random seed. The same traffic matrices are used by all of the compared methods.

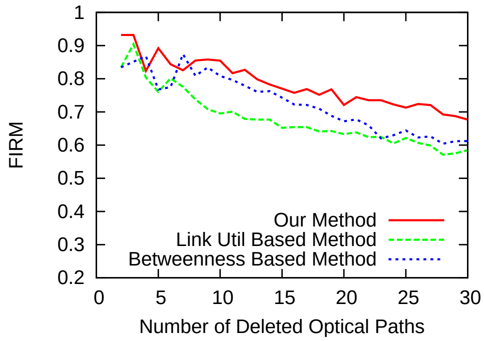
c) Method to add optical paths: We used the same method as we did in the evaluation described in Section III-C4a.

3) Results:

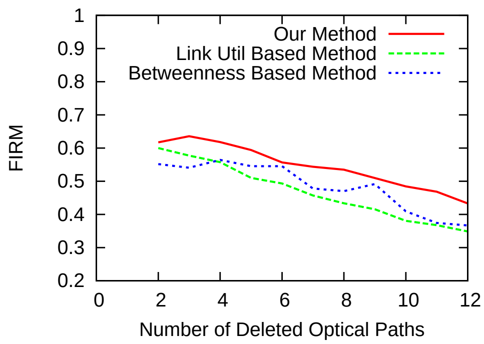
a) Comparison of FIRM values: Before discussing the impact of considering the FIRM, we check the FIRM values of the virtual networks constructed by each method. Figure 9 shows the FIRM values after optical paths were deleted by our method, the link utilization based method, or the betweenness based method. The horizontal axis is the number of deleted optical paths, and the vertical axis is the average FIRM value of all patterns in the evaluation. From this figure, both of the betweenness based method and the utilization based method do not keep the large FIRM values compared with our method. Thus, we need to consider the FIRM to keep the large FIRM. In the rest of this section, we discuss the impact of considering the FIRM.

b) Average number of added optical paths after traffic changes: In this paragraph, we compare the average number of optical paths required to be added when sudden traffic changes occur. Figure 10 compares the numbers of optical paths to be added. The horizontal axis is the number of optical paths deleted before the traffic change, and the vertical axis is the average of the number of optical paths added after the traffic change in all patterns in the evaluation.

From this figure, in the case that the initial virtual network is the fully connected network, the average number of optical paths required to be added to the virtual network constructed by the utilization based method is significantly larger than the other methods. This is because the utilization based method constructs the virtual network specially focused on the initial traffic. Though the virtual network is suitable to the initial traffic, the optical paths necessary to accommodate the traffic changes are deleted. On the other hand, our method and betweenness based method do not delete such optical paths required to accommodate traffic changes. As a result, most of the traffic changes can be mitigated by adding only one or two optical paths.

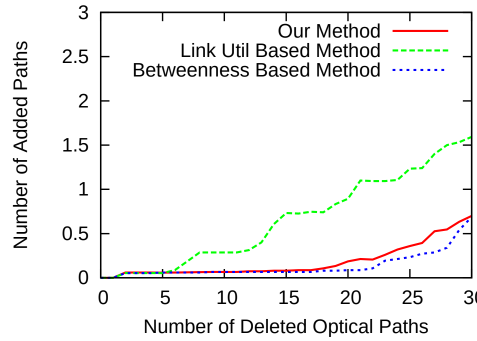


(a) Fully connected network

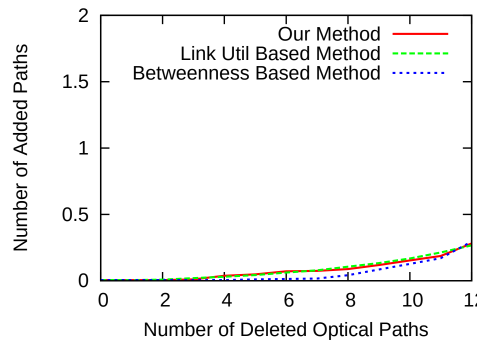


(b) Grid base network

Fig. 9. Comparison of Virtual Networks: FIRM values



(a) Fully connected network



(b) Grid base network

Fig. 10. Comparison of Virtual Networks: Average Number of Additional Paths

Unlike the case that the fully connected network is used as the initial network topology, when the initial network is the grid base network, the average number of optical paths required to be added is almost the same in all methods. This is because the grid base network has only a small number of candidate optical paths to be deleted. As a result, unlike the case of the fully connected network, in many cases, even when we use the utilization based method, the constructed virtual network does not become very different from the virtual network constructed by the other methods.

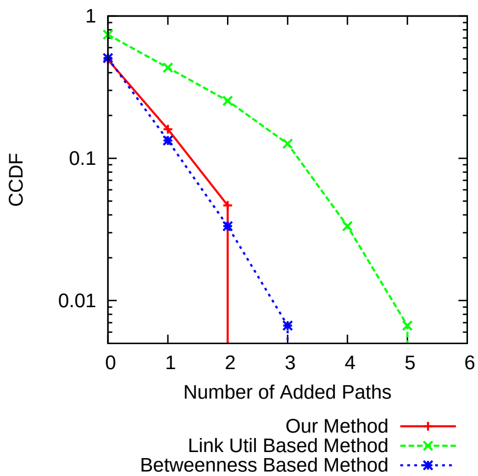
c) Distribution of the added optical paths after traffic changes: The aim of this paper is to avoid a large number of optical paths required to be added even when a large traffic change occurs. Comparing the average number of added optical paths is not sufficient for this aim. Thus, we also compare the distribution of the number of optical paths required to be added when the traffic changes.

Figure 11 shows the distribution of the numbers of optical paths required to be added after 30 optical paths are deleted from the fully connected network or 12 optical paths are deleted from the grid base network. In this figure, the horizontal axis is the number of optical paths required to be added after the traffic changes. The vertical axis is the complementary cumulative distribution function. This figure shows that more optical paths are required to be added when the deletion process is performed by the utilization base method in the fully-connected network, similar to the results shown in Fig. 10.

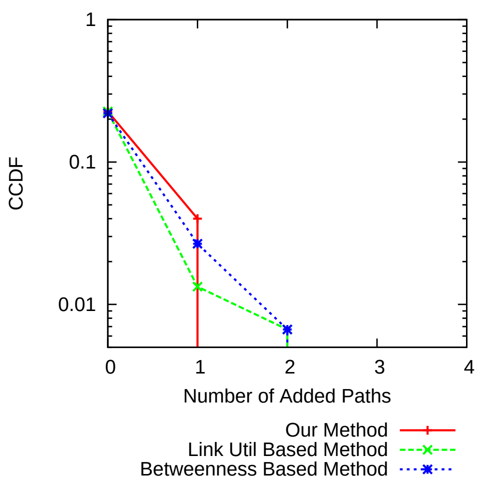
Comparing our method with the betweenness based method, there is a case that the betweenness base method requires addition of more optical paths than our method. 3 optical paths are required to be added in some cases when using the betweenness based method in the fully connected network, while adding only two optical paths is sufficient in all cases when using our method to delete optical paths. Similarly, in the case of the grid base network, 2 optical paths are required to be added in some cases when using the betweenness based method, while adding only one optical path is sufficient in all cases when using our method. This is because the FIRM indicates the number of optical paths required to be added more accurately than the betweenness centrality as discussed in Section III-C5. As a result, the virtual network constructed by considering the FIRM keeps the high adaptability.

Unlike the results shown in Fig. 10, the difference of the distribution of the number of added optical paths can be seen even in the case of the grid base network. In our evaluation of the grid base network, virtual network can accommodate the traffic after the change without adding no optical paths in most cases. This causes the similar average number of added optical paths.

However, as shown in Figure 9, the FIRM values are different even in the case of the grid base network, where the number of candidate virtual networks



(a) Fully connected network (in case that 30 paths are deleted)



(b) Grid base network (in case that 12 paths are deleted)

Fig. 11. Comparison of Virtual Networks: Distribution of Number of Added Paths

after the deletion of optical paths is much smaller than the case of the fully connected network. Then, the maximum number of optical paths required to be added becomes different and is the smallest when using our method. That is, considering the FIRM has an impact not only when there are a large number of candidate virtual networks, but also when there are only a limited number of candidate virtual networks.

V. Conclusion

In this paper, we discussed a method to control a virtual network by taking account of the adaptability to changes in traffic. We proposed a new index called *flow inclusive relation modularity (FIRM)* that was inspired by a model of lifeforms which survive and evolve in response to significant environmental changes.

Through simulations, we clarified that a virtual network with a high FIRM value can handle changes in traffic by adding a small number of optical paths. We also evaluated a virtual network control that uses FIRM and found that it reduces the number of optical paths that have to be added when there are significant traffic changes relative to a virtual network configured using only link utilization as a control metric.

Our future research topics will include an evaluation of our virtual network control using actual traffic data and improvement of the index of adaptability to traffic changes.

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