Master's Thesis

Title

Increasing Adaptability to Traffic Changes by Proactive Virtual Network Control

Supervisor

Professor Masayuki Murata

Author

Masahiro Yoshinari

February 12th, 2013

Department of Information Networking
Graduate School of Information Science and Technology
Osaka University

Master's Thesis

Increasing Adaptability to Traffic Changes by Proactive Virtual Network Control

Masahiro Yoshinari

Abstract

In recent years, various applications such as cloud storage service have been deployed over the Internet. Such application leads the increase of the traffic amount and the unpredictable traffic changes. A network must accommodate such large and time-varying traffic efficiently. One approach to accommodate such traffic is to construct a virtual network over the backbone network and dynamically reconfigure the virtual network. However, some virtual networks require adding a large number of optical paths to handle traffic changes, and take a long time to be reconfigured so as to suit the current traffic after the significant traffic change.

In this thesis, we propose a method to control a virtual network proactively so as to increase the adaptability to traffic changes. In the proactive virtual network control, we add or delete optical paths considering the adaptability of the virtual network to the traffic changes.

To consider the adaptability of the virtual network in the proactive virtual network control, we also propose a new index inspired by the model of lifeforms which survive and evolve under significant environmental changes. Lipson et al. [1] focused on the relation of the function of the lifeforms, and defined the index called modularity which indicates the number of modules when the functions of the lifeforms are divided into modules so that the closely related functions belong to the same module. They clarified that the lifeforms with high modularity survive and evolve.

Inspired by this, we focus on the relation of the function of the virtual network. The function of the virtual network is to accommodate flows between the source and the destination nodes. Thus, we define the relation between the functions of the flow accommodation, and the modularity of the function called *flow inclusive relation modularity (FIRM)*.

Through simulation, we clarify that the virtual network with the high FIRM can handle traffic changes by adding a small number of optical paths. We also evaluate the proactive virtual network control using the FIRM, and clarify that the virtual network reconfigured proactively by using the FIRM reduces the number of optical paths requried to be added in the case of the significant traffic changes by more than 30% compared with the virtual network configured considering only the link utilization.

Keywords

Traffic Change; Traffic Engineering; Topology; Optical Network; Reconfiguration

Contents

List of Figures

List of Tables

1 Introduction

In recent years, various new applications such as cloud storage service have been deployed over the Internet. Such application leads the increase of the traffic amount and the unpredictable traffic changes [2]. A network must accommodate such time-varying traffic efficiently. However, even if a backbone network suitable for the current traffic is constructed, the backbone network becomes no longer suitable to traffic after the traffic change.

One approach to accommodate such large time-varying traffic is to reconfigure the virtual network. Several methods to reconfigure the virtual network have been proposed [3–7]. In these methods a virtual network is constructed over the WDM optical network, which is constructed of the optical cross connects (OXCs) and IP routers. In this optical network, each outbound port of an edge IP router is connected to an OXC port. Lightpaths (hereafter called optical paths) are established between two IP routers by configuring OXCs along the route between the routers. A set of routers and optical paths between the routers forms a virtual network. Traffic between two routers is carried over the virtual network using IP layer routing. In this network, the virtual network is reconfigured dynamically by adding or deleting optical paths so as to suite the current traffic.

In case of significant traffic change, a large number of optical paths may be required to be added to accommodate the traffic after the change. However, adding a large number of optical paths may take a large overhead because we require setting OXCs for each optical path.

One approach to avoid adding a large number of optical paths is to proactively construct a virtual network adaptive to traffic changes. In this approach, even when the significant traffic changes do not occur, the virtual network is reconfigured periodically considering the adaptability to traffic changes. By proactively reconfiguring the virtual network, even if the significant traffic change causes the congestion, adding only a small number of optical paths may mitigate the congestion. In this thesis, we call the periodical reconfiguration considering the adaptability *the proactive virtual network control*. We also call the virtual network reconfiguration to handle traffic changes *the reactive virtual network control*.

To perform the proactive virtual network control, we require an index of the adaptability of the virtual network to the traffic changes. There are several indices of the network topology. The betweenness centrality of a link [8] indicates the probability that traffic from a source node to a destination node passes the link. The link criticality [9, 10] is obtained by dividing the betweenness centrality by the bandwidth of the link. The link whose betweenness centrality or link criticality is high may be passed by a large amount of traffic. Thus, the topology containing links with high betweenness centrality or link criticality is easy to be congested. However, these indices do not indicate the number of optical paths required to be added when congestions occur.

Therefore, we propose a new index of the adaptability of the virtual network to the traffic changes. Our index is inspired by the model of the lifeforms which survive and evolve under significant environmental changes. Lipson et al. [1] focused on the relation of the function of the lifeforms, and defined the index called modularity which indicates the number of modules when the function of the lifeforms are divided into modules so that the closely related functions belong to the same module. They clarified that the lifeforms with high modularity survive and evolve.

Inspired by this, we focus on the relation of the function of the virtual network. The function of the virtual network is to accommodate flows between the source and the destination nodes. Thus, we define the relation between the functions of the flow accommodation, and the modularity of the function based on the routes of the flows. We call the modularity *flow inclusive relation modularity*

In this thesis, we investigate the property of the FIRM, and clarify that the FIRM identifies the virtual network that can handle traffic changes by adding only a small number of optical paths. We also evaluate the proactive virtual network control using the FIRM to clarify that the proactive virtual network control considering the adaptability reduces the number of optical paths required to be added when traffic changes occur.

This thesis is organized as follows. In Section 2, we introduce a control method for virtual networks over WDM optical networks. Then we explain the necessity of an index which indicates an adaptability of a virtual network. In Section 3, we explain the characteristics of the lifeforms, which survive and evolve under significant environmental changes. Then, inspired by the characteristics of the natural lifeforms, we propose the FIRM. In Section 4, we develop and evaluate a proactive virtual network control using the FIRM. We conclude and mention about future work in Section 5.

2 Overview of Virtual Network Reconfiguration

2.1 Virtual Network over WDM Optical Network

Wavelength Division Multiplexing (WDM) is a technology that carries multiple wavelength channels on a single fiber. WDM carries a large amount of traffic with low cost. Thus, network architectures using WDM have been developed.

As shown in Fig. 1, IP over WDM network is one of the architecture using the WDM technology. In this architecture, the network is constructed of IP routers and optical cross connects (OXCs). In this architecture, lightpaths (hereafter called optical paths) are established by configuring the OXC along the routes between routers. At the intermediate OXCs binds an input wavelength channel to a specified output wavelength channel. The IP routers at the 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.

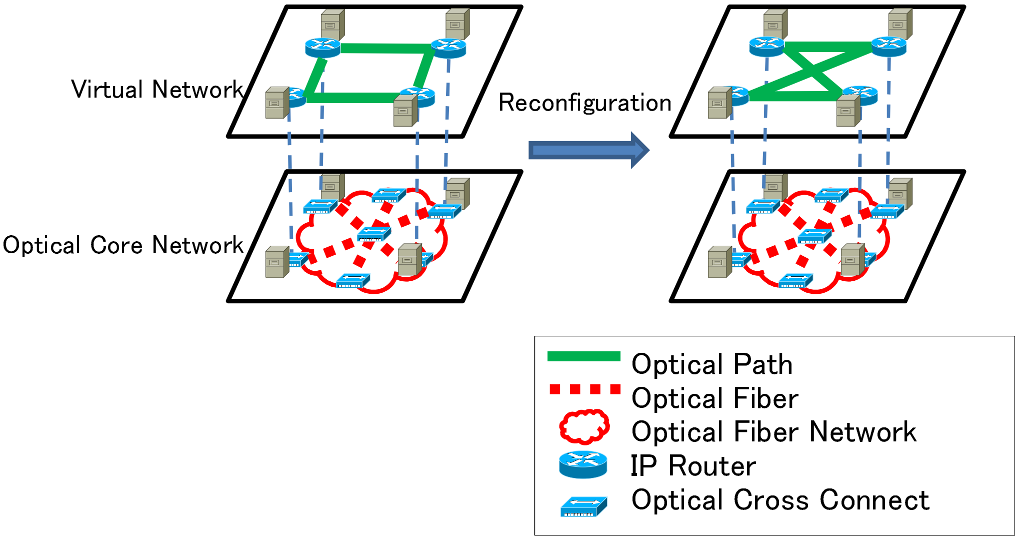
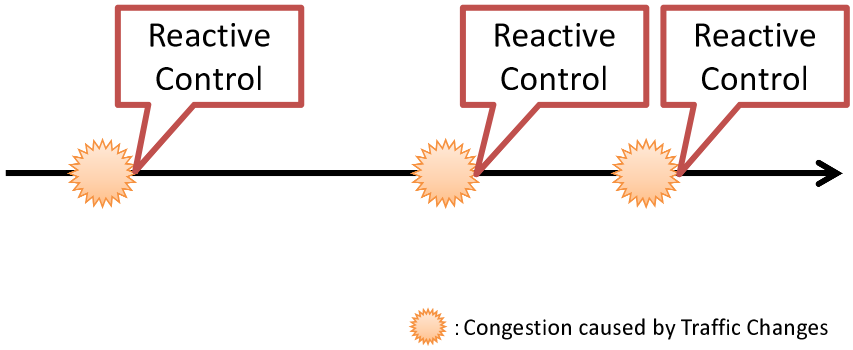


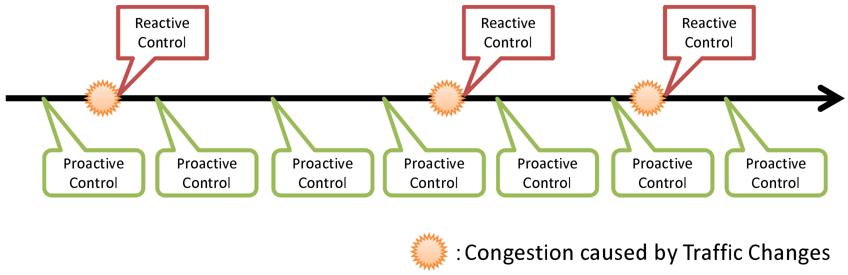
Figure 1: Reconfiguration of a Virtual Network over WDM Optical Network

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

To handle significant traffic change, a large number of optical paths may be required to be added. However, adding a large number of optical paths may take a large overhead, because the amount of control message increases as the number of optical paths to be added increases. Thus, in this thesis, we propose a method to configure the virtual network proactively so as to handle significant traffic changes by adding only a small number of optical paths.



(a) Conventional Control of Virtual Networks



(b) Control of Virtual Networks with Periodical Pretreatment

Figure 2: Control of Virtual Networks

2.2 Reactive Control

Even if the virtual network suitable for the actual traffic is constructed, traffic could significantly differ from the initial traffic as time goes on. As a result, the previously constructed virtual network becomes no longer suitable to the current traffic, and congestion may occur. In this case, the reconfiguration of the virtual network is required.

Several virtual network reconfiguration methods have been proposed [3–7]. These methodsconfigure the virtual network so as to make the maximum link small to mitigate the congestion.

As shown in Fig. 2a, in these methods, the virtual network is reconfigured only when the reconfiguration is required to accommodate the current traffic, and the reconfiguration aims to mitigate the current problems such as congestions. We call this type of reconfiguration *reactive control*.

The problems such as congestions should be solved as quickly as possible. Thus, the reactive control focuses only on the current problem, and reconfigures the virtual network so as to solve the current problem.

2.3 Proactive Control

In the reactive control, if the significant traffic changes occur, a large number of optical paths may be required to be added to handle the traffic change. To avoid adding a large number of optical paths even when the significant traffic changes occur, we proactively reconfigure the virtual network considering the adaptability to the traffic changes. We call this approach *proactive control*.

Figure 2b shows the combination of the proactive control and the reactive control. As shown in this figure, the proactive control is performed periodically considering the adaptability to traffic changes. The proactive control may add a small number of required optical paths or delete a small number of unnecessary optical paths considering the adaptability to traffic changes. As a result, if the significant traffic change occurs and the reactive control is required, the reactive control handles the traffic changes by adding only a small number of optical paths.

To consider the adaptability, we use an index to measure the adaptability to the traffic changes. By using the index, we construct the virtual network whose index is the best among the candidate of the virtual network. In Section 3, we propose and discuss the index to measure the adaptability.

3 Index for Adaptability to Environmental Changes

In this section, we propose an index that identifies the adaptive virtual network that can handle significant traffic changes by adding only a small number of optical paths. Our index is inspired by the natural lifeforms that survive and evolve in the case of significant environmental changes. The rest of this section, we explain the characteristics of the natural lifeforms that survive and evolve under the significant environmental changes. Then, we explain and evaluate our index inspired by the natural lifeforms.

3.1 Functional Modularity and Environmental Changes in Lifeforms

Lipson et al. [1] clarified one of the characteristics of the lifeforms that survive and evolve under significant environmental changes through simulations. They modeled individuals as a suite of functions, which synthesizes products from environmental resources as shown in Fig. 3. In this model, each individual dies if enough products for survival cannot be generated, while it duplicates itself and evolves if enough products are generated. Through the simulation using this model, they investigated the characteristics of lifeforms that can survive and evolve in significant environmental changes.

Among the characteristics of the lifeforms, they focus on the relationship between functions. Each function consumes some resources and generates products. The relationship between functions exists when those functions consumes the same resources or when those functions carries out or blocks the production of the same product. By using the relationship, they define the index called *modularity*, which is defined by the number of groups after dividing the functions into groups that includes the related functions. According to the results of Lipson et al., the lifeforms with higher modularity survive and evolve. In addition, the lifeforms evolves so as to have higher modularity.

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

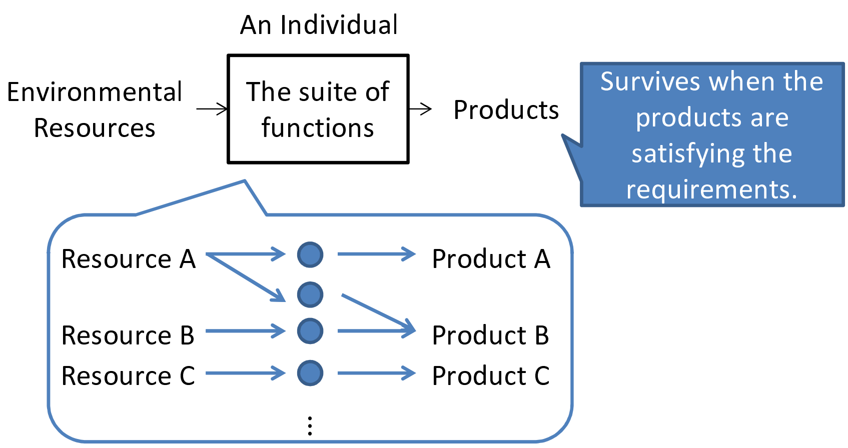


Figure 3: Model of Functions of Lifeforms

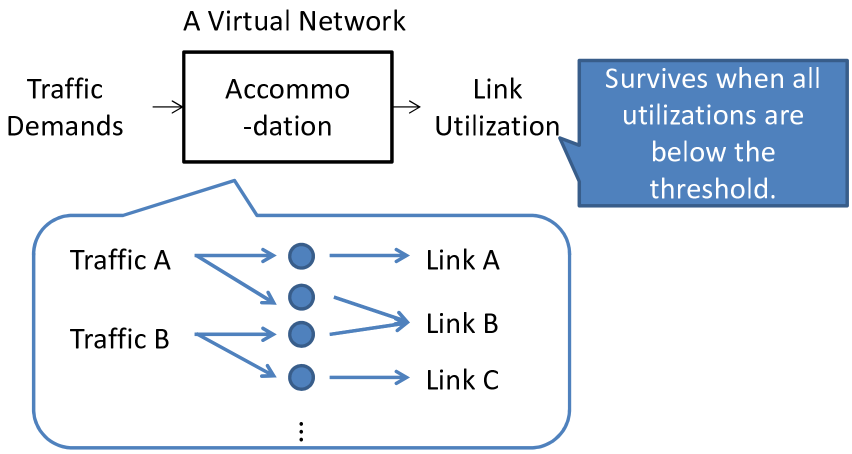


Figure 4: Model of Functions of Virtual Network

3.2 Flow Inclusive Relation Modularity and Traffic Changes in Virtual Networks

Inspired by the lifeforms which survive and evolve in the significant environmental changes, we model the virtual network, and propose an index that identifies the virtual network 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 of the virtual network as shown in Fig. 4. In this model, a virtual network accommodates traffic demands by assigning traffic demands with links. When the utilizations of all links are less than the threshold, we regard the virtual network as being operated properly.

The model shown in Fig. 4 is similar to the model of lifeforms shown in Fig. 3. The traffic demands of the model in Fig. 4 correspond to the resources of the model in Fig. 3.

Therefore, applying the results of the lifeforms, a virtual network whose functions have large modularity may be adaptive to the significant traffic changes. Thus, in this thesis, we define the modularity of the functions of the virtual network, and investigate the relationship between the modularity and the number of optical paths required to be added to accommodate significant traffic change.

To define a modularity of a virtual network, we need to define the relationship among the functions in the virtual network. In this thesis, the function of the virtual network is modeled as the suite of the function that accommodates each flow passing between source and destination nodes. In this subsection, we define the relationship between functions. There are several approaches to define the relationship between functions. For example, one approach is to regard the functions related to the flows passing the same link as the related functions. In this thesis, we focus on the close relationship between the functions. We define the relationship as follows; the functions for flow A and for flow B are regarded to have the relationship if the all links passed by the flow A are also passed by the flow B. Hereafter we call this relationship *flow inclusive*

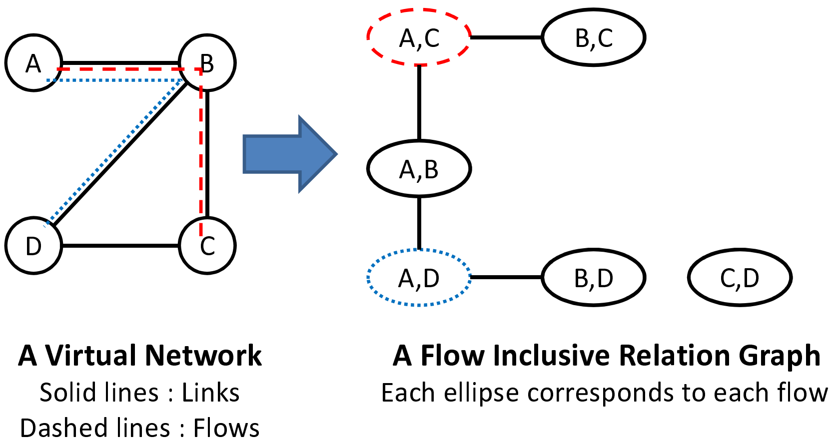


Figure 5: Example of Flow Inclusive Relation

relation (FIR).

As shown in Fig. 5, the FIR is described as a graph where a vertex is defined for each flow. The vertices are connected with edges if their corresponding functions have the FIR. Hereafter, we call this graph *flow inclusive relation graph*, and call its vertices *flow nodes*.

Applying the results of Lipson et al. [1] to the virtual network, the virtual network with high modularity has strong adaptability to traffic changes. In this thesis, we define the modularity by the modularity of the flow inclusive graph calculated by the method proposed by Newman [11]. Hereafter we call this modularity the *flow inclusive relation modularity (FIRM)*.

A 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 an 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 a normalized value of $\sum_{ij}\left(A_{ij} - \frac{k_i k_j}{2m}\right)$ by multiplying $\frac{1}{2m}$ so that the maximum value of Q is 1. As Q approaching 1 closer, the structure has denser inner-module edges and sparser inter-module edges.

Newman [11] 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.

In this thesis, we obtain the FIRM of the virtual network by applying this method. The obtained FIRM 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 the high FIRM, several flows are closely related. If the congestion occurs, the congestion is mitigated by adding an optical path to the node pair which are the source and destination node of a flow passing the congested links, and changing the route of the flows. Moreover, the congestion of the other links may also be mitigated, because adding the optical path enables the route change of the other flows belonging to the same module. As a result, the congestion of all links may be mitigated by adding a small number of paths.

Table 1: FIRM vs. the Number of Nodes in a Grid Topology

Grid size	# of nodes	FIRM
3×3	9	0.4762
2×5	10	0.4647
3×4	12	0.4899
3×5	15	0.5192
4×4	16	0.5062
4×5	20	0.5169
5×5	25	0.5031

3.3 Property of the Flow Inclusive Relation Modularity

3.3.1 Relationship between Number of Nodes in a Network and FIRM

We investigate the relationship between FIRM and the number of nodes in the virtual network. by calculating the FIRM of the 2D grid topologies with various numbers of nodes. When calculating the FRIM, we set the routes of flows by the shortest path first algorithm.

Table 1 shows the FIRM of the 2D grid topologies with various numbers of nodes. As shown in this table, the FIRM depends on the size of the network. That is, the FIRM cannot be used to compare the adaptability of the virtual networks with different numbers of nodes.

3.3.2 Relationship between Number of Edges in a Network and FIRM

In this paragraph, we investigate the relationship between the FIRM and the addition of the links in a virtual network. To investigate the relation, we use a 5×5 grid topology as an initial virtual network. Then, we add a link to the node pair where the direct link does not exist. Finally, we compare the FIRM of the initial topology and the topology after adding a link. The number of node pairs where the direct link does not exist is 520 in the 5×5 grid topology. In this paragraph, we investigate all patterns of the virtual networks after adding a link. That is, we investigate 520 virtual networks.

Table 2 shows the results. As shown in this table, adding links increases the FIRM in most cases. That is, the virtual network with more links has a tendency to have the larger FIRM.

However, there are the cases that adding a link decrease the FIRM. Thus, to increase or keep the FIRM, we should carefully select the node pairs where a link is added or deleted.

Table 2: FIRM after Adding An Optical Path

	# of virtual networks
Virtual Network with the Increased FIRM	462
Virtual Network with the Same FIRM	4
Virtual Network with the Decreased FIRM	54

3.4 Evaluation of the Flow Inclusive Relation Modularity

We evaluate the relationship between the FIRM of a virtual network and the number of optical paths required to be added to accommodate significant traffic changes.

3.4.1 Overview

We evaluate the FIRM by the following steps. First, we prepare some initial virtual networks having various FIRMs. We calculate the FIRMs of the initial virtual networks. Then we generate the traffic changes by randomly generating the traffic, and reconfigure the virtual network so as to accommodate the traffic. We count the number of optical paths added to accommodate the traffic. In this evaluation, we generate 10 patterns of traffic matrices for each initial virtual network.

In the rest of this section, we describe the details of the generation method of the initial virtual networks and traffic matrices, and the reconfiguration method of the virtual network used in the evaluation.

3.4.2 Evaluation Environment

Generation Method of Initial Virtual Networks In order to generate the initial virtual networks with the various FIRMs, we use a method to generate topologies with various spatial modularities proposed by Hidaka [12]. This method uses the number of groups n and probability parameter p as inputs, and generates the topology by the following steps.

First, this method generates n groups and locate one node in each group. The nodes are connected so as to form a ring. Then, this method adds the nodes. When adding a node, the group of the node is selected randomly. The additional node is connected to one node randomly selected from the nodes in the group. Furthermore, an edge between the additional node and the node which belongs to other group is added with probability p or an edge between the additional node and the node in the same group is added with probability $(1 - p)$. This method generates various topologies depending on the value p. Though this method generates the topologies with various spatial modularity, the topologies with different spatial modularities have the different FIRMs.

In this thesis, we generate 255 initial virtual networks by changing the parameter p from 0.00 to 1.00 at 0.02 intervals. We set the number of nodes to 49 and the number of groups to 5.

Generation Method of Traffic Matrices Antoniou et. al [13] monitored the traffic in ISPs and clarifies that the traffic between source and destination router pairs follows a log normal distribution. Thus, in this thesis, we generate traffic matrices so as to follow the lognormal distribution, whose parameters are set to the same value as the results by Antoniou et. al [13].

Reconfiguration Method of Virtual Networks In this thesis, we use a reconfiguration method based on the method proposed by Gençata et al. [4]. This method continues to add optical paths until the utilizations of all links become lower than the threshold Th.

In this thesis, we use a method that accommodates the traffic by a small number of optical paths. To make the number of optical paths required to be added small, we add the optical paths where we can minimize the maximum link utilization.

In this method, the virtual network is reconfigured by the following steps.

1. Calculate all the utilizations of links. Denote the maximum link utilization as L.
2. If $L \leq Th$ the reconfiguration is over. Otherwise go to 3.
3. For each node pair, calculate the maximum link utilization when the optical path between the pair is added.
4. Add the lightpath between the node pair that minimizes the maximum link utilization. Then go back to 1.

In the above steps, we calculate the routes over the virtual network by the CSPF so as to avoid the link utilization larger than Th. To avoid a large overhead, when adding an optical path, we change only the routes of the flows passing the link whose utilization is larger than Th.

3.4.3 Evaluation Metrics

In this evaluation, we investigate the relation of the FIRM and the number of the optical paths required to be added, by plotting the scatter diagram.

In addition, to evaluate the relation more clearly, we investigate the accuracy of the identification of the virtual network that requires only a small number of additional optical paths to handle traffic changes. To evaluate the accuracy of the identification, we use a threshold based method where the virtual network with the FIRM higher than a threshold is identified as the network that requires only a small number of additional optical paths.

In this evaluation, we use the false negative rate (FNR) and the false positive rate (FPR) as metrics to evaluate the accuracy. FNR is defined by

$$FNR = {}^{m_{fn}}/_{m_p}, \qquad (2)$$

where m_p is the number of virtual networks whose average numbers of additional paths are less than a certain threshold R_{th}, and m_{fn} is the number of virtual networks which are identified as the virtual networks that require more than R_{th} additional optical paths but require only less than R_{th} additional optical paths.

Similarly, the false positive rate (FPR) is defined by

$$FPR = {}^{m_{fp}}/_{m_n}, \tag{3}$$

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

3.4.4 Results

Relation between Flow Inclusive Relation Modularity and the Number of Added Paths Fig. 6 shows the relation between the flow inclusive relation modularity and the number of added paths. In this figure, the horizontal axis indicates the FIRM of each virtual network, and the vertical axis indicates the number of added paths of each virtual network. Each circle indicates the average number of added paths and each error bar indicates the 68.27% confidence interval of the added paths.

From Fig. 6, there are negative correlation between the FIRM and the number of added paths except for 2 virtual networks, which do not contain links with utilization larger than Th. This is because adding an optical path between a source and destination nodes of a flow whose corresponding function belongs to a module mitigates not only the congestions of the links passed by the flow but also the congestions of the links passed by the flows whose corresponding functions belong to the same module.

The modules in the flow inclusive relation graph correspond to the cohesion of flows passing the same links. If the FIR in the module is close, by adding an optical path between the source node and destination node of a flow in the module, we change not only the routes of the flow but also the routes of the other flows in the same module. As a result, by adding a small number of optical paths, all of the congestions may be mitigated. On the other hand, if the FIRM is low, a large number of optical paths are required to be added because the number of flows whose routes can be changed by adding optical paths is small.

We also compare the FIRM with the betweenness centrality. The betweenness centrality of a link indicates the probability that the congestion occurs at the link. In this subsection, we investigate the maximum betweenness centrality among all links. Fig. 7 shows the relation between the maximum betweenness centrality and the number of optical paths required to be added. In this figure, the horizontal axis indicates the maximum betweenness centrality of each virtual network, and the vertical axis indicates the number of added paths of each virtual network.

From Fig. 7, there are the positive relation between the maximum betweenness centrality and the number of optical paths required to be added. This is because the virtual network with the smaller maximum betweenness centrality has less possibility to congest. Therefore, in the virtual network with the small maximum betweenness centrality, few links are congested, and the number of optical paths required to be added is small.

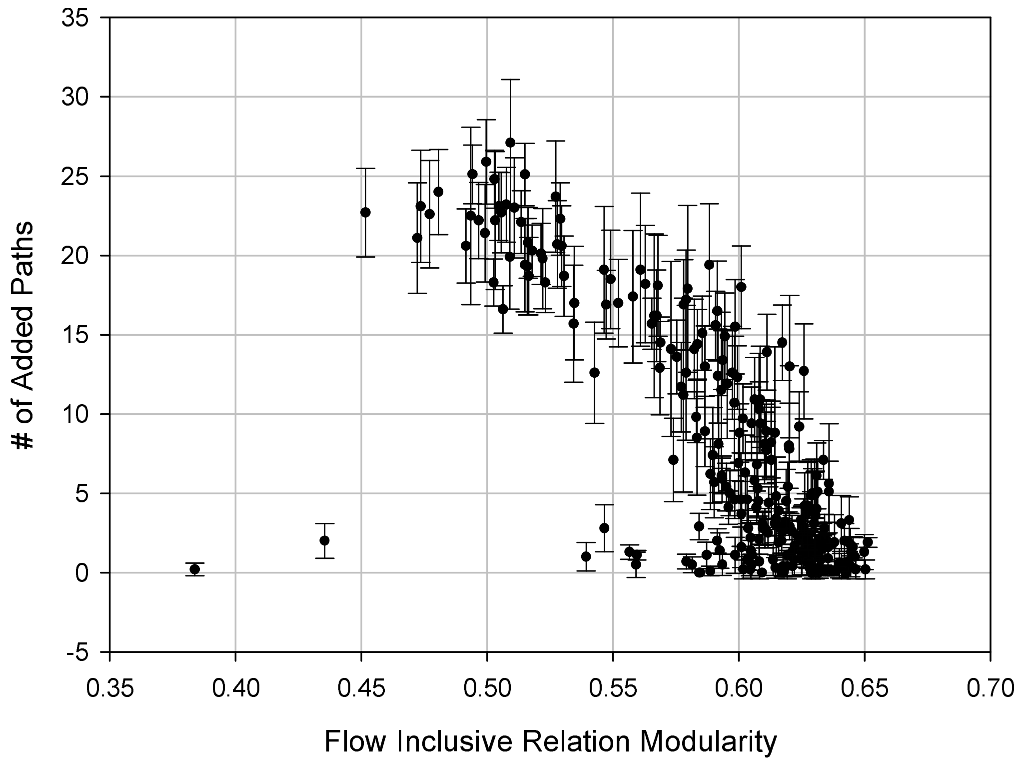


Figure 6: Flow Inclusive Relation Modularity vs. the Number of Added Paths

However, the above discussion does not indicates that the virtual network with the smaller maximum betweenness centrality is adaptive to any traffic changes by adding only a small number of optical paths. If the traffic changes more significantly, the number of the congested links becomes large. Even in this case, the virtual network should accommodate traffic by adding only a small number of optical paths.

Therefore, we focus on virtual networks having the multiple congested links. In this comparison, we use the virtual networks whose maximum betweenness centralities are from 0.4 to 0.5. In this comparison, we also exclude the virtual networks with the larger maximum betweenness centralities than 0.5, because the virtual network with the large betweenness centrality should not be constructed, because it is too easy to be congested.

Fig. 8 shows the relations between the FIRM or the maximum betweenness centrality and the number of optical paths required to be added, among the virtual networks whose maximum betweenness centralities are from 0.4 to 0.5. There is clearly observable negative correlation in Fig. 8a. On the other hand, several virtual networks have the similar maximum betweenness centralities, but have the various numbers of the added optical paths. This is because the maximum betweenness centrality identifies only the virtual network easy to congest and cannot identify the virtual networks that handle traffic changes by adding only a small number of optical paths.

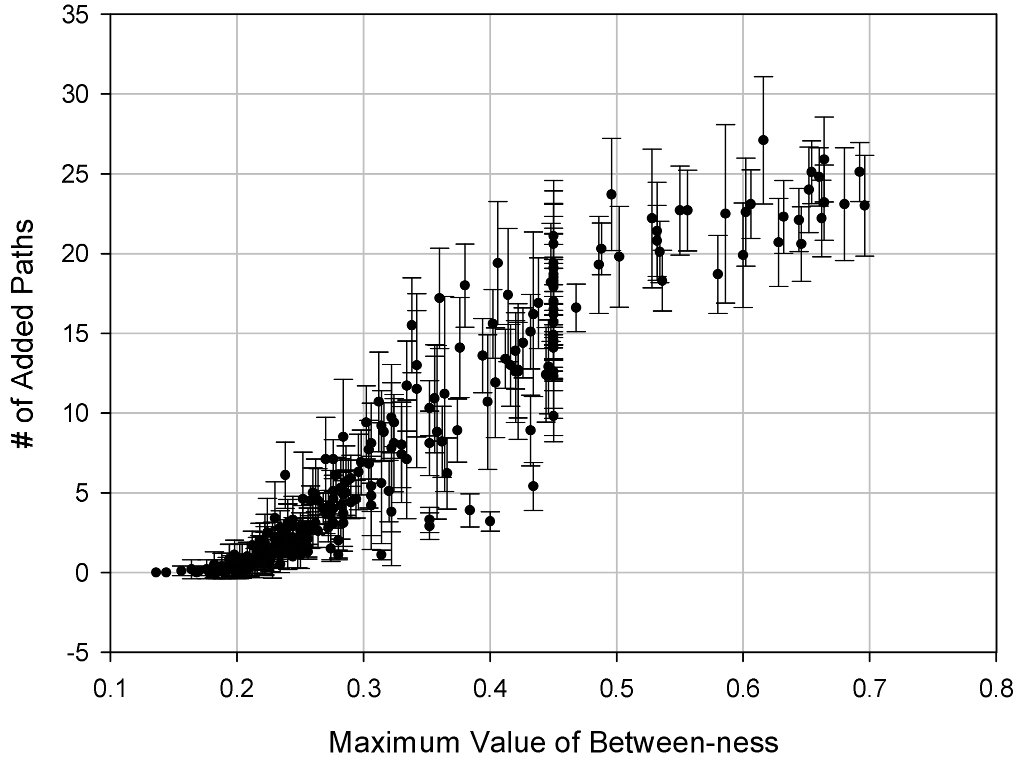
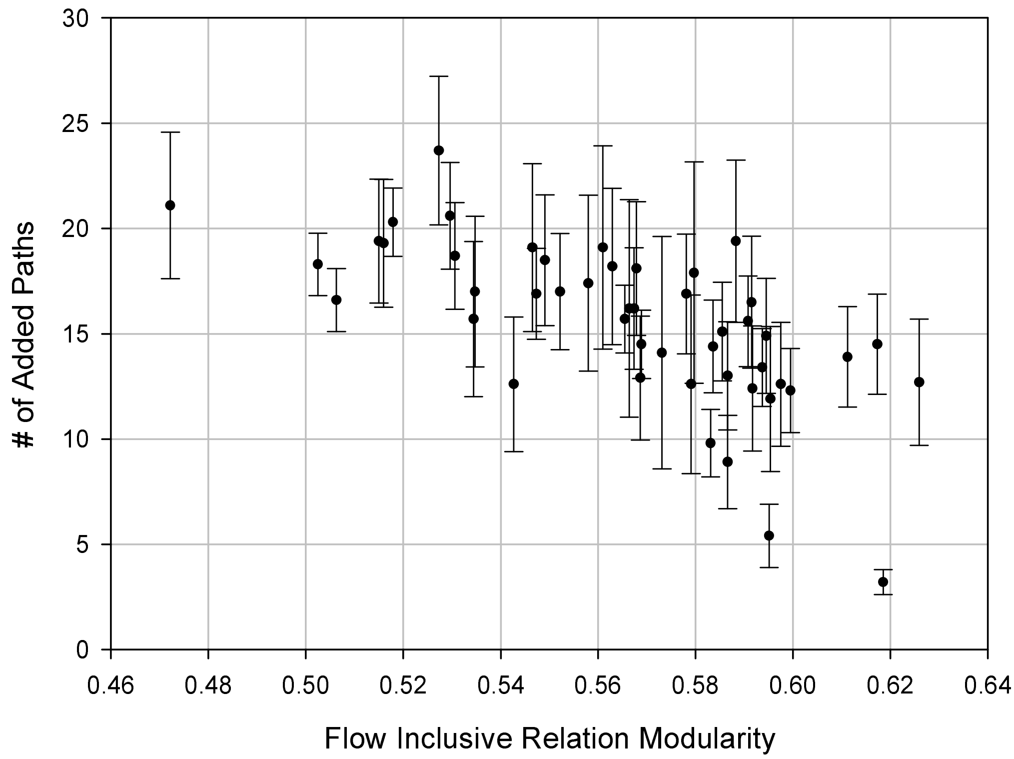
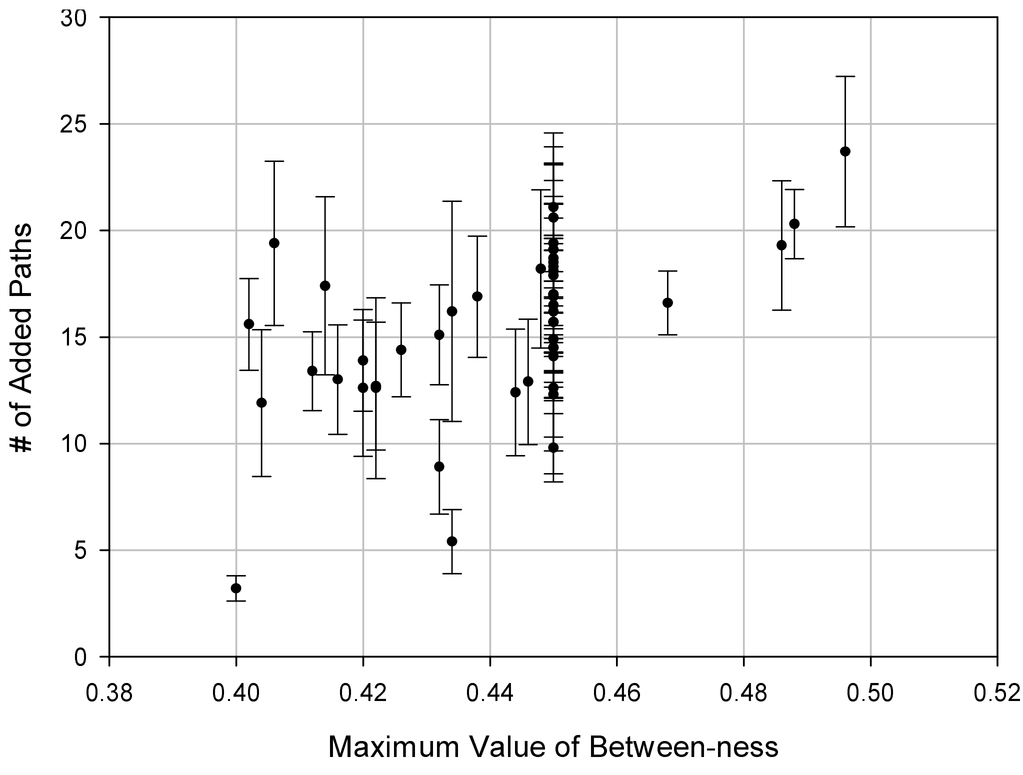


Figure 7: Maximum Betweenness vs. the Number of Added Paths



(a) Flow Inclusive Relation Modularity



(b) Maximum Betweenness

Figure 8: Comparison of Virtual Networks (Maximum Betweenness from 0.4 to 0.5)

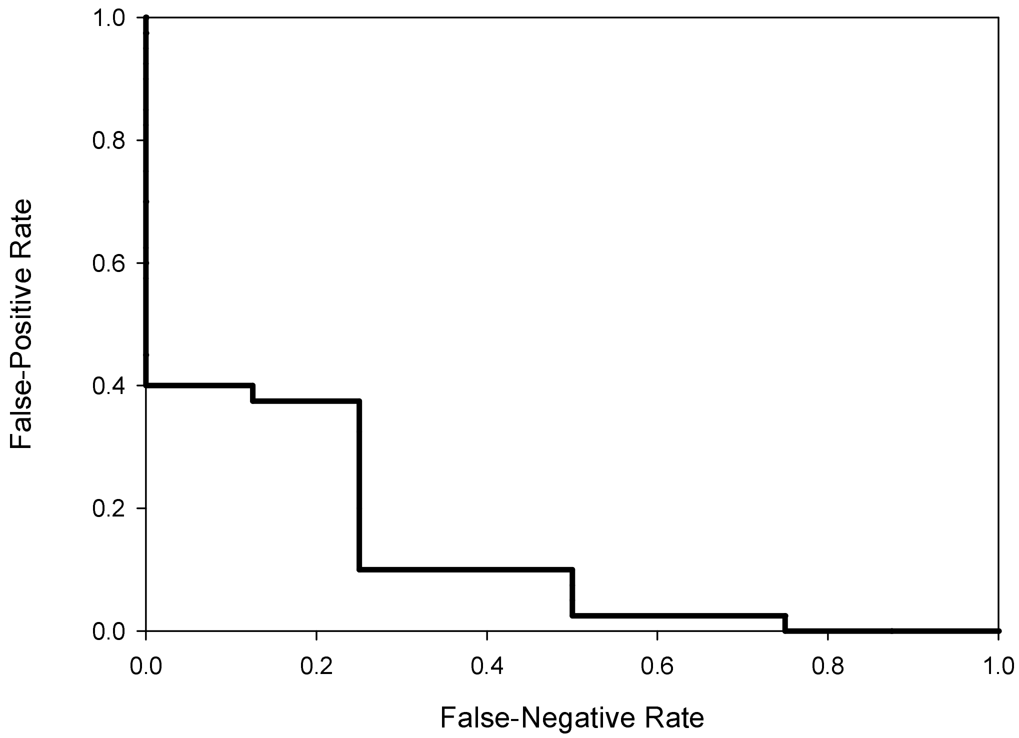


Figure 9: The Relationship between FNR and FPR in the case of FIRM

Evaluation Result with False Negative Rate and False Positive Rate We investigate the relationship between FNR and FPR of virtual netwoks with the maximum betweenness centrality from 0.4 to 0.5, changing the threshold for each index. Fig. 9 shows the relationship between FNR and FPR in the case of the FIRM. The horizontal axis indicates the FNR, and the vertical axis indicates the FPR. In the same manner, Fig. 10 shows the relationship between FNR and FPR in the case of maximum betweenness centrality. In these figures, R_{th} is set to 10. The horizontal axis indicates the FNR, and the vertical axis indicates the FPR.

Comparing Fig. 9 with 10, the method using FIRM achieves both lower FNR and lower FPR at the same time. This result means that FIRM identifies the virtual networks which can accommodate significant traffic changes with less additional paths more accurately. Therefore, to construct the adaptive 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.

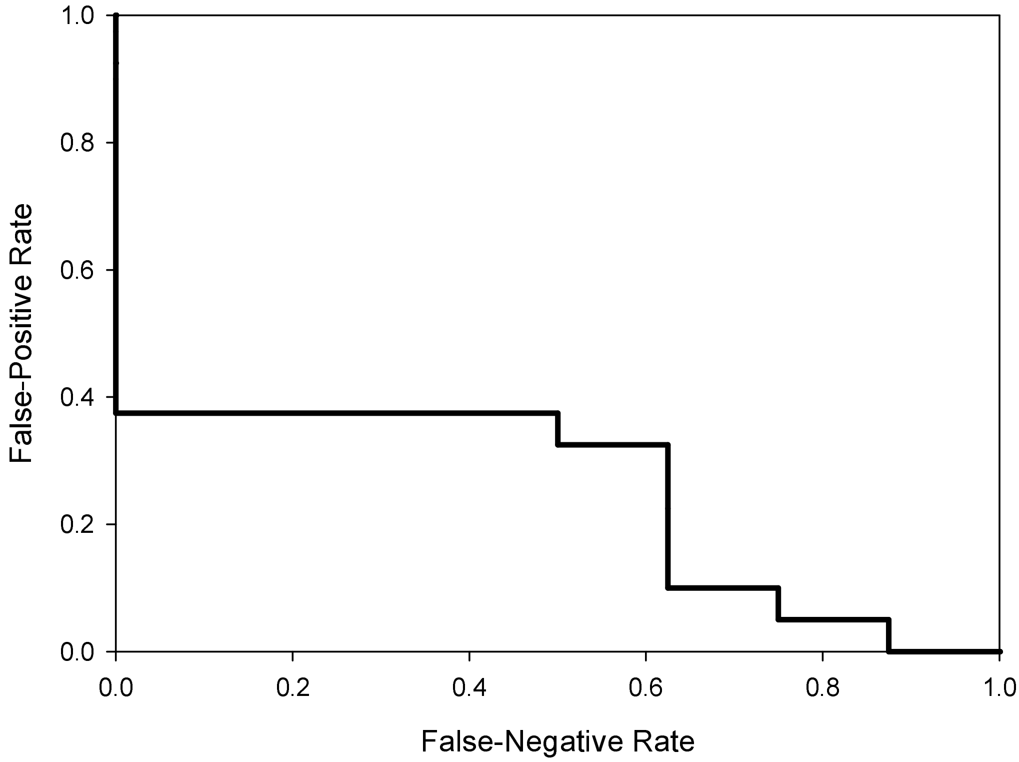


Figure 10: The Relationship between FNR and FPR in the case of Maximum Betweenness

4 Proactive Reconfiguration Method using the Flow Inclusive Relation Modularity

4.1 Overview

In this section, we introduce the proactive virtual network control considering the FIRM. The virtual network with a high FIRM has the adaptability to traffic changes. Thus, in our proactive virtual network control, we aim to increase the FIRM or keep the high FIRM.

The virtual network control has two types of operations; addition and deletion of the optical paths. Similar to the existing virtual network control methods, our proactive virtual network control performs the both types of operations.

If the virtual network has low adaptability and the link utilization are increasing, the proactive virtual network adds optical paths to increase the FIRM so as to increase the adaptability to future traffic increases. On the other hand, if the link utilization is sufficiently low, the proactive virtual network control deletes the optical paths to release the resources so as to be used by the future reconfiguration. When deleting the optical paths, by considering the FIRM, we keep the adaptability to traffic changes. The rest of this subsection describes the details of the addition and deletion of the optical paths considering the FIRM.

4.1.1 Link Deletion Method Considering FIRM

If the optical paths can be deleted without degrading the adaptability to traffic changes, we delete the optical paths to so as to release the resources for the future reconfigration.

The optical paths can be deleted when both of the following conditions are satisfied. (1) The utilizations of any links do not become larger than a threshold T_u even when the optical path is deleted. (2) The FIRM does not become larger than a threshold T_f even when the optical path is deleted.

When the optical paths can be deleted, we delete only one optical path at each step of the virtual network control to make the impact of the deletion small. Our proactive virtual network control selects the links to be deleted by the following steps where the current traffic matrix is given.

1. For each optical path, calculate the maximum link utilization by using the current traffic matrix when the optical path is deleted. Then the optical paths whose deletion does not make the link utilization larger than T_u as the candidate optical paths.

2. For each candidate optical path, calculate the FRIM of the network after the deletion of the optical path.

3. Select the optical paths so that the FIRM of the network after the selected optical path is deleted is the largest among the candidate optical paths.

4.1.2 Link Addition Method Considering FIRM

If an optical path is required to be added to keep the adaptability high, the proactive virtual network control adds the optical paths.

The addition of the optical paths is required in the following cases. (1) The first case is that the link utilization is increasing. When the link utilization is increasing, the current virtual network may become insufficient to accommodate the future traffic demand. In this case, we aim to accommodate the future traffic demand by adding optical paths proactively. The increase of traffic can be detected by comparing the current link utilization with a threshold T_u. (2) The other case is that the FIRM is small. If the FIRM is small, the virtual network does not have enough adaptability to future traffic changes, and a large number of optical paths may be required to be added when a significant traffic change occurs. Thus, the proactive virtual network control adds the optical paths also in this case. This case also can be detected by using the threshold to the FIRM.

Unlike the situation that the reactive virtual network control is required, the problem such as congestion does not occur in both of the above cases. Thus, the immediate virtual network reconfiguration is not required. Our proactive virtual network control selects the node pair where an optical path is added after checking the FIRMs of all candidates.

The proactive virtual network control selects the node pair where an optical path is added by the following steps.

1. Select the candidate node pairs. If the link whose utilization exceeds the threshold T_u, the candidates should be the node pair passed by the traffic passing the link with large utilization in order to decrease the link utilization. In other cases, all node pairs are selected as the candidates.

2. For each candidate node pair, calculate the FIRM of the virtual network after addling an optical path to the node pair.

3. Select the node pair whose corresponding virtual network has the highest FIRM.

4.2 Evaluation

4.2.1 Environment

In this section, we evaluate the virtual network control considering the FIRM. This evaluation focuses on the case of the deletion of the optical paths. The deletion of the optical path is also performed by the existing virtual network control [4] to release the unnecessary resources. Comparing the virtual network control considering the FIRM with the existing virtual network control, we clarify the advantage of the virtual network control considering the FIRM.

Exisiting Virtual Network Control Gençata et al. have proposed a virtual network control that reconfigures the virtual network so as to follow the traffic changes [4]. This method adds optical paths to mitigate the congestion. In addition, this method deletes the optical paths if the optical paths are not necessary. In this method, the optical path to be deleted is selected by the following steps.

1. Set the optical paths whose link utilization is less than a threshold as the candidate optical paths.
2. Calculate routes and maximum link utilization after deleting the candidate optical paths for each candidate.
3. Select the optical paths from the candidates so that the link utilization after the deletion of the selected optical path is the smallest.

Evaluation Method In this evaluation, we compare the number of added path when the traffic change occurs after several steps of the proactive virtual network control. Our evaluation is performed by the following steps.

1. Generate the initial virtual network and initial traffic matrix.
2. Perform the deletion of the optical paths by the proactive virtual network control several times.
3. Generate the traffic changes.
4. Perform the reactive virtual network control, and count the number of added optical paths.

In our evaluation, we use 3×3 grid based network which is recofigured so as to accommodate the initial traffic matrix as the initial virtual network. The initial traffic matrix is generated as the random values following the lognormal distribution similar to the evaluation of Section 3.4.2. Then we generate the significant traffic change by adding random values to the 27 randomly selected node pairs. The added random traffic amount is generated as a uniform random values so that the average of the added traffic amount becomes a quarter of the capacity of an optical path. We use the same reactie virtual network control as the evaluation of Section 3.4.2.

4.2.2 Results

Fig. 11 shows the comparison of the number of optical paths required to be added. As shown in this figure, the number of the optical paths required to be added to the virtual network after the proactive virtual network control considering the FIRM is smaller than that of the virtual network control without considering the FIRM. This is caused by the difference of the FIRM. As shown in Fig. 12, the FIRM after the virtual network control without considering the FIRM becomes low. As a result, the adaptability to traffic changes is degraded by the deletion of the optical paths. On the other hand, the virtual network control considering

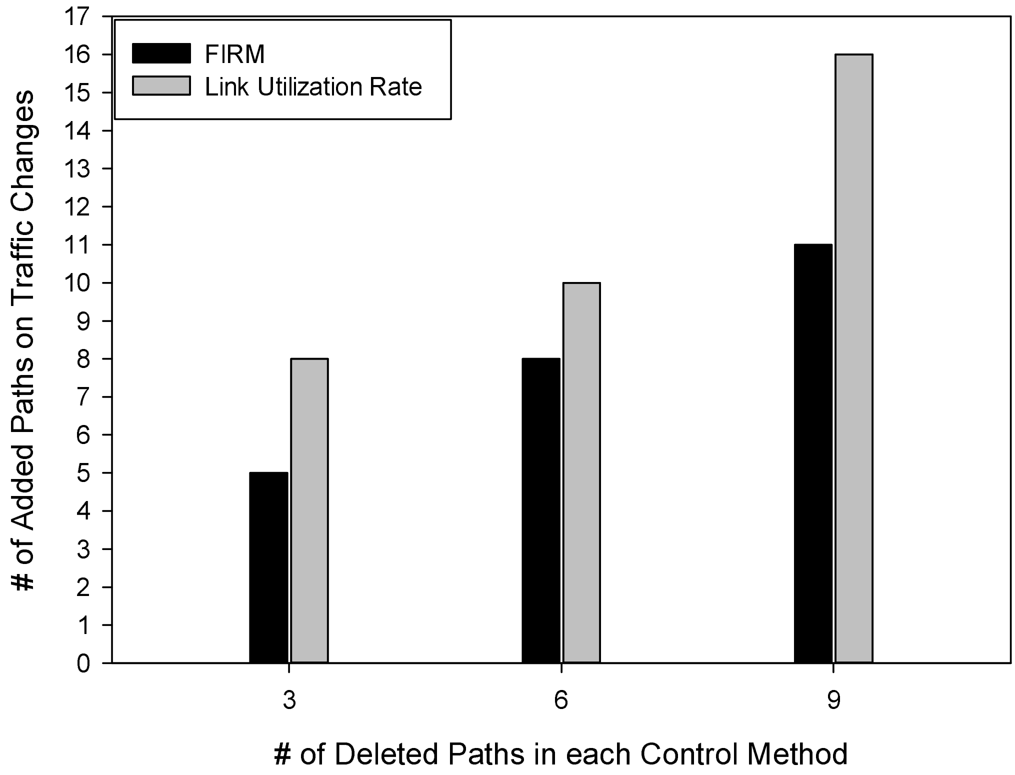


Figure 11: Comparison of Virtual Networks constructed by Proactive Control in Number of Additional Paths

the FIRM keeps the high FIRM. As a result, only adding a small number of optical paths handles the significant traffic changes.

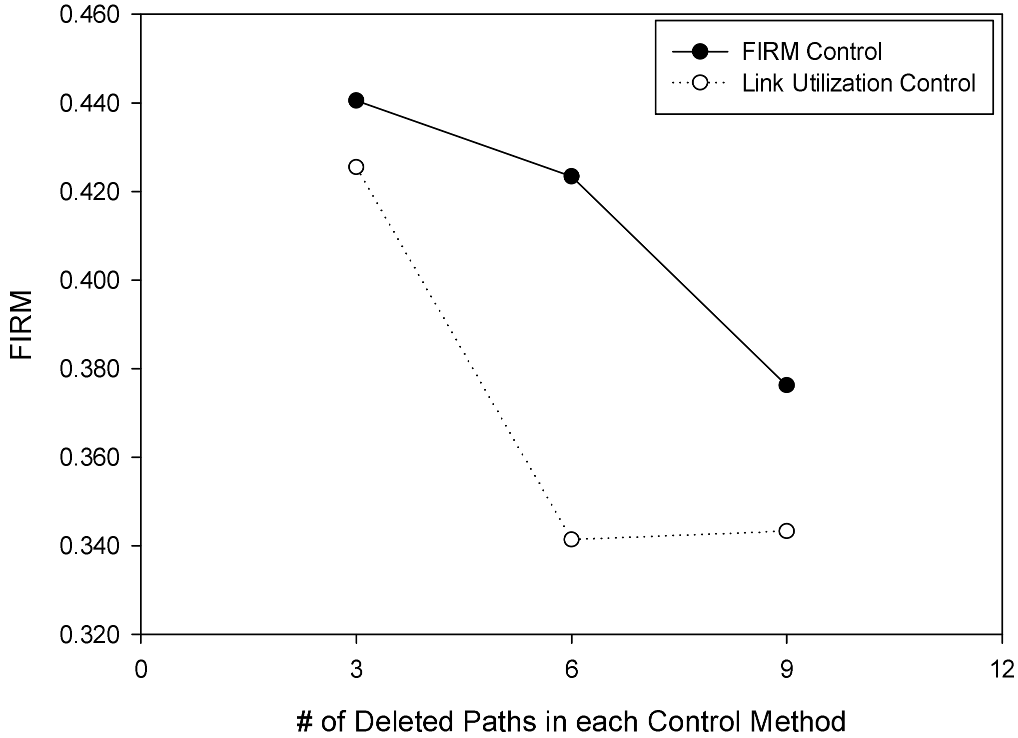


Figure 12: Comparison of Virtual Networks constructed by Proactive Control in FIRM

5 Conclusion

In this thesis, we proposed a proactive virtual network control to increase the adaptability of the virtual network. In the proactive virtual network control, we add or delete optical paths considering the adaptability of the virtual network to the traffic changes. To consider the adaptability of the virtual network in the proactive virtual network control, we also proposed a new index called Flow Inclusive Relation Modularity (FIRM). FIRM is an index inspired by the model of lifeforms which survive and evolve under significant environmental changes.

Through simulation, we clarified that the virtual network with the high FIRM can handle traffic changes by adding a small number of optical paths. We also evaluated the proactive virtual network control using the FIRM, and clarified that the virtual network reconfigured proactively by using the FIRM reduces the number of optical paths requried to be added in the case of the significant traffic changes by more than 30% compared with the virtual network configured considering only the link utilization.

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

Acknowledgements

I am deeply grateful to Professor Masayuki Murata of Osaka University whose enormous support and insightful comments were invaluable during the course of my study.

I sincerely appreciate Assistant Professor Yuichi Ohsita of Osaka University who gave me invaluable comments and warm encouragements. My work would not have succeeded without his excellent support.

I also acknowledge the helpful advice from Professor Naoki Wakamiya of Osaka University and Associate Professor Shin'ichi Arakawa of Osaka University.

Finally I express my thanks to all the members who belong to Advanced Network Architecture Research Laboratory of Graduate School of Information Science and Technology of Osaka University. If it had not been for their help, I could not have spent my treasurable laboratory life.

References

[1] H. Lipson, J. B. Pollack, and N. P. Suh, “On the origin of modular variation,” *Evolution*, vol. 56, pp. 1549–1556, Aug. 2002.

[2] Ministry of Internal Affairs and Communications, “2012 WHITE PAPER Information and Communications in Japan,” July 2012.

[3] Y. Ohsita, T. Miyamura, S. Arakawa, S. Ata, E. Oki, K. Shiomoto, and M. Murata, “Gradually reconfiguring virtual network topologies based on estimated traffic matrices,” *IEEE/ACM Transactions on Networking*, vol. 18, pp. 177 –189, Feb. 2010.

[4] A. Gençata and B. Mukherjee, “Virtual-topology adaptation for WDM mesh networks under dynamic traffic,” *IEEE/ACM Transactions on Networking*, vol. 11, pp. 236–247, Apr. 2003.

[5] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, “Some principles for designing a wide-area wdm optical network,” *Networking, IEEE/ACM Transactions on*, vol. 4, pp. 684 –696, Oct. 1996.

[6] K. Shiomoto, E. Oki, W. Imajuku, S. Okamoto, and N. Yamanaka, “Distributed virtual network topology control mechanism in gmpls-based multiregion networks,” *Selected Areas in Communications, IEEE Journal on*, vol. 21, pp. 1254 – 1262, Oct. 2003.

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

[8] L. C. Freeman, “A set of measures of centrality based on betweenness,” *Sociometry*, vol. 40, pp. 35–41, Mar. 1977.

[9] A. Tizghadam and A. Leon-Garcia, “Autonomic traffic engineering for network robustness,” *IEEE Journal on Selected Areas in Communications*, vol. 28, pp. 39–50, Jan. 2010.

[10] A. Bigdeli, A. Tizghadam, and A. Leon-Garcia, “Comparison of network criticality, algebraic connectivity, and other graph metrics,” in *Proceedings of SIMPLEX*, pp. 4:1–4:6, ACM, July 2009.

[11] M. E. J. Newman, “Modularity and community structure in networks,” *Proceedings of the National Academy of Sciences*, vol. 103, pp. 8577–8582, June 2006.

[12] N. Hidaka, “A topology design method for sustainable information networks,” Master’s thesis, Graduate School of Information Science and Technology, Osaka University, Feb. 2009.

[13] I. Antoniou, V. Ivanov, V. V. Ivanov, and P. Zrelov, "On the log-normal distribution of network traffic," *Physica D: Nonlinear Phenomena*, vol. 167, pp. 72 – 85, July 2002.