Virtual Network Topologies Adaptive to Large Traffic Changes by Reconfiguring a Small Number of Paths

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***Abstract*—A virtual network reconfiguration is one efficient approach to accommodate the traffic that changes significantly. By reconfiguring the virtual network, the network accommodates the traffic even when the traffic pattern changes significantly. The reconfigure has a large impact on the traffic passing the reconfigured paths. Thus, the number of reconfigured paths should be minimized. The number of reconfigured paths depends on the virtual network topology before the reconfiguration, and some topology requires a large number of reconfigured paths to handle the traffic changes. In this paper, we investigate the virtual network topology, which can handle significant traffic changes by reconfiguring only a small number of paths. To investigate the virtual network, we propose a index based on the evolution model in the changing environments. We evaluate our index through simulation, and clarify that our index indicates the adaptability of virtual networks. We also compare our index with betweenness centrality, and clarify that our index identifies the virtual network with high adaptability to traffic changes more accurately.**

Keywords*—*Traffic Change; Traffic Engineering; Topology; Optical Network; Reconfiguration

I. Introduction

In recent years, various new applications have been deployed over the Internet. Such application leads the increase of the traffic amount and the unpredictable traffic changes [1]. A network must accommodate such a time-varying traffic efficiently. However, accommodating time-varying traffic efficiently is difficult, because 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 a large time-varying traffic is to reconfigure the virtual network. Several methods to reconfigure the virtual network have been proposed [2], [3], [4]. In these methods, a virtual network is constructed over the 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 overheadbecause we require setting OXCs for each optical path.

One approach to avoid adding a large number of optical paths is to construct an adaptive virtual network, which can handle any traffic change by adding a small number of optical paths in advance. Thus, we investigate the adaptive virtual network.

There are several metrics of the network topology. The betweenness centrality of a link [5] indicates the probability that traffic from a source node to a destination node passes the link. The link criticality [6], [7] 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 with 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.

In this paper, 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. To propose the index, we are inspired by the natural lifeforms that survive and evolve in the case of significant environmental changes. The natural lifefroms are modeled [8] as a suite of functions, which synthesizes products from environmental resources. 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.

We model the virtual network by the similar way to the natural lifeforms, and propose an index called *flow inclusive relation modularity* (FIRM).

The rest of this paper is organized as follows. In Section II, 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 an index that identifies the adaptive virtual network. In Section III, we mention the steps to evaluate our index. In Section IV, we show the result of the evaluation. Finally, we conclude and mention about future work in Section V.

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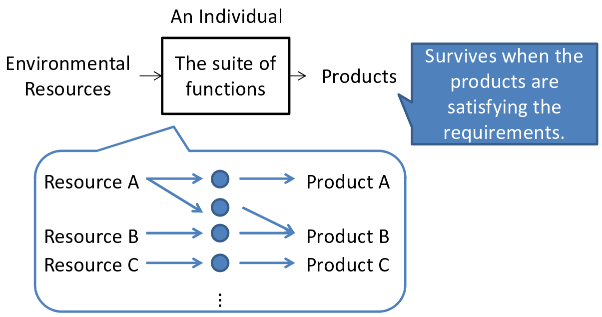

Figure 1. Lifeform Model

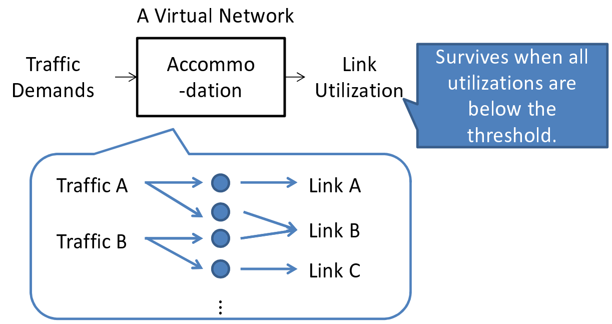

Figure 2. Virtual Network Flow Model

II. Adaptability to Environmental Changes and Modularity

A. Environmental Changes and Modularity in Lifeforms

Lipson et al. [8] 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. 1. 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 generate 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. [8], 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 survive and evolve in the environmental changes.

B. Traffic Changes and Modularity in Virtual Network Operation

Inspired by the lifeforms that 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.

1) Functions in Virtual Network: The function of the virtual network is to accommodate traffic. We model this function of the virtual network, as shown in Fig. 2. 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. 2 is similar to the model of lifeforms shown in Fig. 1. The traffic demands of the model in Fig. 2 correspond to the resources of the model in Fig. 1.

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 paper, 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.

2) Relationships between Functions in Virtual Network: To define a modularity of a virtual network, we need to define the relationship among the functions in the virtual network. In this paper, 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 paper, we focus on the close relationship between the functions. We define the relationship as follows; the functions for flow A and for flow B is 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 relation* (FIR).

As shown in Fig. 3, 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 FIR. Hereafter, we call this graph *flow inclusive relation graph*, and call its vertices *flow nodes*.

3) Flow Inclusive Relation Modularity: Applying the results of Lipson et al. [8] to the virtual network, the virtual network with high modularity has strong adaptability to environmental changes. In this paper, we define the modularity by the modularity of the flow inclusive graph calculated by the method proposed by Newman [9]. Hereafter, we call this modularity the *flow inclusive relation modularity (FIRM)*.

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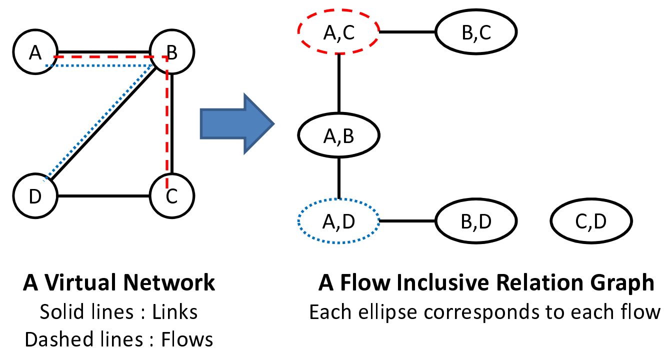


Figure 3. Flow inclusive relation model

A modularity of a graph is defined as

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

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 (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 [9] 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 paper, we obtain a flow inclusive relation modularity of the virtual network by applying this method [9]. The obtained flow inclusive relation modularity 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 large flow inclusive relation modularity, 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.

III. Evaluation Method

A. Overview of the Evaluation Method

In this paper, we evaluate the relationship between the flow inclusive relation modularity of a virtual network and the number of optical paths required to be added to accommodate significant traffic changes. In our evaluation, we perform the following steps. First, we prepare some initial virtual networks having various flow inclusive relation modularities. We calculate the flow inclusive relation modularities of 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 initial virtual networks and traffic matrices, and the reconfiguration method of virtual network used in the evaluation.

B. The Generation Method of Initial Virtual Networks

In order to generate initial virtual networks with various FIRMs, we use a method to generate topologies with various modularity proposed by Hidaka [10]. 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.

In this paper, 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.

C. The Generation Method of Traffic Matrices

Antoniou et al. [11] monitored the traffic in ISPs and clarifies that the traffic between source and destination router pairs follows a log normal distribution. Thus, in this paper, we generate traffic matrices so as to follow the lognormal distrubution, whose parameters are set to the same value as the results by Antoniou et al. [11].

D. The Reconfiguration Method of Virtual Netowrks

In this paper, 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 paper, 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.

The reconfiguration method performs 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 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 CSPF. 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.

IV. Evaluation Result

A. Relation between Flow Inclusive Relation Modularity and the Number of Added Paths

Fig. 4 shows the relation between the flow inclusive relation modularity and the number of added paths. In this figure, the horizontal axis indicates FIRMs 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. 4, 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.

B. Comparison with Betweenness

In this subsection, we compare the FIRM with the betweenness centrality. The betweenness centrality of a link indicates the probability that the congestion occur at the link. In this subsection, we investigate the maximum betweenness centrality among all links. Fig. 5 shows the relation between the maximum betweenness centrality and the number of optical paths required to be added. In this figure, the horizontal axis

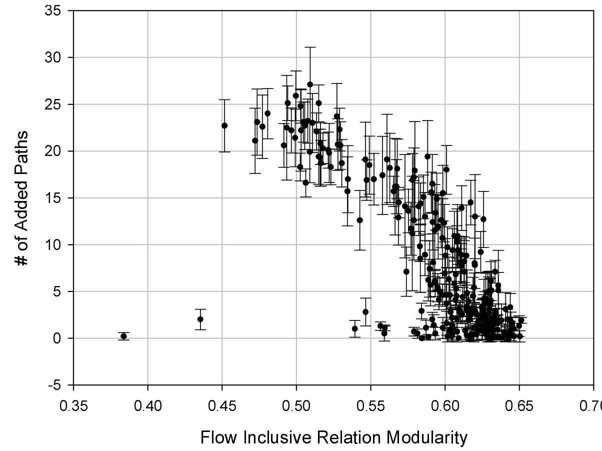


Figure 4. Flow Inclusive Relation Modularity and the Number of Added Paths

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. 5, 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.

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. 6 shows the relations between the flow inclusive relation modularity 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. 6a. On the other hand, several virtual networks have the similar maximum betweenness centralities, but have various numbers of 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

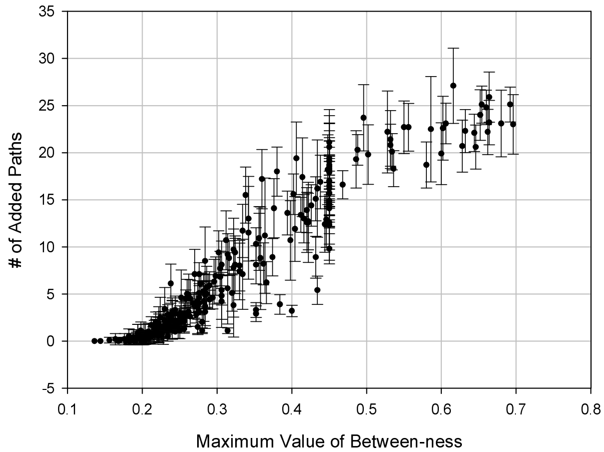


Figure 5. Maximum Betweenness and the Number of Added Paths

small number of optical paths.

C. Evaluation Result with False Negative Rate and False Positive Rate

To evaluate the relation between the flow inclusive modularity and the number of optical paths required to be added more clearly, we investigate the accuracy of the method to identify the virtual network that only a small number of additional optical paths to handle traffic changes. In this evaluation, we use the following method to identify the virtual networks based on the flow inclusive relation modularity or the maximum betweenness centrality. In the case of FIRM, we set a threshold to the FIRM, and identify a network with FIRM higher than the threshold as the network that requires only a small number of additional optical paths. In the case of maximum betweenness centrality, we identify a network with the maximum betweenness centrality lower than the threshold as the network that requires only a small number of additional paths.

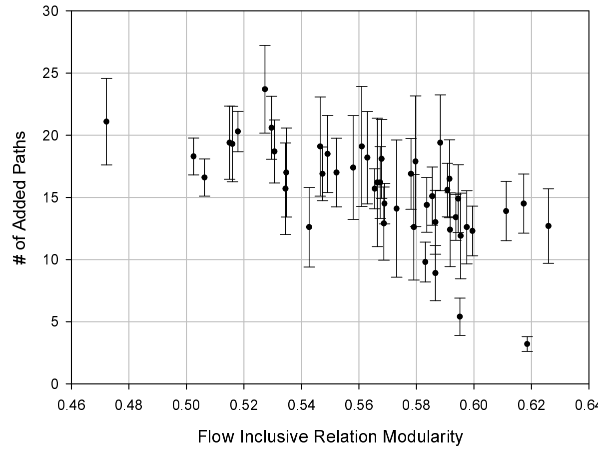
In this paper, we use the false negative rate (FNR) and the false positive rate (FPR) as metrics to evaluate the accuracy. FNR is defined by

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

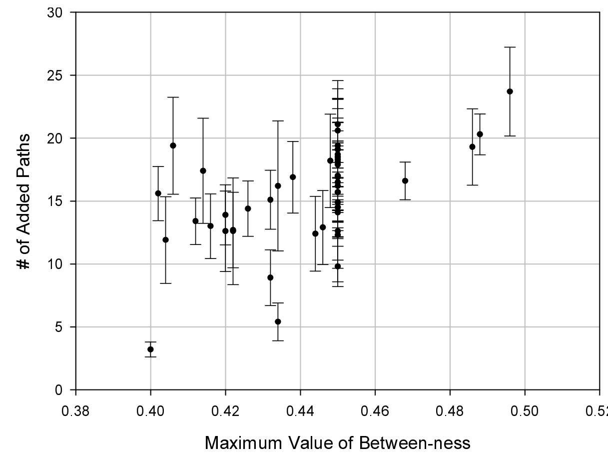
where m_p is the number of virtual networks whose average numbers of additional paths are less than a certain threshold R_{goal}, and m_{fn} is the number of virtual networks which are identified as the virtual networks that require more than R_{th} additional optical paths but require only less than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

$$FPR = {}^{m_{fp}}/_{m_n}, \qquad (3)$$

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.



(a) Flow Inclusive Relation Modularity



(b) Maximum Betweenness

Figure 6. Partial Comparison of Virtual Networks with Their Maximum Betweenness from 0.4 to 0.5

In this section, we investigated 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. 7 shows the relationship between FNR and FPR in the case of FIRM. In Fig. 7, R_{th} is set to 10. The horizontal axis indicates the FNR, and the vertical axis indicates the FPR.

In the same manner, Fig. 8 shows the relationship between FNR and FPR in the case of maximum betweenness centrality. In Fig. 8, R_{th} is set to 10. The horizontal axis indicates the FNR, and the vertical axis indicates the FPR.

Comparing Fig. 7 with Fig. 8, the method using FIRM achieves both lower FNR and lower FPR at the same time. This result means that FIRM identifies 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

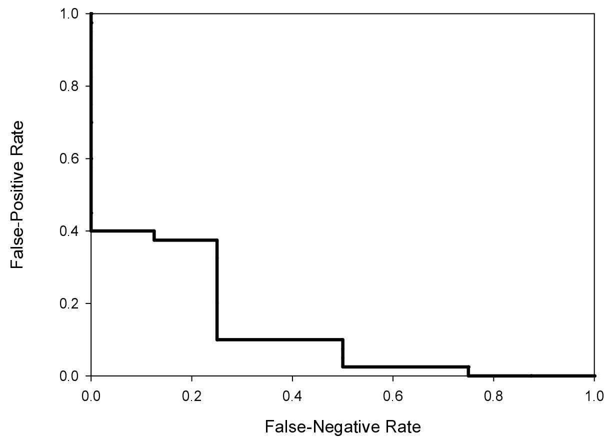


Figure 7. The Relationship between FNR and FPR Using FIRM

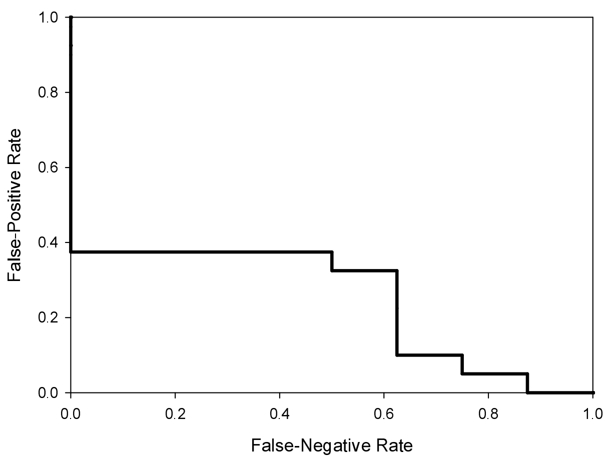


Figure 8. The Relationship between FNR and FPR Using Maximum Betweenness

should construct the virtual network whose FIRM is large.

V. Conclusion and Future Work

In this paper, we proposed the flow inclusive relation modularity (FIRM) as an index to identify the virtual network, which can handle significant traffic changes by reconfiguring only a small number of optical paths. Through the evaluation of relationship between the FIRM and the number of optical paths required to be added, we clarified that the FIRM identifies the virtual networks, which can accommodate any traffic changes with a small number of additional paths. Our future work includes a method to construct virtual networks with the large FIRM. For example, if the virtual network has low adaptability and the link utilization are increasing, some optical paths should be added 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, some optical paths should be deleted 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.

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