Master's Thesis

Title

Strategy of making reliable and efficient interdependent networks

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Abstract

The Internet plays an important role as a social infrastructure. Because of its importance, it needs to keep connectivity and be able to communicate without serious drop of flow rate even if network equipment breaks or disasters happen. However, there are a lot of large-scale incidents so that today’s Internet is no longer sufficiently reliable. There are a lot of studies to enhance the reliability of a single network but they are insufficient because the Internet consists of mutual connections among many of ASes. Therefore, it is required to figure out which nodes in each network should be used for mutual connections. In this thesis, we show what properties of nodes to use for high reliability and efficiency constructing interdependent networks. Nodes in networks are classified into two properties, Central and Peripheral, based on eigenvector centrality. We generate interdependent networks by connecting Central nodes and Peripheral nodes variously. Then, we evaluate the reliability and efficiency of them before and after failures. Evaluation results showed that high reliability and efficiency are achieved by using nodes around core nodes as interdependent nodes.

Keywords

Interdependent Networks
Efficiency
Reliability
Network Design
Eigenvector Centrality

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1 Introduction

Recently, the Internet plays an important role as a social infrastructure. The Internet provides various services, such as transportation systems or financial transaction, and it becomes an essential one for our life. Because of its importance, it needs to keep connectivity and be able to communicate without serious drop of flow rate even if network equipment breaks or disasters happen.

However, as the size of the Internet becomes large, then it is more difficult to be robust. This is because a large number of ASes which construct the Internet makes mutual connection based on their individual determination. Since there is no network administrator who manages whole of the Internet, it may take more time to investigate reasons of failures or recover damage for a large-scale network. For example, in August 2014, serious performance problems of communication networks, such as disconnection or bad throughput, were occurred. The reason was considered about influence of ISP's maintenance at first but in fact, it was due to BGP (Border Gateway Protocol) table. The routers with small memory cannot study growing BGP table. As another example, according to Ministry of Internal Affairs and Communications, there are dozens of serious failures which affect 30,000 people and continue over 2 hours per year from 2008 to 2013 [1]. Some of the failures affect more than a million people or continue all the day. Through these incidents, today's Internet is no longer sufficiently reliable. However, since the Internet has to meet the role as a social infrastructure even if failures occur, it is required to design more reliable networks against failures.

The reliability of a network is dependent on the structure of a topology within a network. Therefore, the relationship between reliability and the physical topology within each AS has been studied for enhancing reliability of networks. Dodds et al. [2] evaluated the relationship between connection structure among nodes with each layer and the robustness for congestion or failures, focusing on layer structure of networks. It is well-known that a power-law network, such as the Internet, is reliable against random node failures but loses its connectivity easily when nodes with high degree are failed [3]. In another example, Ref. [4] showed that the relationship between reliability and characteristic of network structure, such as layer structure and power-law attributes.

However, the previous studies are insufficient to enhance the reliability of the Internet. It is because most of them consider a single network although the Internet consists of mutual connections among many of ASes. To enhance the reliability of the Internet, it is required to figure out which routers in each network should be used for mutual connections. This is because difference of connecting structure affects the routes of traffic flow. Ref. [5, 6] showed that when the connecting structure between networks is not suitable, it can cause long delay and high packet loss rates. In this thesis, we therefore investigate on the connecting structure between networks, not only on the structure of a single network.

Some studies discuss connecting structure between two or more networks, interdependent networks. Refs. [7,8] analyzed the relationship between the difference of connecting structure among networks and the reliability of a whole network. The former study focused on connecting structure among ER or scale-free network models and the latter study focused on connecting structure between a port network and airport network. These studies revealed that as degrees of nodes at both ends of an inter-network link (interdependent nodes) are closer and interdependent nodes in the same network are more tend to be connected each other. In addition, it was also revealed that these structural properties make the networks more robust for cascade failures. Brummit et al. [9] showed that too many interdependent links increases the risk of large-scale failures because interdependent links help to propagate failures from one network to connected networks. Domenico et al. [10] focused on a hierarchical network with multiple layers, and addressed that the strength of connection between layers determines the connectivity of nodes. In the case of interconnections between communication networks, these evaluations are not sufficient for two reasons. One is that they did not consider about traffic flow. Their evaluations are only based on topological metrics. However, in communication networks, traffic flow is so important because the quality of communication is dependent on not only connectivity but also on the traffic concentration of some nodes. The other reason is that they did not consider about which nodes are used for constructing an interdependent network. Even in the studies about AS networks, most of them focus on which AS to connect, not on what properties of nodes to use. The difference of connecting structure between networks is dependent on which nodes are connected. Therefore, it needs to think about the amount of traffic flow on links and which nodes are connected for making an interdependent network.

In this thesis, we will reveal that what node properties are required and how nodes of each network connect with each other when making interdependent networks for enhancing the reliability of a whole network. We simply think the case where two networks are connected (Figure 1). Between two networks, there is a cooperative relationship in which the information of nodes

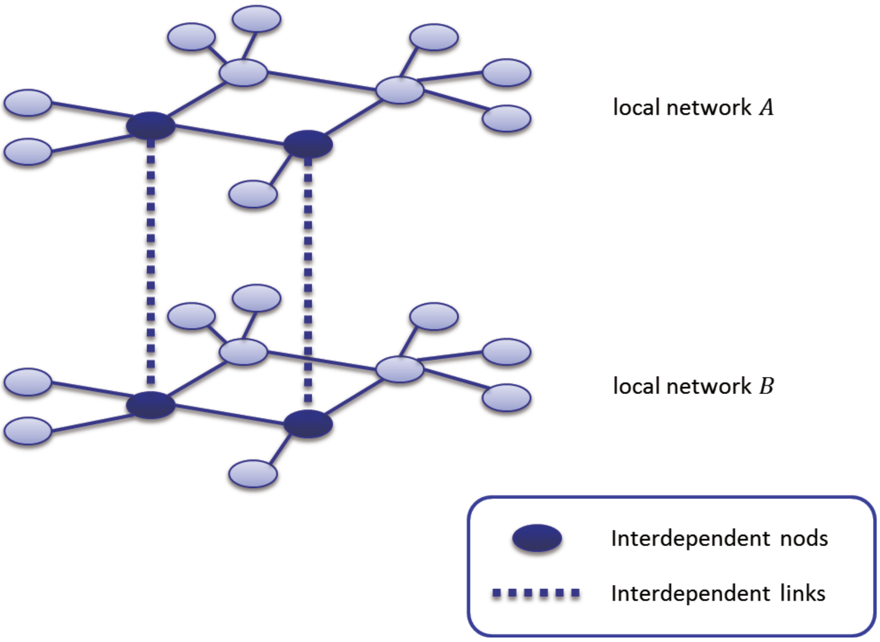

Figure 1: Image of an interdependent network

that are required to connect between networks can be exchanged each other. In this situation, we will provide an approach to generate an interdependent network and evaluate the reliability of generated interdependent networks before and after failures. As our approach, at first, nodes are classified as Central (high centrality) and Peripheral (low centrality) according to their roles of nodes in the network. Next, we prepare some connection strategies such as CC (Central node connects to Central node) or CP (Central node connects to Peripheral node), and construct interdependent networks with different inter-connected structure by the connection strategies. We will evaluate the reliability from the viewpoint of not only topological metrics but also traffic flow when failures occur. Finally, we will reveal a connecting strategy for enhancing the reliability of a whole network.

This thesis is organized as follows. We survey interdependent networks in Section 2. Section 3 shows our strategy making interdependent networks. In Section 4, we evaluate performance of interdependent networks and its reliability against node failures. Finally, Section 5 concludes this paper.

2 Examples of Interdependent Networks

An interdependent network is a networks formed by connecting some small networks each other. Recently, it is discussed enthusiastically interdependent networks, focusing on the connecting structure among networks. To construct an interdependent network by connecting communication networks, we investigate the studies about interdependent networks in various fields.

At first, we investigate interdependent networks of communication networks. For constructing stable and efficient networks, connection strategies are revealed when ASes made peering links [11]. Peering means that ASes can exchange their traffic each other without any charge. ASes construct interdependent networks to be stable and efficient networks. A stable network means a complete network. Because of many available routes of communication, a stable network is reliable against failures. An efficient network means a network with large profits. The authors make a model of total profit using profits of transit links and costs for constructing interdependent links. In the purely non-cooperative game where three ASes decide on peering agreements individually, they solve for Subgame Perfect Nash Equilibria through backward induction. They analyzed the other decision made by each AS and revealed that the stable network is not efficient network and vice versa. Note that, this study focuses on which ASes to connect but do not focus on which nodes to connect.

As a research discussed which nodes to connect for interdependent networks, we investigate Ref. [12]. This study assumes an interdependent network of Web networks. The authors focus on eigenvector centrality, and nodes in networks are classified into Central (high centrality) and Peripheral (low centrality) according to eigenvector centrality of nodes. Eigenvector centrality is defined as the eigenvector $\vec{x}$ which correspond with the first eigenvalue λ_{max} of the adjacency matrix M. The centrality of node i is given by the ith factor of $\vec{x} = \{v_1, v_2, ..., v_N\}^T$ (N is the number of nodes in network) and it is known for the metrics of importance of a node's neighbors. They assume that two networks are competitive relationship for enhancing eigenvector centrality of its own network (sum of eigenvector centrality of nodes in its own network). Under this situation, they discuss what properties of nodes to use. As a result, for the strong network (whose largest eigenvector centrality is higher than that of an opposite network), connecting with peripheral nodes can increase the eigenvector centrality of its network. On the other hand, for the weak network B (whose largest eigenvector centrality is lower than that of an opposite network), connecting with central nodes can increase the eigenvector centrality of its network. However, in the communication networks, there is no reason that ASes behave to enhance eigenvector centrality of networks. Probably they construct interdependent networks for enhancing reliability.

The reliability of interdependent networks is studied in Ref. [7, 8, 10]. Ref. [7] focuses on the connecting structure between ER networks and BA networks. Ref. [8] focuses on the connecting structure between port and airport networks. The authors show that they can obtain reliable interdependent networks as connecting to enhance two metrics. One is inter degree-degree coefficient (IDDC) and the other is inter clustering coefficient (ICC). IDDC represents the tendency that degree of nodes at the both end of interdependent links are close. ICC represents the tendency that interdependent nodes are connected each other. In addition, the reliability of an interdependent networks composed of civil transportation systems are evaluated in Ref. [10]. They revealed that the interdependent networks are more resilient to random failures than each individual network. The evaluation of these studies is based on only topological metrics. However, it is required to think about link capacity. Therefore, when connecting communication networks, flow rate needs to be considered.

For these investigations, in the field of interdependent networks, it is revealed that which ASes to connect when considering costs. Also, connecting strategies for enhancing eigenvector centrality of networks are discussed and figured out what properties of nodes should be used to connect. Moreover, for enhancing the reliability, the topological metrics constructing interdependent networks are revealed. However, for enhancing reliability in communication networks, it remains unsolved that what properties of nodes should be used.

3 Construction of Interdependent Networks

As discussed in the previous section, it is important to consider the connecting structure among networks for designing reliable and efficient networks. We reveal what properties of nodes to be suitable for interdependent nodes when two networks make interdependent links cooperatively for the common goal of constructing a reliable and efficient interdependent network. Here, reliable represents that a network can keep the connectivity among nodes as much as possible even if failures occur, and efficient represents that a network can communicate with high throughput. In this section, we first explain a basic strategy and some premise on making an interdependent network. Second, we define the properties of nodes to use. Finally, we refer to connecting strategies to generate interdependent networks.

3.1 Basic Strategy for Communication Networks

When constructing an interdependent network by connecting communication networks under the number of interdependent links is not limited, resilience of the interdependent network between networks is the highest if all nodes have interdependent links. That is, it is more difficult to cut off an interdependent network when failures occur. However, it is not realistic because of a lot of operational cost. Owing to this, under the number of interdependent links is limited, ASes have to construct an interdependent network to enhance the reliability.

A problem is what properties of nodes to make interdependent links. The properties represent the role or importance of nodes. One of approaches is to attach interdependent links to nodes in the core part of networks, thinking as in the past. Nodes in the core part of networks are the placed at the center of networks and play an important role in networks. Another approach may use nodes around periphery nodes. In this thesis, we investigate which is better whether core or periphery nodes for interdependent nodes.

To classify nodes into core and periphery, what criteria should be used? In our study, we use eigenvector centrality as criteria. Eigenvector Centrality indicates the importance of a node's neighbors, and can be high because a node has either numerous or important neighbors. In the communication networks, eigenvector centrality can be regarded as the amount of traffic through nodes. Intuitively, it is natural that the amount of traffic traversing a node increases when its neighbors also process so much traffic. Hence, using eigenvector centrality of nodes, we can suppose how much traffic is processed on each node, i.e. the importance of each node in networks. Thereby, Nodes with high eigenvector centrality can be regarded as core nodes and nodes with low eigenvector centrality can be regarded as periphery nodes, such as placed on the edge of networks. Although the study focusing on an interdependent network of Web pages [12] also use eigenvector centrality as criteria to classify nodes, their goal of the interdependent is to enhance eigenvector centrality of networks (the sum of eigenvector centrality of each node in network). Because in communication networks regarding eigenvector centrality as traffic, enhancing eigenvector centrality of only a part of nodes means enhancing loads of them, as for our study, we construct an interdependent network to enhance reliability and efficiency, not to enhance eigenvector centrality.

In the real world, the information of opposite networks is required to calculate eigenvector centrality of opposite networks. However, in today's Internet, the structure within ASes is not opened information because they are competitive relationship. It may be hard to know the information such as eigenvector centrality of an opponent network. However, under cooperative relationship, the essential information required for interdependent can be shared. For example when making peering links, they can be cooperative relationship to achieve common goal [13]. Therefore, here, we consider that ASes make peering links. They construct an interdependent network cooperatively for common goal of achieving high reliability and efficiency.

3.2 Criteria of Central and Peripheral Nodes

In this section, we explain criteria of Central and Peripheral nodes. For reference [12], the nodes are classified into Central nodes and Peripheral nodes based on eigenvector centrality of nodes. Eigenvector centrality is calculated as the first eigenvector $\vec{x}$ of the adjacency matrix M. Centrality of node i is the ith factor of $\vec{x} = \{v_1, v_2, ..., v_N\}^T$ (N is the number of nodes). Eigenvector Centrality indicates the importance of a node's neighbors, and can be high because a node has either numerous or important neighbors. In the communication networks, eigenvector centrality can be regarded as the amount of traffic through nodes. Intuitively, it is natural that the amount of traffic traversing a node increases when its neighbors also process so much traffic. Hence, we can regard nodes with higher eigenvector centrality as more important nodes.

According to eigenvector centrality, we classify nodes into Central and Peripheral. Central nodes are the placed at the center of networks. They process a lot of traffic. On the other hand, Peripheral is interpreted as not the edge of networks but around Central nodes. Their role is to aggregate traffic and pass to Central nodes all at once.

3.3 Making Reliable and Efficient Interdependent Networks

Assume an interdependent network constructed of network A and B. We consider four connecting strategies based on Central and Peripheral of interdependent nodes as follows.

- CC: Central node in network A connects to Central node in network B
- CP: Central node in network A connects to Peripheral node in network B
- PC: Peripheral node in network A connects to Central node in network B
- PP: Peripheral node in network A connects to Peripheral node in network B

When choosing interdependent nodes, we consider following intentions. One is that each node in network A and B with closer distance are connected. This is because, it is known that the costs of constructing links are dependent on their length [14], we consider connecting nodes in the closer place in each network. For example, in CC, a Central node in the east of network A connects a Central node in the east of network B. As a result, we can get interdependent networks with different connecting structure between networks. The other is that interdependent nodes in a network with far distance geographically are selected. As usual, interdependent nodes should be selected so as not to concentrate on one place. Owing to concentration of interdependent nodes on one place, all interdependent nodes might be broken simultaneously when large-scale disasters occur. For example, considering the topography in the United States, it is better to pick nodes from New York, Chicago and San Francisco than to pick nodes from only New York. This is because, interdependent nodes should be selected so as not to concentrate on one place, we think about the module structure of network. We use the information of module structure of networks to distinguish nodes with geographically different place. According to the information of module structure and eigenvector centrality of nodes, Central and Peripheral nodes are defined as follows.

- Central

  We pick nodes with links between modules as the candidate of Central. We calculate eigenvector centrality for adjacency matrix of a local network. In each module, a node with the highest eigenvector centrality is defined as Central node.

- Peripheral

  We calculate eigenvector centrality with adjacency matrix of each module, which means the regarding each module as network. In each module, a node with the highest eigenvector centrality is defined as Peripheral node. Peripheral nodes can be chosen as the same nodes as Central but we allow that.

Assuming that the number of Interdependent links equals to the number of modules at first of evaluation. It is the situation that the place of interdependent nodes is well distributed. However, it is better that the number of interdependent links is few as much as possible. Therefore, we regard the number of interdependent links as a parameter, and consider decreasing the number in evaluation.

4 Evaluation of Interdependent Networks

4.1 Simulation Environment

4.1.1 Local Networks

Assume an interdependent network constructed of network A and B. We use ISP topologies, AT&T as network A and B. The details of topologies are showed in Table 1. Since all nodes have the properties of states according to its location information, we regard one state as one module. However, there are some exceptions because of the size of states. In AT&T topology, 82 nodes belong to California while only one node belongs to Kentucky. Since small-scale states (with a few nodes) are a part of large-scale states (with many nodes) generally, it is not suitable for using such nodes as interdependent nodes, under the purpose of obtaining distributed interdependent nodes. Thereby, small-scale states are not regarded as modules. 12 states remain after excluding small-scale states, where the number of nodes in states is less than 11. To the contrary, there is a so large-scale state. The number of nodes in California is about 1.5 times larger than that of in New York, which is the second largest state. In addition, the area of California is large and its domain expands from north to south widely. To select interdependent nodes adequately, here, we divide California into two states heuristically. Consequently, we can obtain 13 states as shown in Figure 2. In this figure, nodes are colored by module structure. The same colored nodes are in the same module and non-colored nodes are in small-scale modules. We choose interdependent nodes from each state. In Table 1, the values in the state column represent "the valid number of states (the real number of states)".

Table 1: ISP topologies

ISP	Nodes	Links	States
AT&T	523	1304	13 (40)

4.1.2 Link Capacity

The link capacity of links in an interdependent network, c_i, is defined as follows.

- links within network A

  The link capacity of links within networks A is set based on the amount of traffic through

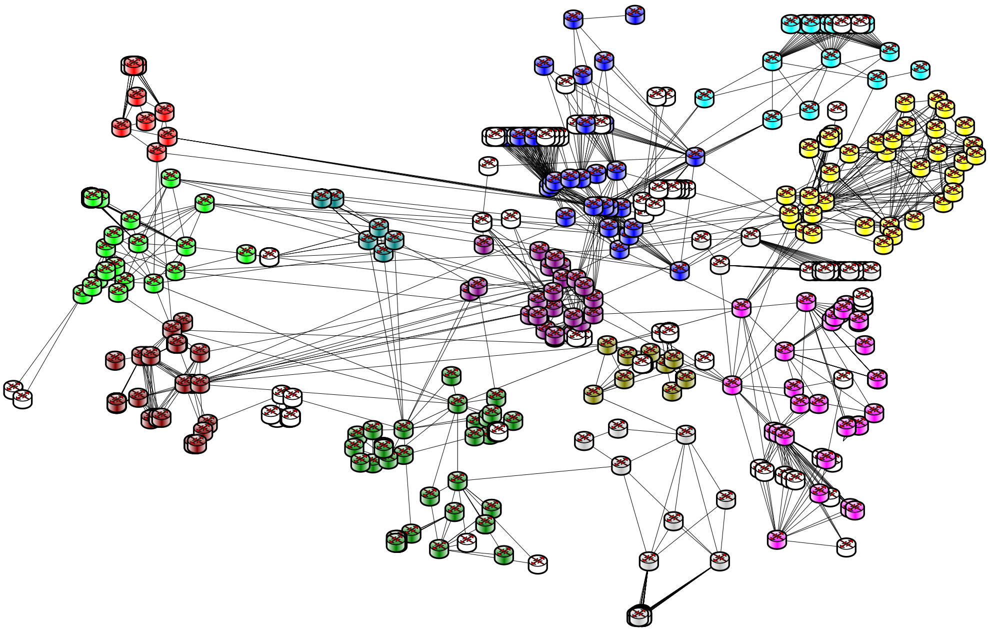

Figure 2: AT&T topology

its link when all node pairs in network A communicate.

- interdependent links

  The link capacity of interdependent link i is based on the amount of traffic S_i through its link when all node pairs in interdependent network communicate. Then, the capacity of interdependent link i is defined as

$$c_i = \frac{S_i}{N_A * N_B} * C_{total}, \tag{1}$$

  where C_{total} denotes the total capacity of interdependent links and N_A and N_B denote the number of nodes in network A and B.

4.2 Performance Metrics

4.2.1 Hop Length

We evaluate the connectivity of networks by hop length. It becomes shorter if topology is well-connected. d_{pq} denotes hop length of node pairs $(p, q)(p, q \in V, p \neq q; V$ is the set of nodes in an interdependent network.$)$. It is calculated by Dijkstra's shortest path algorithm.

4.2.2 Edge Betweenness Centrality

We evaluate the loads on links by edge betweenness centrality. e_i denotes edge betweenness centrality for link $i \in E$. It is defined as

$$e_i = \Sigma_{s \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}}, \tag{2}$$

where σ_{st} is the number of shortest paths from node s to node t and $\sigma_{st}(i)$ is the number of shortest paths from node s to node t that pass through link i.

4.2.3 Flow Rate

We evaluate the throughput of communication by flow rate. F_{pq} denotes flow rate when node pairs $(p, q)(p, q \in V, p \neq q)$ are communicated. The input variables and steps of calculation are as follows.

- Input variables
    - L_{pq}

      L_{pq} is the set of links which communication path of (p, q) pass through. Communication path is calculated by Dijkstra's shortest path algorithm.
    - c_i

      c_i denotes the link capacity of link $i \in E$.
- How to calculate

  Assuming that $P_{undecided}$ is the set of node pairs whose flow rate are not decided and B is the set of bottleneck links which are not chosen.

  At first, we initialize each variable as follows.
    - $P_{undecided}$

      Add all node pairs (p, q) which communicate into $P_{undecided}$, excepting for node pairs which are not reachable.
    - B

      Add all links in an interdependent network into B.

- C_i

  C_i denotes the vacant capacity of link $i \in E$. It is given by link capacity c_i initially.

- S_i

  S_i denotes the number of traffic flows which pass through link $i \in E$. It can be calculated as $S_x \leftarrow S_x + 1$ on $x \in L_{pq}$, where x is a link passed through when all node pairs (p, q) communicate.

Next, flow rate of each node pairs is calculated according to following steps.

step.1 As long as $P_{undecided} = \emptyset$, loop for the following steps 2 and 3. If $P_{undecided} = \emptyset$ is true, move to step 4.

step.2 Look for the bottleneck link $k \in E$. A bottleneck link is a link whose available capacity per flow is the lowest. Assuming link $i \in B$'s available capacity per flow is given by $f_i = C_i/S_i$, the bottleneck link k is calculated by $k = \arg\min_i f_i$. Then, remove k from B.

step.3 Calculate flow rate F_{pq} of a node pair (p, q) which passes through link k. $F_{pq} = f_k$ when the set of communication path include k ($k \in L_{pq}$) on node pair $(p, q) \in P_{undecided}$. Then, remove (p, q) from $P_{undecided}$. Furthermore, update vacant capacity C_i and the number of traffic flows S_i on each link i in L_{pq}.

$$\begin{cases} C_i \leftarrow C_i - F_{pq} \\ S_i \leftarrow S_i - 1 \end{cases} \tag{3}$$

step.4 End.

4.3 Performance of Interdependent Networks before Failures

In this section, we evaluate the performance of interdependent networks before failures. Using the simulation, interdependent networks which made of CC, PP, CP and PP are compared. We set the number of interdependent links to 13, which equals to the number of modules, and the sum of link capacity of interdependent links C_{total} to the number of node pairs which communicate between networks. We take a look at communication within a local network and communication between local networks. The former is called intra-communication and the latter is called inter-communication. Under any circumstances, intra-communication never passes through interdependent links. Our evaluation are simulated from view of network A. Thereby, the number of node pairs of intra-communication is calculated as $N_A(N_A - 1)$ and the number of node pairs of inter-communication is calculated as $N_A N_B$.

We describe again that we evaluate the usual performance in this section. However, in this paper, our goal is to evaluate the reliability and the efficiency of interdependent networks. We want to compare the performance before and after failures. Therefore, in this section, we just investigate the performance of interdependent networks and do not discuss which connection strategy is superior.

First, we evaluate hop length. We omit the results of intra-communication because they are all equal regardless of connection strategy. Figure 3 shows average hop length $\overline{d}$ of inter-communication. $\overline{d}$ is calculated as $d = \Sigma d_{pq}/N_A N_B$, where N_a, N_B is the number of nodes in network A, B. In this figure, X-axis shows each connecting strategy and Y-axis shows average hop length $\overline{d}$. We can see that $\overline{d}$ is the shortest in CC network and is the longest in PP network. Although $\overline{d}$ in both of CP and PC network is the same, this is because the topology structure of network A and B is the same now.

Then, we think about module structure. We divide inter-communication into two type; communication of node pairs in the different module communication of node pairs in the same module. Note that, module we say here represents module which we said in Section 4.1.1. Figure 4 shows average hop length of node pairs in the different module. The definition of X-axis and Y-axis is the same to the definition of Figure 3. The relationship of magnitude of values is the same. However, as for communication of node pairs in the same module, it is not like the results of communication of node pairs in the different module. In Figure 5, X-axis shows the name of module (State) and Y-axis shows average hop length in each module. We can see that in 9 modules, average hop length is the shortest in PP network and is the longest in CC network. This is because, Peripheral nodes are closer than Central nodes from nodes in the same module. The role of Peripheral nodes is aggregating traffic in module so that these results are so natural. In the remaining 4 states, where average hop length of CC network is shorter than that of PP network, we can consider the reasons as follows. (i) In State PA, average hop length is all equal because Central node equals to Peripheral node. (ii) In State NY, although Central node also equals to Peripheral node, in CC network, there are some node pairs which can communicate using interdependent links in other

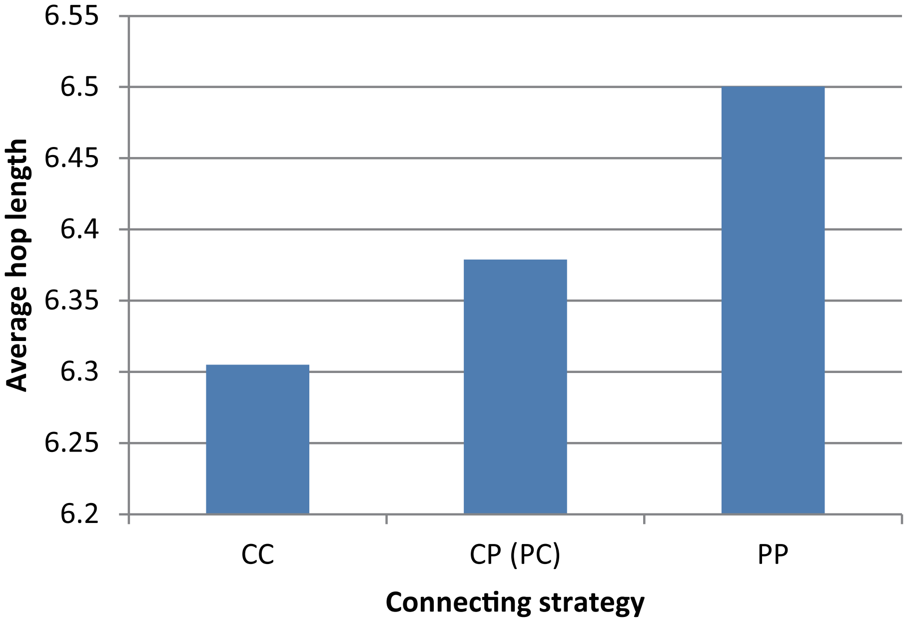

Figure 3: Average hop length before failures

modules for shorter hop length. As a result, average hop length becomes shorter but it may not be recommended. Since there are a lot of traffic in links between modules usually, using links between modules for communication of node pairs in the same module can impose more loads on links between modules. (iii) (iv) In State TX and CA2, it is due to the structure of module. We really want average hop length of node pairs in the same module in PP network to be shorter than that of in CC network. The one of the reasons of not achieving that is the complex structure of AT&T topology. Actually, we may need to more discuss method of dividing modules.

Second, we show edge betweenness centrality of links. In Figure 6, X-axis shows each connecting strategy and Y-axis shows the variance of edge betweenness centrality of links within network A. We can see that the value is the largest in CP network and is the smallest in PC network. The value in CC network is near to the value in PP network. Next, we show the variance of edge betweenness centrality of interdependent links in Figure 7. Since the topology of network A and B is the same, the amount of traffic through each interdependent link in CP and PC network is the same. Because the variance of edge betweenness centrality in CP and PC network is the same, we focus on CC and PP network. The value of PP network is near to the value of CP/PC network,

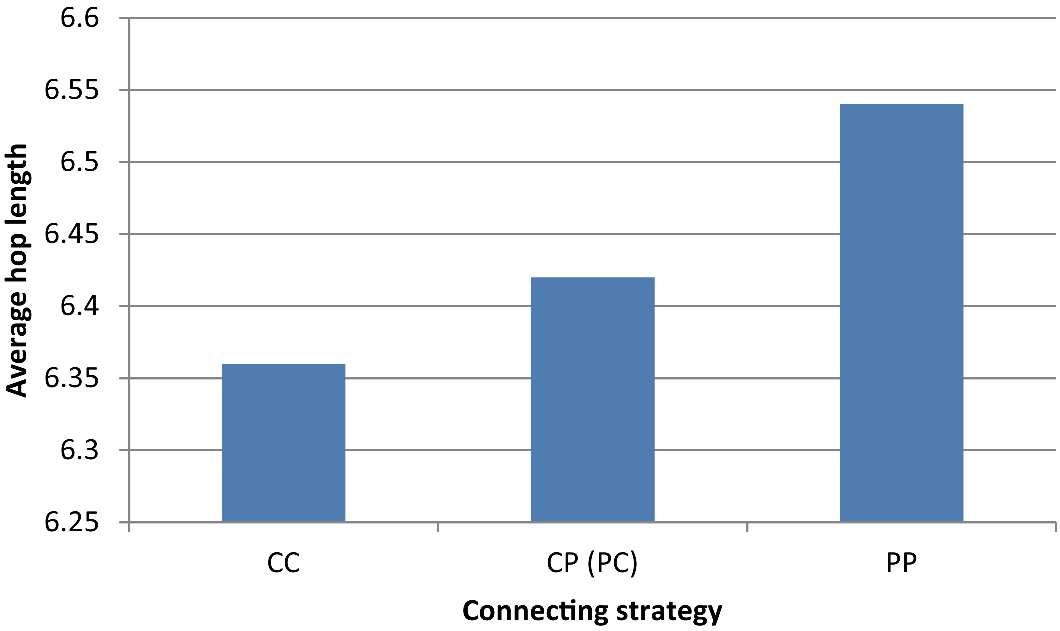

Figure 4: Average hop length of node pairs in the different module before failures

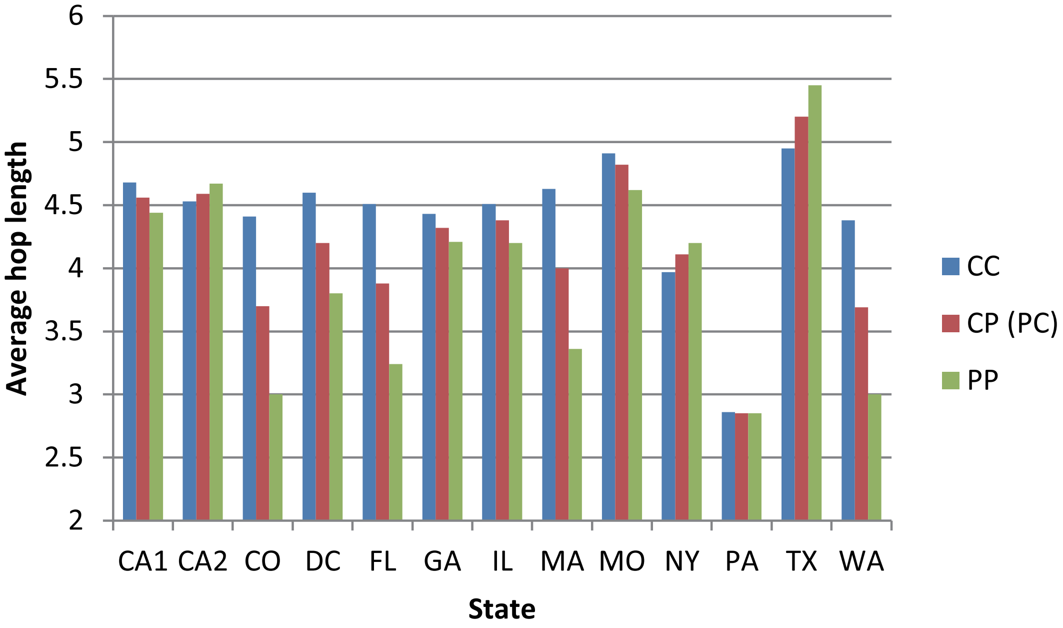

Figure 5: Average hop length of node pairs in the same module before failures

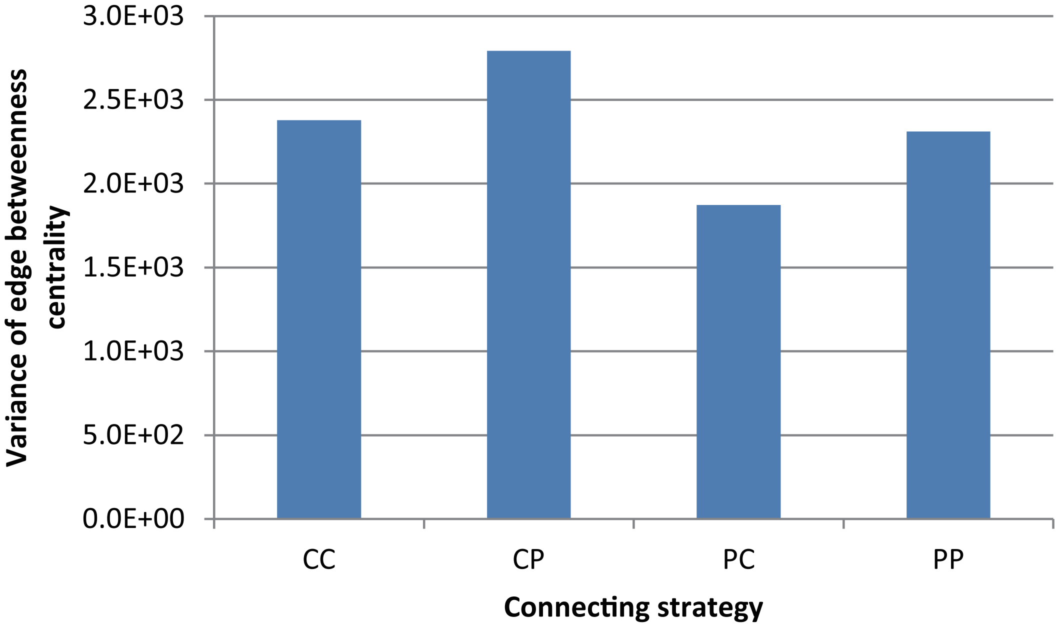

Figure 6: Variance of edge betweenness centrality of links within network A before failures

while the value of CC network is about twice larger than the value of other network. The result represents that some interdependent links are imposed on a lot of loads. In other words, traffic concentrates on a part of interdependent links.

Third, we show flow rate. Figure 8, 9 shows the average flow rate of intra-communication. Here, we focus on node pairs in network A as intra-communication. In these figures, X-axis shows the hop length of node pairs and Y-axis shows the average flow rate per hop length of node pairs. Figure 9 is extended of Figure 8 for seeing the difference clearly. We can see that, in CC and CP network which use Central nodes in network A as interdependent nodes, the average flow rate of long-range communication becomes low. On the other hand, in PC and PP network which use Peripheral nodes in network A as interdependent nodes, the average flow rate is still large even in long-range communication.

Next, we show the average flow rate of inter-communication. As for inter-communication, hop length of node pairs is dependent on connecting strategy. Since we cannot use the same graph as intra-communication, we focus on the module structure as with the evaluation of hop length. Figure 10 shows the average flow rate of node pairs in the same module and Figure 11 shows the

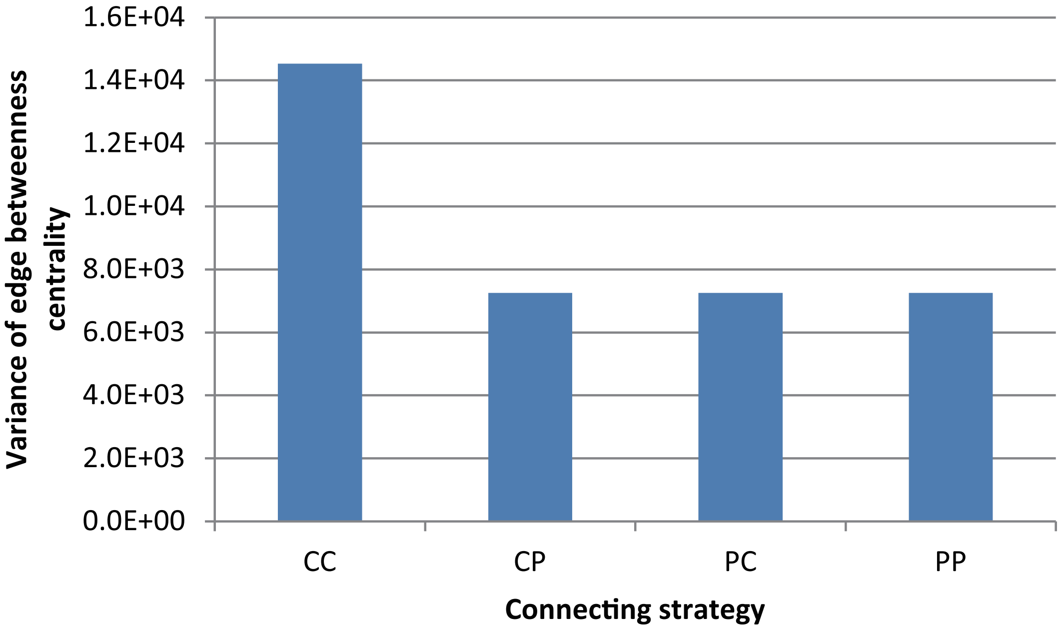

Figure 7: Variance of edge betweenness centrality of interdependent links before failures

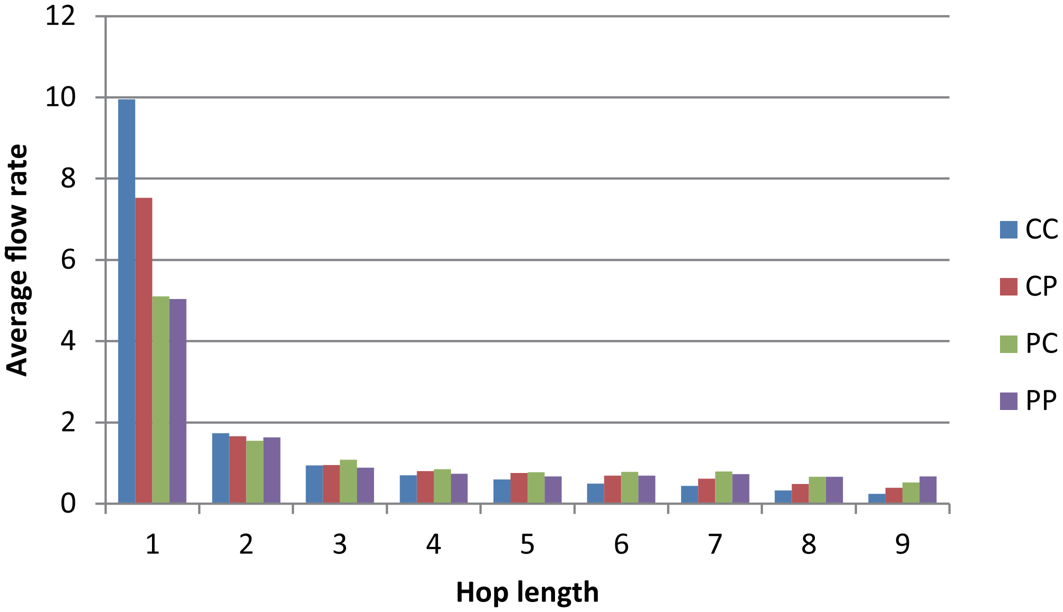

Figure 8: Average flow rate of intra-communication before failures

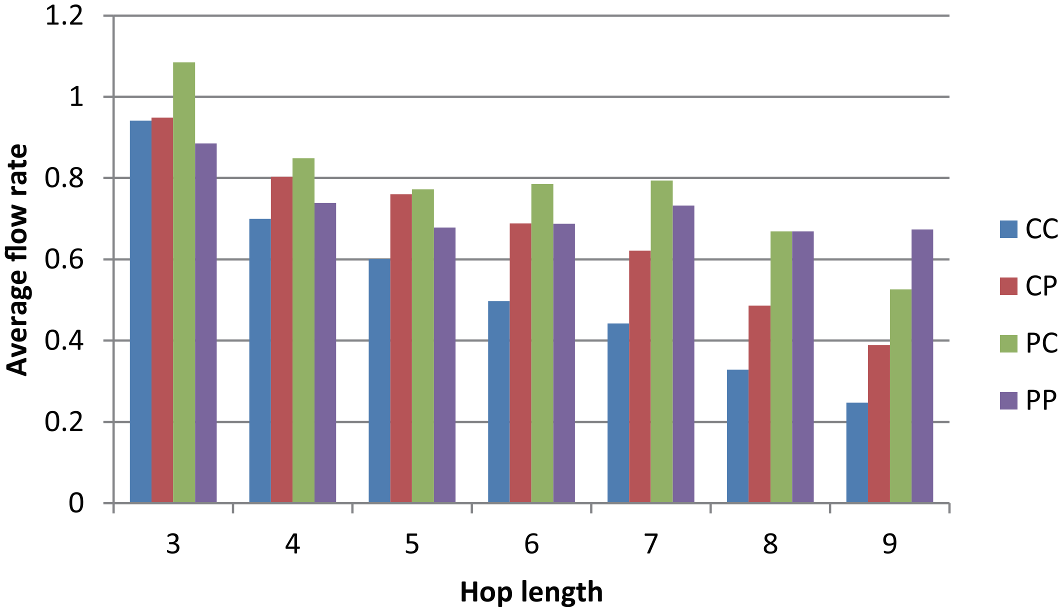

Figure 9: Average flow rate of intra-communication before failures ($d_{pq} \geq 3$)

average flow rate of node pairs in the different module. In these figures, X-axis shows individual connecting structure. We can see that it achieves higher flow rate of node pairs in the same module by using Peripheral nodes regardless of network A or B. However, simultaneously, it caused low flow rate of node pairs in the different module.

4.4 Performance of Interdependent Networks after Failures

In this section, we evaluate the performance of interdependent networks after a node failure compared to values before failures. We can assume accidental failures of equipment. Hence, we evaluate performance of interdependent networks when a single node failure occurs. In a single node failure, a node in a network is broken at random. We assume that the probability of a failure on each node is equal. Besides, we use the same topology as network A and B. Thereby, we assume that the node in network B in the same place of broken node in network A is also broken simultaneously.

First, we evaluate hop length. We omit the results of intra-communication as in the previous section because they are all equal. Figure 12 shows average hop length of inter-communication. In this figure, X-axis shows each connecting strategy and Y-axis shows average hop length. Note that,

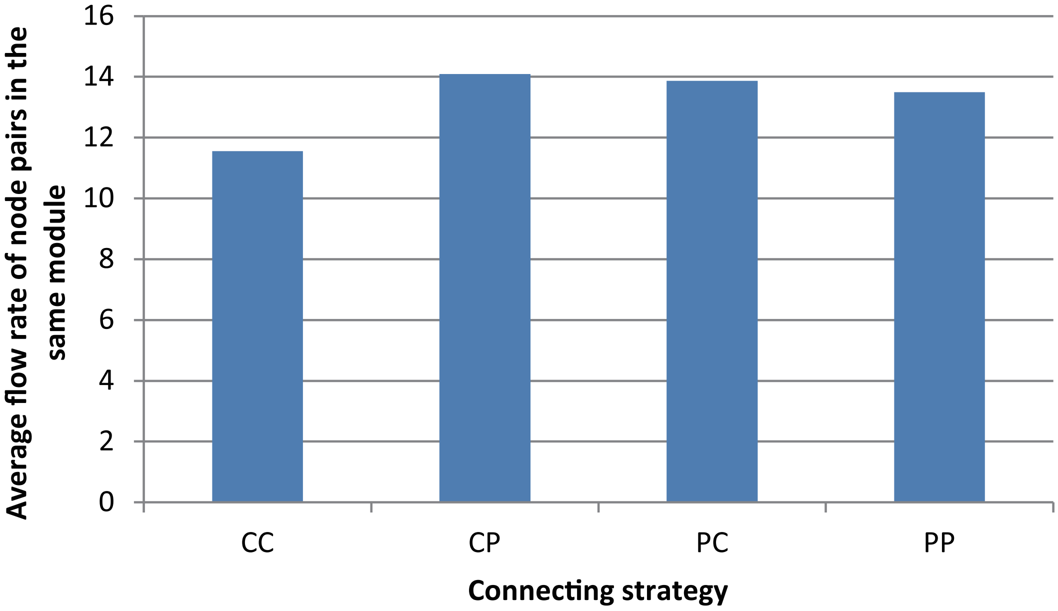

Figure 10: Average flow rate of node pairs in the same module

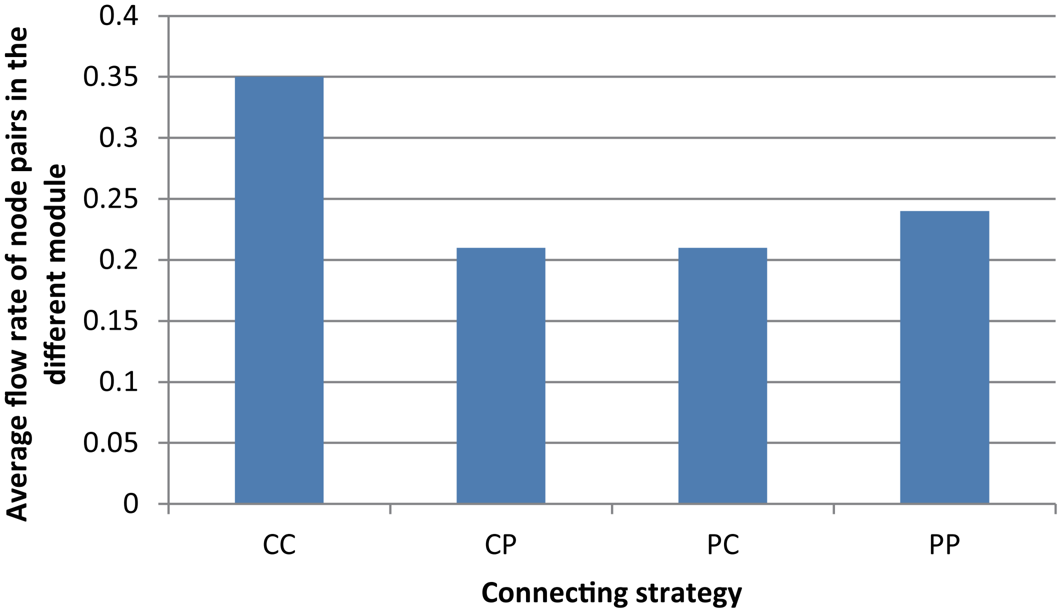

Figure 11: Average flow rate of node pairs in the different module

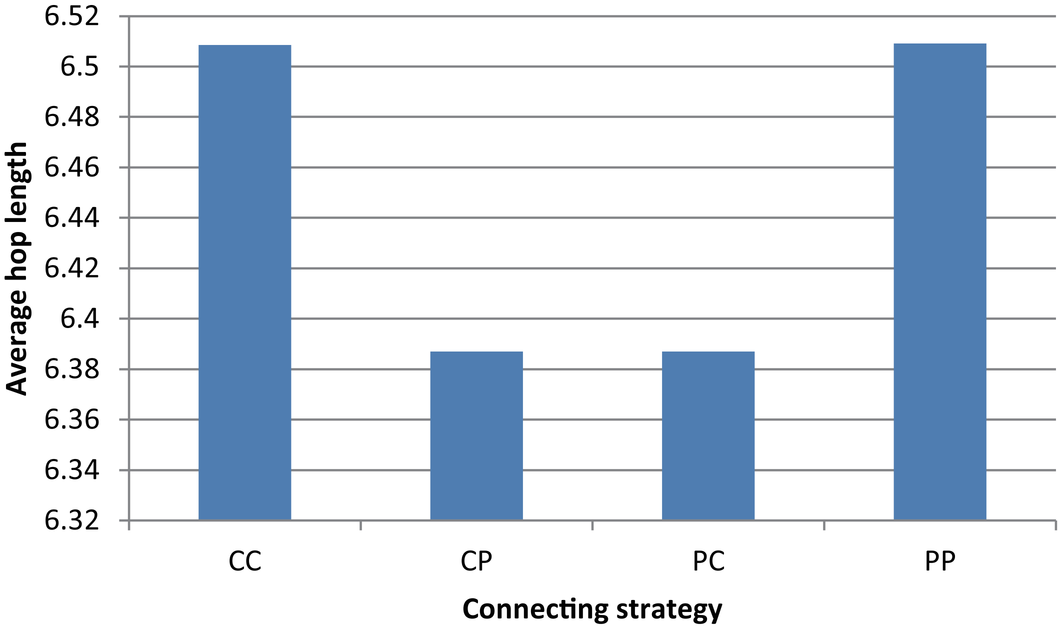

Figure 12: Average hop length after a single node failure

average hop length here is calculated as average of average hop length of all pattern of a single node failure. We can see that the values of CC and PP network are large and the values of CP and PC network are small. However, it is how a failure affect interdependent networks that we really want to know. Therefore, we show the increasing rate of average hop length in Figure 13. The increasing rate is calculated as the ratio of the value after failures to the value before failures. In this figure, X-axis shows each connecting strategy and Y-axis shows the increasing ratio. Blue bar represents average of average hop length of all pattern of a single node failure. Red bar represents the maximum increasing ratio, such that meaning worst case. We can see that CC network receive the worst influence from failures, compared to other connecting strategy. In addition, PP network can keep the increasing rate low even in the worst case. Thus, it is revealed that PP network is not affected largely by failures.

Second, we show edge betweenness centrality of links. Here, we focus on the result of breaking the node with the largest node betweenness centrality. Node betweenness centrality is calculated as the sum of edge betweenness centrality of its connecting links. As a rule, nodes of large node betweenness centrality treat a lot of traffic. Such nodes work harder and harder, so they may

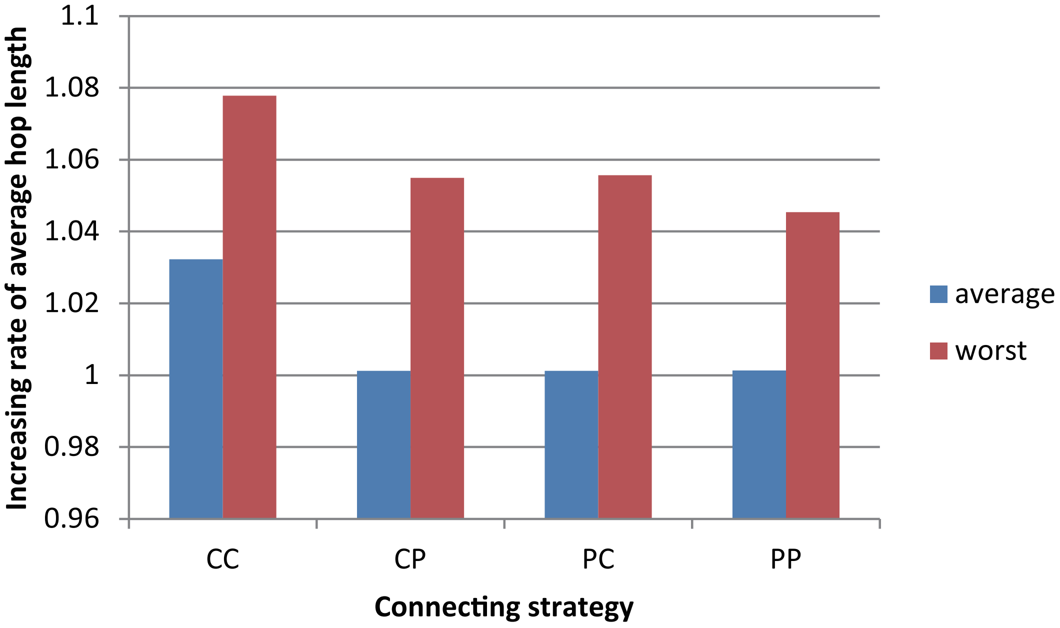

Figure 13: Increasing rate of hop length after a single failure in average and worst case

be likely to break down. In addition, breaking nodes which pass much traffic may affect a whole network. Therefore, we can assume the larger failure with serious damage by simulating failures of the node with the largest node betweenness centrality.

We show edge betweenness centrality of links within network A in Figure 14. In this figure, X-axis shows each connecting strategy and Y-axis shows the variance of edge betweenness centrality of links within network A. We can see the same relationship of magnitude of values as Figure 6. Then, we focus on individual link, and investigate how much whether the value has increased. We show the increasing rate of edge betweenness centrality in Figure 15. Increasing rate is calculated as the ratio of the value after failures to the value before failures. In this figure, X-axis shows each connecting strategy and Y-axis shows the worst increasing ratio. The worst increasing rate is defined as the maximum of increasing rate. We can see that the increasing rate in PC network is the largest and the increasing rate in PP network is the lowest. In other words, in PP network, traffic flow which had to change routes by failures is well-balanced distributed to many links.

Next, we show edge betweenness centrality of interdependent links in Figure 16. The definition of X-axis and Y-axis is the same to the definition of Figure 14. Then, we focus on individual

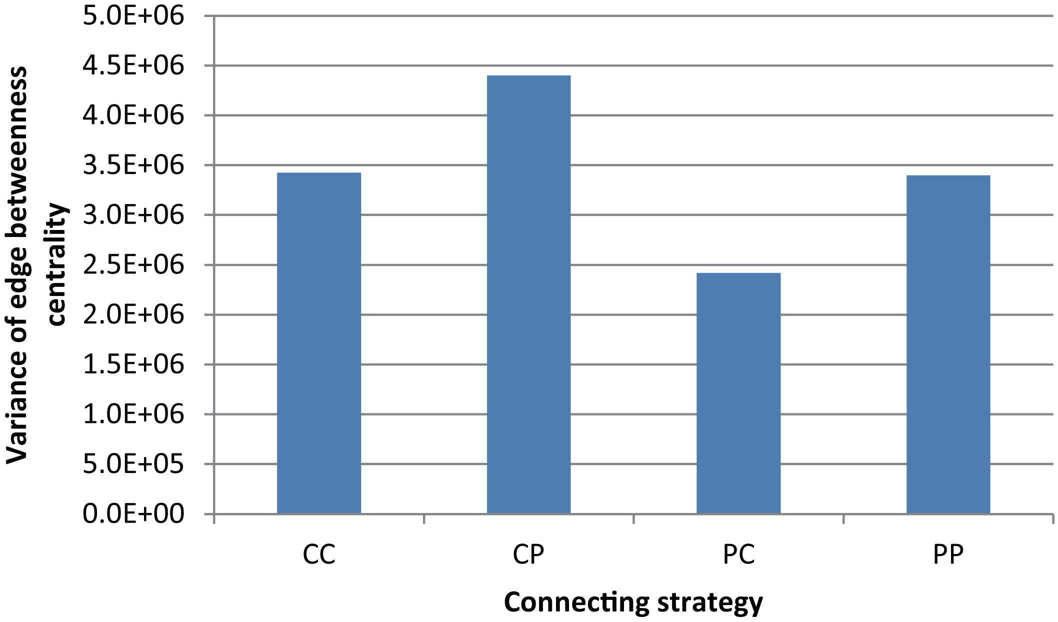

Figure 14: Variance of edge betweenness centrality of links within network A after a single node failure

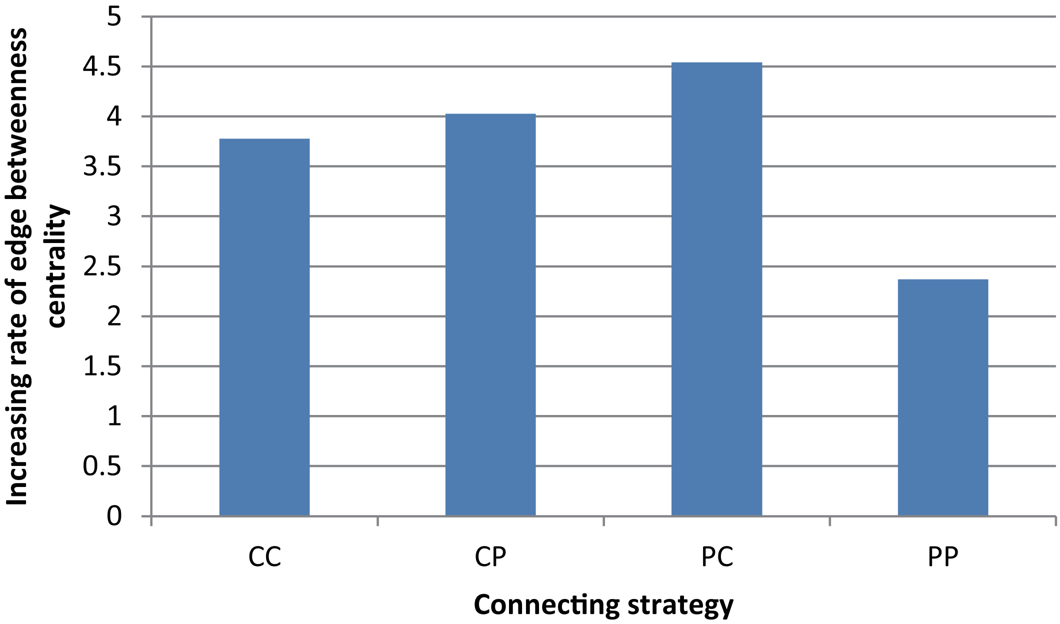

Figure 15: Increasing rate of edge betweenness centrality of links within network A after a single node failure

link as with the former. Note that, in CC, CP and PC network, the number of interdependent links decreases when the node with the largest node betweenness centrality breaks down. Since the number of interdependent links affects connectivity between networks, we keep in mind of high reliability of PP network. PP strategy is not using core nodes in network. Thereby, PP network can keep connectivity between networks, even if some nodes with large betweenness centrality break down.

Then, we take a look at the increasing rate of interdependent links in Figure 17. In this figure, X-axis shows each connecting structure and Y-axis shows the worst value of increasing rate. We can see that the increasing rate in PP network is the largest. Although interdependent links do not broken down, and although the variance of edge betweenness centrality is low, why would such results? To reveal this, we investigate the values of edge betweenness centrality of individual link. We figure out that the link with the largest increasing rate is the link with the lowest betweenness centrality originally. Although the increasing rate is large, the value is not large actually. Traffic which had to change routes concentrate on a part of nodes but the amount of traffic passed through the link is equal to or less than that of other links. This suggests that the reliability of PP network may not be inferior to other networks.

Third, we show flow rate. For all pattern of a single failure, we focus on fluctuation of flow rate between before and after failures. As for intra-communication, we show the results when non-interdependent nodes break in Figure 18. In this figure, X-axis shows the rank of node betweenness centrality of broken nodes and Y-axis shows the number of node pairs decreasing flow rate by failures. This represents that the smaller values are better. We can see that the values can be kept low for PC network, so it is revealed that PC network is the most reliable. However, it is too simple to use PC strategy for constructing interdependent networks. This is because, this results represent flow rate of node pairs in only network A. From a viewpoint of network B, PC strategy equals to CP strategy. We can see that the values are larger in CP network. When network A wants to use PC strategy, does network B agree with such unfair connection? Then, we pick up the results of CC and PP network and show them in Figure 19. We can see that the values in CC network are mostly larger than the values in PP network. The discussion about CP and PC strategy are also applied to intra-communication. Therefore, in the following evaluation, we will show the result in CC and PP network. As for inter-communication, we show the results when non-interdependent nodes break in Figure 20. The definition of X-axis and Y-axis are the same as Figure 19. We can

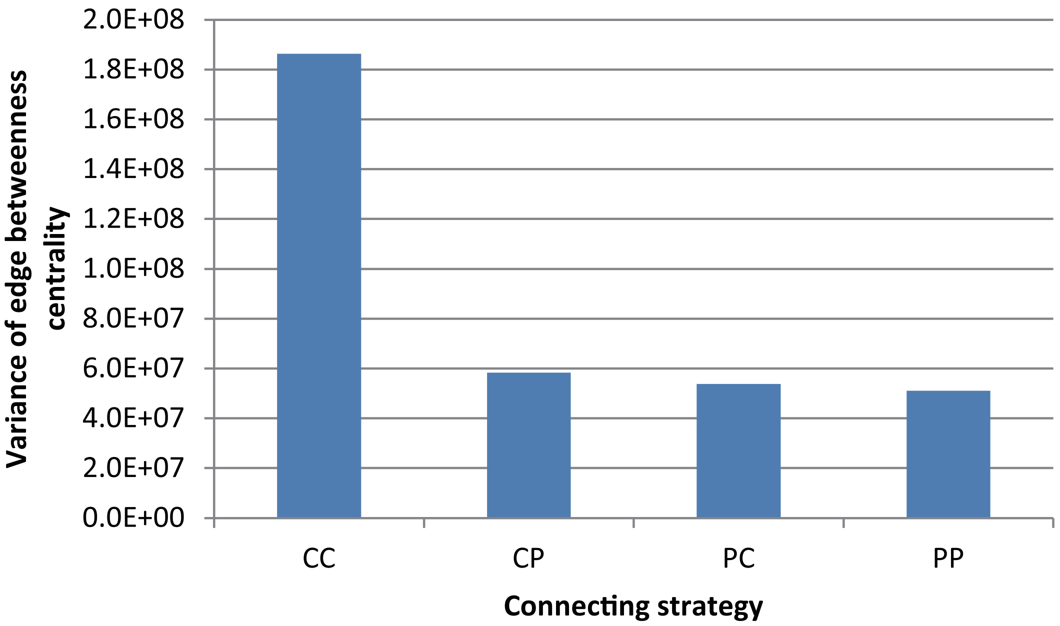

Figure 16: Variance of edge betweenness centrality of interdependent links A after a single node failure

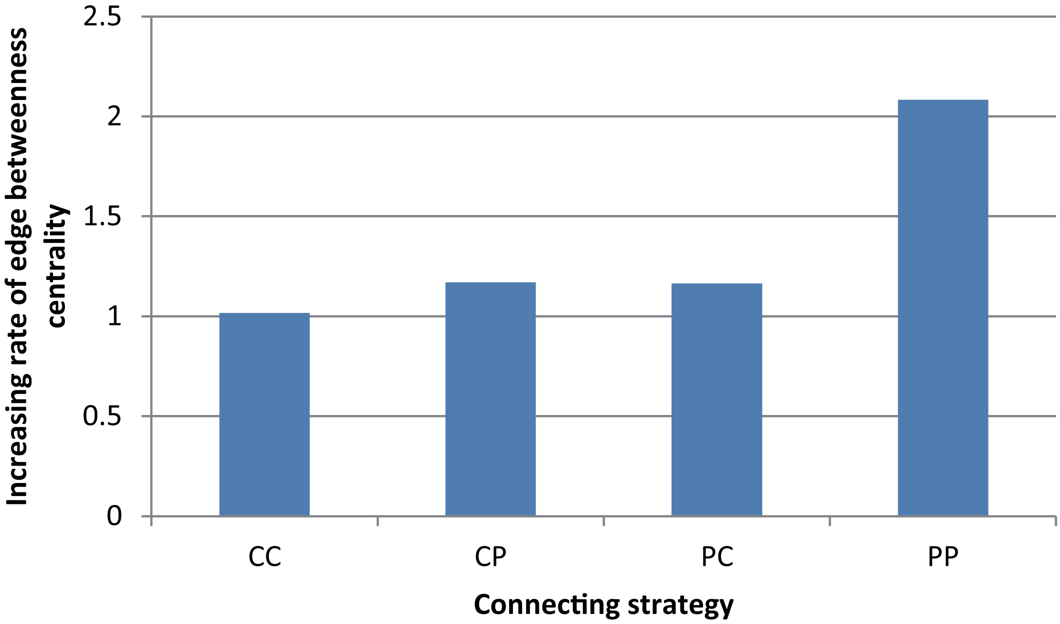

Figure 17: Increasing rate of edge betweenness centrality of interdependent links after a single node failure

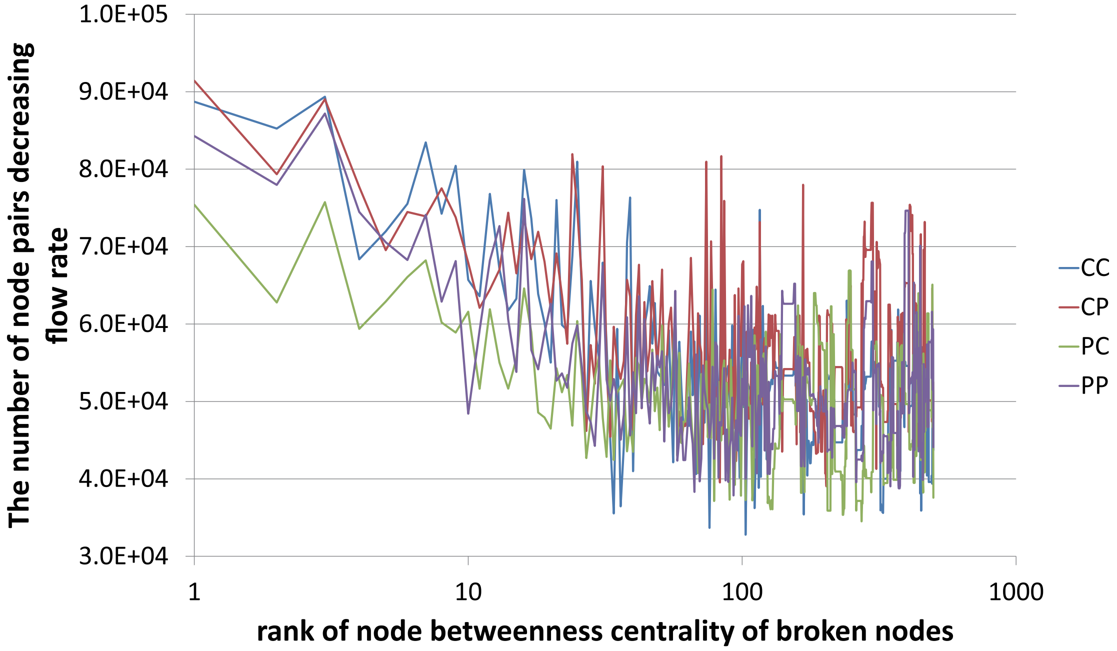

Figure 18: The number of node pairs of intra-communication decreasing flow rate when non-interdependent nodes fail

see that the values in CC network are larger than the values in PP network. In other words, CC network is affected by failures more than PP network. For these results, when we compare CC and PP network, PP network is more reliable than CC network.

Next, we show flow rate when interdependent nodes fail. Figures 21 and 22 show the results of intra-communication and Figures 23 and 24 show the results of inter-communication. In these figures, X-axis shows the rank of node betweenness centrality of broken interdependent nodes. In Figures 21 and 23, these represent the case where Central nodes break down. In Figures 22 and 24, these represent the case where Peripheral nodes break down. Y-axis shows the number of node pairs decreasing flow rate by failures. We can see that many node pairs have bad flow rate in PP network at the right side of graph. We think, this is because the number of interdependent links equals to the number of modules. Peripheral nodes exist in center of module. In other words, Peripheral nodes are near to edge of networks. Thereby, when Peripheral node breaks down, nodes which have to change routes are assumed to use interdependent nodes in other modules. Under such circumstances, Peripheral nodes in other modules are far from nodes looking for new routes than Central nodes. To prevent this, it is easy to increase interdependent link in a module. In fact,

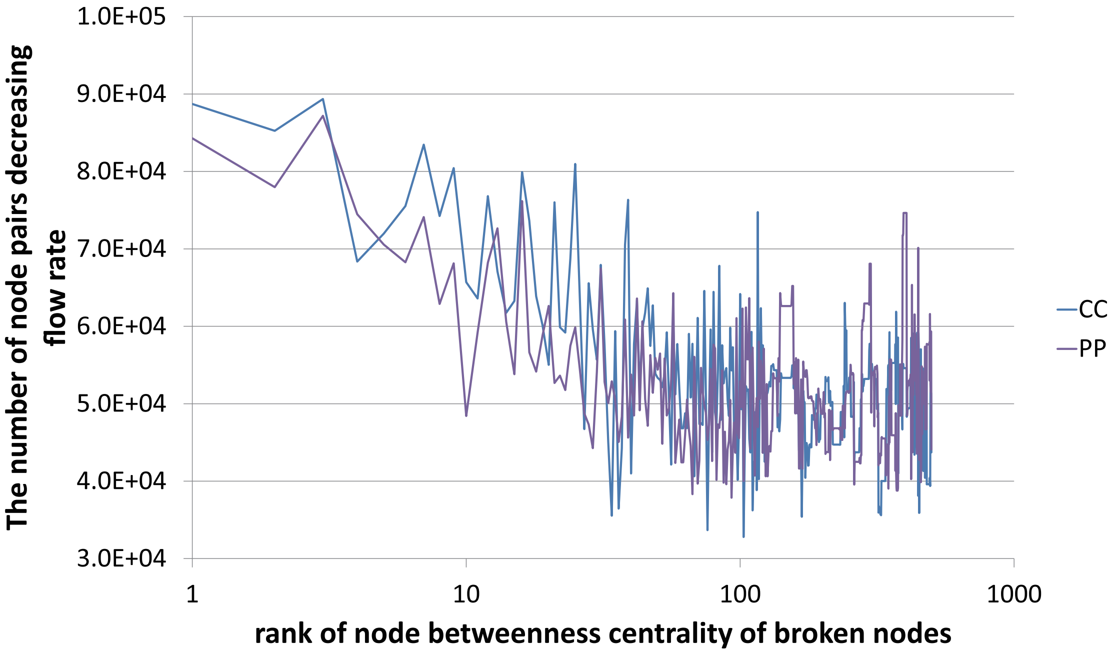

Figure 19: The number of node pairs of intra-communication decreasing flow rate when non-interdependent nodes fail (CC, PP)

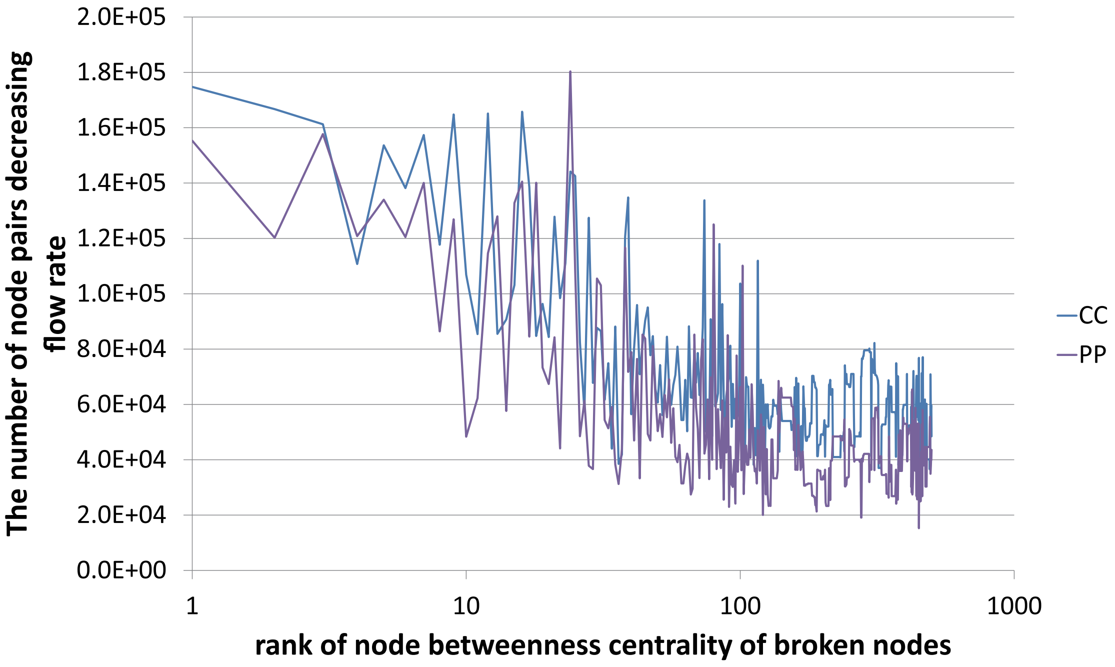

Figure 20: The number of node pairs of inter-communication decreasing flow rate when non-interdependent nodes fail

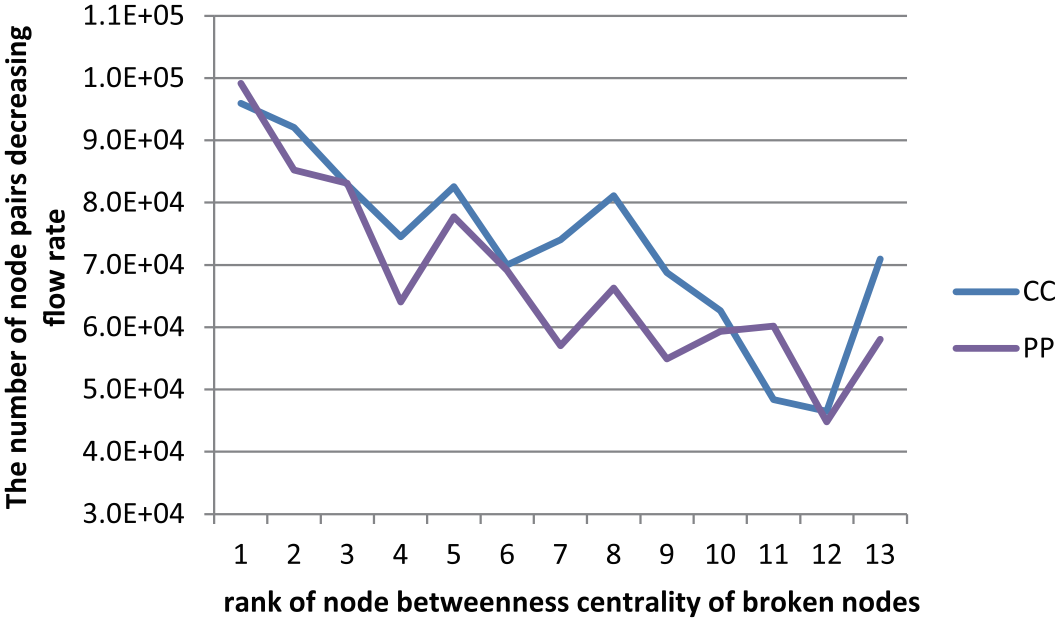

Figure 21: The number of node pairs of intra-communication decreasing flow rate when Central nodes fail

however, ASes are connected to the more than two ASes. When ASes connect to some ASes, the number of PP interdependent links can be increased by using some Peripheral nodes to each connection besides distributed loads. We have already revealed that PP networks are more reliable than other networks. Therefore, we can conclude that we achieve high reliability by placing plural PP interdependent links in each module.

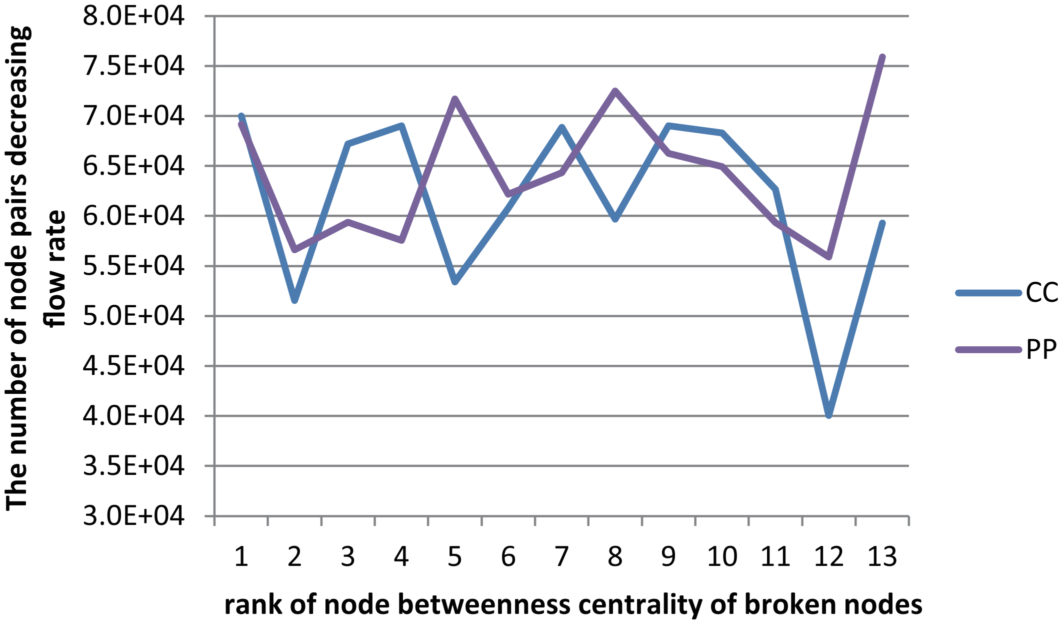

Figure 22: The number of node pairs of intra-communication decreasing flow rate when Peripheral nodes fail

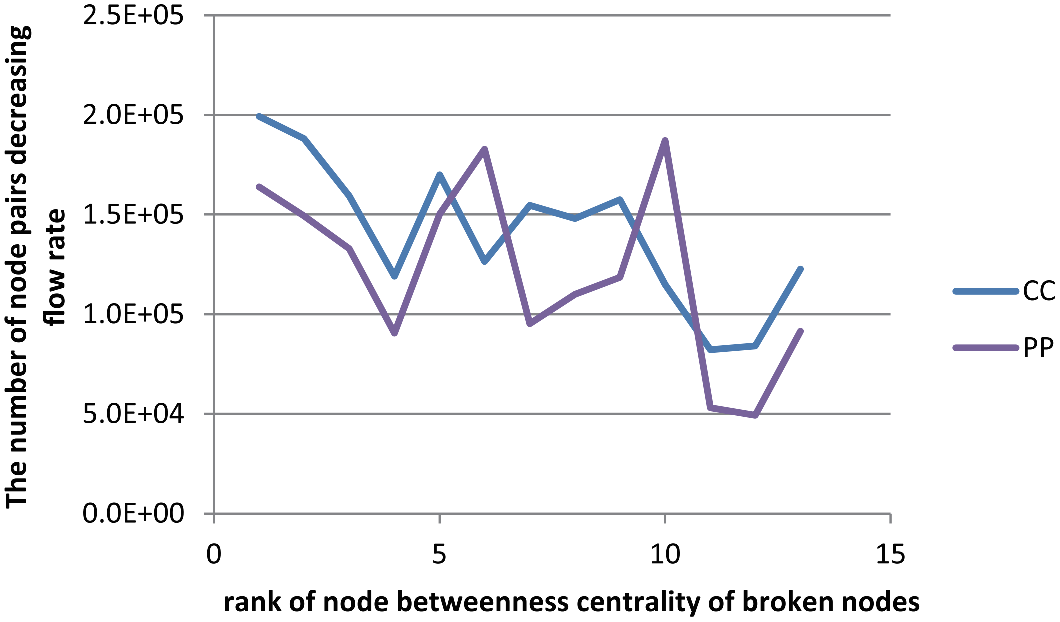

Figure 23: The number of node pairs of inter-communication decreasing flow rate when Central nodes fail

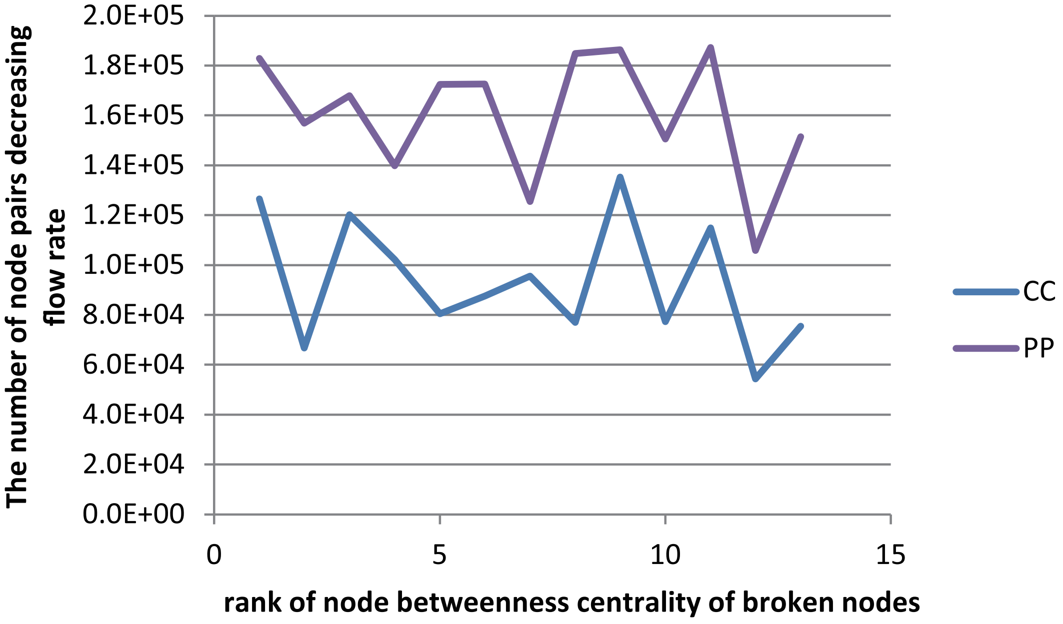

Figure 24: The number of node pairs of inter-communication decreasing flow rate when Peripheral nodes fail

5 Conclusion

In this thesis, we revealed that what node properties are required and how nodes of each network connect with each other when making interdependent networks for enhancing the reliability of a whole network. At first, nodes are classified as Central (high centrality) and Peripheral (low centrality) according to their roles of nodes in the network. Next, we prepare some connection strategies and construct interdependent networks with different inter-connected structure by them. We evaluated the reliability and efficiency from the viewpoint of not only topological metrics but also traffic flow when failures occur. The results showed that high reliability and efficiency are achieved by using nodes around core nodes as interdependent nodes. Especially, using periphery nodes as interdependent nodes can divide route of communication within networks and that of between networks. Owing to this, we can achieve high flow rate even if failures occur.

In the future work, we will evaluate the case where two local networks are not the same. Furthermore, we will apply out method to construct interdependent networks in various fields.

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