Topological Evolutionary Methods for the Reliable and Sustainable Internet

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Preface

The Internet is currently the largest network system in the world, and is becoming ever larger. The number of Autonomous Systems (ASes) and interconnecting links between ASes in the Internet have increased corresponding to the increase in traffic on the Internet. The Internet traffic has rapidly increased due to the increase in the number of users communicating via the Internet, mobile devices and network services. Since these are expected to increase ever in the future, it is considered that the traffic on the Internet will continually increase.

As the Internet has become a social and economic infrastructure, it is essential that the Internet continually accommodates the increase in traffic, which we call sustainability. For the sustainable Internet, ISPs have to continually exchange traffic even if the traffic on the ISP increases. For this, there remain challenges to be addressed. One of challenges is relaxing traffic concentration on a part of links. Traffic concentration occurs on links between ASes aggregating more traffic. As the traffic concentration becomes heavy on a link, cooling costs for routers in ASes connecting the link greatly increase and ASes need to rapidly invest in an improvement of network equipments. In addition, not only ASes connecting links where traffic is heavily concentrated, but also each of ISPs has to continually improve network equipments against the traffic increase. However, since the improvement of network equipments takes cost, it is crucial for each ISP to have sufficient benefit. That is, each of ISPs should get an economic utility through traffic exchange with other ASes. To resolve these challenges, discussion about the future topological evolution is important. This is because a degree of traffic concentration on links and an economic utility of an AS are heavily dependent on traffic flow which changes based on the evolution of the Internet topology. Traffic has to be steadily relayed not only between ASes but also within an intra-domain network of the AS. However, failures of network equipments may occur in an intra-domain network in an AS. Therefore, an intra-domain network that is reachable even if failures of network equipments occur is required to achieve the steady communication within an AS.

We begin this thesis with discussion about the evolution of the Internet topology to relax the traffic concentration. We first identify links where more traffic is concentrated. For this purpose, we develop a method to identify the hierarchical nature of traffic aggregation, in which traffic sent from a regional AS is gradually aggregated to an AS that connects global links. Our basic approach is to extract the "flow hierarchy", which is a hierarchical structure associated with the hierarchy of traffic aggregation, from the Internet topology. With the flow hierarchy, we analyze the structural evolution of the Internet topology from 2000 to 2013. Our results show that the amount of traffic on link between AS aggregating more traffic, which is at higher level of the flow hierarchy, has rapidly increased. We then consider a new evolution process to avoid traffic concentration, and examine how this process could slow down the traffic concentration compared with the actual evolution of the Internet topology. The basic approach behind our evolution process is to construct more links between ASes aggregating relatively small traffic. We show that the process relaxes traffic concentration to less than half compared to the current Internet.

Our next concern is whether each of ISPs can continually improve network equipments against the increase in traffic or not. With an economic utility through traffic exchange with other ASes, ISPs can improve the network equipments against the increase in traffic. An economic utility is heavily depending on the traffic flow which changes corresponding to the topological evolution of the Internet. The Internet topology evolves by link constructions of ASes with their own policies to select ASes to connect links with. We therefore first investigate the change of an economic utility of ISPs and traffic amount on ISPs through the topological evolution from past up to the present. Our results show that half of ISPs does not obtain a sufficient economic utility against increase in traffic, and the ratio tends to increase in recent years. We then develop and evaluate the evolution policies for an AS to select ASes to connect link with for relaxing unsustainable state of an ISP. From the results, we show that an economic utility of each ISP is improved by our policies, and most ISPs become to get a sufficient economic utility against the traffic increase.

Finally, we discuss improving reliability of an intra-domain network in an AS. For this purpose, we investigate topological structures that should be embedded to make router-level topologies more reliable on the basis of knowledge in biological systems. We evaluate the topological structure of a transcriptional regulatory network for several species that have a much longer evolutional history than information networks. In particular, we focus on collaboration structures that the transcription network includes more than the router-level topologies. In collaboration structures, two or more transcription factors co-regulate other transcription factors. Collaboration structures contribute to making the topologies reliable because they introduce multiple paths between transcription factors, and are therefore generally more reliable against failures in transcription factors. We rewire links in the router-level topology such that the topologies have more amount of collaboration structures, and show that the provided topologies are more reliable against failure of routers than the original router-level topologies.

Through these discussions, this thesis reveals the current Internet faces to problems of sustainability for the increase in traffic although it is possible that the Internet can evolve to become more sustainable. In addition, the topological properties for the sustainable Internet are revealed, and the evolution process to make the Internet more sustainable is also shown. We believe that these knowledge is worth considering when operators and researchers who engage in developing network design discuss a future Internet design and architecture for the traffic increase.

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Chapter 1

Introduction

1.1 Background

The Internet is currently the largest network system in the world, and is becoming ever larger. The number of ASes and interconnected links of between ASes has doubled over the last decade; there were 46,120 Autonomous Systems (ASes) and 172,271 links at Nov. 2014. The number of ASes has increased corresponding to the traffic increase on the Internet. The traffic amount on the Internet had increased by five times since 2012 [1]. Cisco forecasted that the traffic amount would increase at about 21% of an annual growth rate from 2013 to 2018 [1] owing to the current increase in the number of mobile traffic [2] and traffic from new and emerging applications using, e.g., sensor devices with a communication function [3].

The Internet is currently used in various fields such as the financial trading, medical services and government services, i.e., it has a role of a social and business infrastructure. To meet a requirement as the social and business infrastructure, it is essential that the Internet continually accommodate the future increase in the traffic amount, and we call the characteristic as sustainability. However, traffic concentration which is caused by the increase in the traffic amount degrades the sustainability of the Internet. By the traffic concentration, cooling costs for routers in an AS greatly increase and the ASes need to heavily invest in improvement of network equipments. As a result, the ASes cannot steadily exchange traffic. Therefore, the traffic concentration has to be relaxed for the sustainable

Internet.

In the current Internet, each AS tries to form new links with ASes that have not yet been connected according to the traffic concentration on existing links. Since the Internet is a decentralized system that consists of thousands of independent ASes of various business types such as Internet Service Providers (ISPs) and contents providers, each AS selfishly selects ASes to connect. Generally, an AS attempts to connect links with other ASes to improve performance and to increase an economic utility through traffic exchange with other ASes. For the purpose, an AS usually has its own policy for selecting which ASes to connect with from among many candidates. To reveal criteria that ASes use when they construct a link, some studies modeled policies of ASes to select ASes to connect links with. Ref. [4] studied what feature of policies leads the current structural properties of the Internet topology. From the results, it is found that some topological properties of the Internet topology, such as the power-law degree distribution, non-decreasing clustering coefficient [5] as the evolution of the topology size, result from link constructions of each AS for improvement of its economic utility. Ref. [6] also proposed a simple dynamic model that captures salient features of the provider selection process, and revealed that most ASes today select its provider based on price, rather than performance or other criteria.

In the current Internet, each AS constructs links based on the local decision of two ASes, and do not consider a global structure of the Internet topology. However, a degree of traffic concentration on links is heavily dependent on the global structure of the Internet topology [7]. This is because traffic flow changes based on the change of the global structure of the Internet topology. That is, the local decision-making is inadequate to fundamentally avoid the future traffic concentration associated with the traffic increase. Therefore, an evolution that considers the global structure of the Internet topology is necessary for the sustainable Internet against the future traffic increase.

For the past dozen years, various structural properties of the Internet topology have been widely investigated since various performances of the Internet, such as the amount of traffic that can be accommodated in the Internet and reliability against network failures, are also dependent on the structure of the Internet topology. In Ref. [8], Faloutsos et al. revealed that the degree distribution of the Internet topology exhibits power-law attributes, and Satorras et al. [9] showed that the distribution of betweenness centrality [10] also follows a power law. These analyses are needed for a network operator of an AS to add new links and network equipments based on a design considering the properties of the topology. However, these studies analyzed the structural properties at a point in time. A network design requires the prediction of the future structure of the Internet topology. To predict the future structure, the trend in changes of the Internet topology has to be clarified. Therefore, the evolution of the Internet topology has been studied intensively in recent years [11–13]. Dhamdhere et al. [11] investigated the long-term change in the number of peering/transit links. The authors also discussed the factors behind the emergence of the current topological structure, and gave graph generation models for the Internet topology. Shavitt et al. [13] used clustering coefficient and betweenness centrality to characterize this evolution, while Gregoria et al. [12] extracted well-connected subgraphs from the Internet topology, and discussed how these subgraphs were connected to the rest of the Internet topology. These studies longitudinally analyzed the change in the Internet topology from a graph metrics perspective. Therefore, determined properties by these studies are also vital to evaluate the performance of new applications and protocols on a topology reflecting structural properties of the Internet. For example, a topology reflecting properties of the Internet is required to evaluate the scalability of BGP [14]. However, a more important metric for the sustainable Internet is related to the change in the structure of the Internet topology associated with spatial dynamics of the traffic flow. An analysis of the change in the structure associated with traffic flow can help to reveal where the traffic concentration occurs and how to deal with it.

Recently, some studies reported that the trend of traffic flow greatly changed by the appearance of large content providers, which is also referred as "Hyper Giants". In Ref. [13], Shavitt et al. analyzed changes in topological structure, such as betweenness centrality and link density, by focusing on Hyper Giants [15,16]. From this analysis, it was found that the structure of the Internet topology has changed from a "hierarchical" to a "flat" structure. This is because Hyper Giants construct links with a lot of small ISPs. Because they have influenced the Internet topology, considerable attention is currently focused on Hyper Giants. However, Hyper Giants do not contribute to the moderation of traffic concentration over certain parts of the links, because the traffic flow between two ASes does not traverse the Hyper Giants, i.e., the traffic is not aggregated at the links controlled by the Hyper Giants. Thus, the Hyper Giants are not relevant to an evolution process to reduce traffic concentration at these links.

The traffic concentration occurs on links between ASes that aggregate more traffic. Therefore, we have to investigate a topological structure indicating where traffic on the Internet is aggregated to relax the traffic concentration. Traffic sent from an AS is gradually aggregated until the traffic reaches to large ISPs. This gradual traffic aggregation is associated with the hierarchical structure in the Internet topology. We investigate the longitudinal change of hierarchical structure in the evolution of the Internet, and show the trend of traffic concentration. In addition, we develop and evaluate the evolution process to relax traffic concentration with the hierarchical structure, and show the topological evolution to make the Internet more sustainable. For the sustainable Internet, in addition to ASes connecting the links where traffic is heavily concentrated, each of ISPs also has to continually improve network equipments corresponding to the increase in the traffic. However, since the improvement of network equipments takes cost, it is crucial for ISP to have sufficient benefit. That is, each of ISPs should get an economic utility through traffic exchange with other ASes.

An economic utility of an AS is also dependent on the structure of the Internet topology. This is because an economic utility is dependent on the traffic amount on links connecting with the ISP. The economic utility of an AS is determined by subtracting outcome from income. The income includes the total transit fees to receive from the other ASes at downstream of traffic flow. Transit fee is a charge incurred for the offer of one AS to transfer traffic to the other AS on a link. The outcome includes transit fees to pay to the other ASes, peering costs, and maintenance cost for the AS's network. Peering cost is a cost of maintaining a peering link. Maintenance cost of an AS is a cost incurred for operations, staffs, and equipments to exchange traffic. These income and outcome are dependent on the amount of traffic traversing the AS or links connecting with the AS. Since the amount of traffic on each link is dependent on the structure of the Internet topology, it is needed for the Internet topology to evolve such that each of ISP can continually get a sufficient economic utility for improvement of network equipments. However, it is impossible to optimally manage link constructions for all ISPs to get sufficient economic utility to improve network equipments since the Internet is not a centralized system.

Some studies showed policies to improve an economic utility of ASes. Ref. [17] proposed a framework to decide which type of a link is better as a link with neighbor for improving economic utility between a transit link, in which transit fee occurs to exchange traffic, and a peering link, in which transit fee does not occur. Ref. [18] proposed a model of an ISP's peering strategy to increase economic utility based on the amount of traffic on the ISP and the amount of traffic generated by content providers. However, these policies improve an economic utility of only a part of ISPs that apply these policies, and do not improve an economic utility of all ISPs. Thus, these policies cannot make the Internet more sustainable for the future traffic increase.

Each AS has to consider the effect of its link construction on the economic utility and traffic on the other ISP from information that the AS can know, and coordinately constructs links such that each of ISPs can get a sufficient economic utility. For this purpose, we investigate the feature of ASes that cannot get a sufficient economic utility, and discuss the mechanism of an appearance of these ASes. We then develop and evaluate the evolution policy that selects ASes to connect for relaxing unsustainable state of an ISP. Traffic exchanged between ASes has to be steadily transferred to network users in an intra-domain network within an AS. In addition, traffic relayed from one AS to the other AS traverses though an intra-domain network. Therefore, an intra-domain network in an AS also has to steadily relay the traffic. However, failures of network equipments may occur in an intra-domain network. Therefore, an intra-domain network that is reachable even if failures occur is required to achieve the steady communication in an AS.

Many approaches to improving its reliability have been investigated either at the network layer [19] or higher layers [20] in OSI model. The reliability of optical communication systems has also been improved through protection/restoration techniques [21]. While these approaches have greatly improved the reliability of networks, physical connectivity of networks is more essential to characterize their reliability. That is, if physical connectivity of networks is easily disrupted by network failures, approaches to improving reliability at the network layer will no longer be effective. In fact, the physical topologies used in the previous studies have inherently assumed that physical connectivity is retained after network failures occur. It is important to make the physical topology reliable against network failures to design reliable networks. It is also necessary to investigate the topological characteristics and topological structures that make the physical topology more reliable to achieve this purpose. In particular, reliability from routers connecting links with routers in a

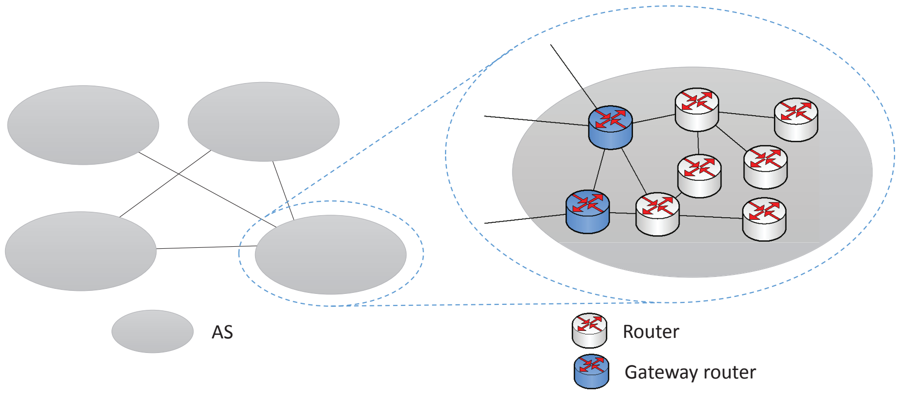


Figure 1.1: Connection between ASes at gateway routers.

different AS to other routers in an intra-domain network is required for steady relaying traffic exchanged between ASes to network users. Routers connecting routers in a different AS is called by gateway routers. Figure 1.1 shows the connection between ASes at gateway routers. Traffic exchanged between ASes reaches to a gateway router, and forwarded to other routers in the same intra-domain network. To improve the reliability, we investigate topological structures that should be embedded to make router-level topologies more reliable on the basis of knowledge in biological systems. More precisely, we evaluate the topological structure of a transcriptional regulatory network for several species that have a much longer evolutional history than information networks, and investigated what effect introducing its topological structure into router-level topologies would have. Transcriptional regulatory networks are biological system where transcription factors regulate the genes in cells, and control the expression of genes to produce the proteins necessary for biological activities [22, 23]. In transcriptional regulatory networks, stimuli by external environment comes to a part of transcription factors. The transcription factors relay the stimuli to the other transcription factors. Although some breaks of transcription factors may occur, functions of the transcriptional regulatory networks do not stop; it has high reliability against failures. Flow of stimuli is comparable with traffic flow in router-level topologies when we regard transcription factors that stimuli from external environment first comes to as gateway routers. Therefore, we investigate the structure that contributes high reliability of the transcriptional regulatory networks.

1.2 Outline of Thesis

Analyzing the evolution and the future of the Internet topology focusing on flow hierarchy [24–27]

In Chapter 2, we investigate the topological evolution of the Internet to relax the traffic concentration. We first identify links where more traffic is concentrated. For this purpose, we develop a method to identify the hierarchical nature of traffic aggregation. Our basic approach is to extract the "flow hierarchy", which is a hierarchical structure associated with traffic aggregation, from the Internet topology. To extract the flow hierarchy, we focus on a structure called a "module" as an unit of traffic aggregation, and retrieve the hierarchy of modules that appear in the Internet topology. A module consists of a set of ASes that are densely connected with each other, and each module is sparsely connected with other modules. The outgoing traffic from one module is first aggregated inside that module, and then the traffic is transferred to the other module through the sparsely connected links. A module may be divided into two or more submodules, that is, there is a containment relationship between the module and submodules. By repeating the division of modules and revealing their containment relationships, we can extract the flow hierarchy of the Internet topology. We analyze the structural evolution of the Internet topology from 2000 to 2013 by the flow hierarchy. Our results show that the amount of traffic on link between modules at higher level, which consists of modules derived by a few divisions, has rapidly increased. We then considered a new evolution process to avoid traffic concentration, and examined how this process could slow down the traffic concentration compared with the actual evolution of the Internet topology. The basic approach behind our evolution process is to construct more links between ASes in different modules at the same level of the flow hierarchy, particularly at lower levels. We evaluate the evolution process, and find that the evolution process can avoid overconcentration on links between modules at higher level while the topology retains the characteristic of traffic aggregation.

A provider and peer selection policy for the future sustainable Internet [28]

In Chapter 3, we investigate the evolution of the Internet topology such that each of ISPs can continually improve its network equipments corresponding to the traffic increase. With the economic utility through traffic exchange with other ASes, ISPs can improve the network equipments against the traffic increase. The economic utility is heavily depending on the traffic flow which changes corresponding to the evolution of the Internet topology. The Internet topology evolves by link constructions of ASes with their own policies to select ASes to connect links with. We therefore first investigate whether each of ISPs can continually get a sufficient economic utility against the traffic increase on the ISP or not even if the Internet topology will evolve with the current policies of ASes. We show that half of ISPs does not obtain sufficient economic utility against traffic increase, and the ratio tends to increase in recent years. We therefore develop and evaluate the policy that selects ASes to connect for relaxing unsustainable state of an ISP, and showed that all ISPs can improve economic utility against the traffic increase by applying our policy longitudinally.

Analyzing and utilizing the collaboration structure for reliable router-level networks [29–31]

In Chapter 4, we investigate topological structures that should be embedded to make router-level topologies more reliable on the basis of knowledge in biological systems. In particular, transcriptional regulatory networks have the same topological properties as router-level topologies, and flow of stimuli in transcriptional regulatory networks is comparable to traffic flow from gateway routers to other routers. We focused on a collaboration structure where two or more transcription factors co-regulate other transcription factors. The collaboration structures contribute to making the topologies reliable because they introduce multiple paths between nodes, and are therefore generally more reliable against failures in transcription factors. There are some types in collaboration structures based on types of transcription factors in the collaboration structures. To identify the characteristic of collaboration structures that transcriptional regulatory network has, we classify three types of nodes in both of router-level topology and transcriptional regulatory networks based on hop count to gateway routers and transcription factor accepting external stimuli. We show that node types in most collaboration structures in both topologies is different. We finally embed collaboration structure by the same types of nodes as that of transcriptional regulatory networks into eight router-level topologies, and show that all of them became more reliable.

Chapter 2

Analyzing the evolution and the future of the Internet topology focusing on flow hierarchy

2.1 Introduction

The Internet is the largest network system in the world, and is becoming ever larger. The amount of traffic on the Internet has been increasing owing to the increase in the number of network users, network services, and communication devices, such as PCs, smartphones, and tablet devices. An AS is a network that is managed by an organization under a single administrative control. The Internet consists of many ASes and the connections among ASes. According to Border Gateway Protocol (BGP) data in [32, 33], the number of ASes has doubled over the last decade; as at November 15, 2013, there were at least 45,980 ASes and 105,540 interconnected links. The number of ASes is estimated to continue increasing in response to the increase in mobile traffic, which doubles each year, and traffic from new and emerging applications using, e.g., sensor devices with a communication function [34, 35].

As the traffic amount increases, more traffic will concentrate on existing links. To relax the traffic concentration, each AS tries to form new links with ASes that have not yet been connected. An

AS usually has its own policy for selecting which ASes to connect with from among the many candidates. For example, an AS attempts to connect with another AS such that the cost, revenue, and performance after connecting are optimized. That is, new links are constructed based on the local decision of two ASes. They do not consider the global structure of the Internet topology. However, because the degree of traffic concentration on links depends heavily on the global structure of the topology [7], local decision-making is inadequate to fundamentally avoid the future traffic concentration associated with the increase in traffic. An evolution that considers the global structure of the Internet topology is necessary to continually accommodate future traffic amount.

The evolution of the Internet topology has been studied intensively in recent years [11–13]. Dhamdhere et al. [11] investigated the long-term change in the number of peering/transit links. The authors also discussed the factors behind the emergence of the current topological structure, and gave graph generation models for the Internet topology. Shavitt et al. [13] used the clustering coefficient [5] and betweenness centrality [10] to characterize this evolution, while Gregoria et al. [12] extracted well-connected subgraphs from the Internet topology, and discussed how these subgraphs were connected to the rest of the Internet topology. These studies longitudinally analyzed the change in the Internet topology from a graph metrics perspective. However, a more important metric to avoid future traffic concentration is related to the change in the structure of the Internet topology associated with spatial dynamics of the traffic flow. An analysis of the change in the structure associated with traffic flow can help to reveal where the traffic concentration occurs and how to deal with it.

We therefore develop a method to identify the hierarchical nature of traffic aggregation in the Internet topology, and use this method to discuss the long-term changes in traffic flow. Our basic approach is to extract the "flow hierarchy", which is a hierarchical structure associated with traffic aggregation, from the Internet topology. Many works have shown that the Internet has a hierarchical structure [9, 36, 37]. Within this hierarchical structure, an AS aggregates traffic from lower-level ASes, and relays the traffic to higher-level ASes. Such traffic aggregation leads to a hierarchy of traffic aggregation, which in turn leads to the traffic concentration on links. Recently, the structure of the Internet topology is becoming "flat" [15], and the trend of traffic flow also is changing from centralized to more distributed. Nevertheless, the flow hierarchy has not disappeared because the flat structure is formed by adding links to existing hierarchical structure. To extract the flow hierarchy, we focus on structures called “modules” as the unit of traffic aggregation, and retrieve the hierarchy of modules that appear in the Internet topology. A module consists of a set of ASes that are densely connected with each other, and each module is sparsely connected with other modules [38]. The outgoing traffic from one module is first aggregated inside that module, and then the traffic is transferred to the other module through the sparsely connected links. A module may be divided into two or more submodules, that is, there is a containment relationship between the module and submodules. By repeating the division of modules and revealing their containment relationships, we can extract the flow hierarchy of the Internet topology. We then investigate the long-term changes in the flow hierarchy of the Internet topology. Our results show that the increase in traffic amount at the top-level module is larger than that at middle-level or low-level module and particularly has slightly accelerated since 2011. This suggests that the current connection policy will lead to a severe traffic concentration in the future Internet topology. Therefore, we urgently need an evolution process that considers the global structure of the Internet topology to slow down the increase in traffic concentration. In this chapter, we examine a new evolution process that attempts to increase the number of links between lower-level modules to relax the traffic concentration in higher-level modules. We apply our evolution process to the Internet topology in 2000, and evolve this scenario for 13 years. We then evaluate the traffic concentration at various levels of containment following the evolution. The results show that our evolution process can suppress the traffic concentration by more than half compared with that without our evolution process.

This chapter is organized as follows. Section 2.2 gives an overview of some related work in the analysis of the Internet topology. Section 2.3 describes the hierarchy concept based on the containment relationship of modules, and presents the method of extracting the flow hierarchy from the Internet topology. Section 2.4 discusses the long-term change in the flow hierarchy of the Internet topology. We first investigate the internal structure in a module, and then illustrate the structure between top-level modules in the flow hierarchy, because a large amount of traffic traverses the links between top-level modules. Finally, we investigate the long-term change in the structure of each level in the flow hierarchy. Section 2.5 studies the links on which a lot of traffic is aggregated. In Sec. 2.6, we examine a new evolution process that attempts to increase the number of links between lower-level modules. We apply the evolution process to the Internet topology in 2000, and confirm that it suppresses the traffic concentration across links between top-level modules. Section 2.7 shows that the appearance of Hyper Giants does not enable the continued accommodation of an increase in traffic amount. Section 2.8 concludes this chapter.

2.2 Related work

Understanding and analyzing the structure of the Internet topology is important, because the properties of the Internet are used for network design. The network performance, such as the amount of traffic that can be accommodated across the Internet, is dependent on the structure of the Internet topology, because this strongly affects the traffic flow. Therefore, when a network operator of an AS adds new links and network equipment, a design based on the properties of the topology is needed to improve the network performance. Determining the structure of the Internet topology is also vital to evaluate the performance of new applications and protocols on a topology reflecting the structure and properties of the Internet. For example, a topology reflecting properties of the Internet is required to evaluate the scalability of BGP [14].

For the past dozen years, various structural properties of the Internet topology have been widely investigated. Refs. [39, 40] visualized the Internet topology to determine its structural properties. However, it is difficult to characterize structural properties from pictures of the Internet topology generated by these studies, because the Internet topology is large and complex. Some studies have investigated structural properties using various graph metrics. In Ref. [8], Faloutsos et al. revealed that the degree distribution of the Internet topology exhibits power-law attributes, and Satorras et al. [9] showed that the distribution of betweenness centrality also follows a power law. However, these studies analyzed the structural properties at a point in time. Network design requires the prediction of the future structure of the Internet topology. To predict the future structure, the trend in changes to the Internet topology has to be clarified. In Ref. [11], Dhamdhere et al. quantified the ability of an AS to attract customer ASes that pay a transit fee for traversing traffic, and found that Internet Service Providers (ISPs) connecting to a lot of customer ASes had acquired more customer ASes. These studies analyzed the evolution of the Internet topology using some graph metrics. Each graph metric shows a characteristic of the Internet topology; however, these are not directly related to network performance. For instance, even if two networks have the same degree of distribution, the amount of network equipment needed to accommodate traffic demand will differ depending on the structure of the networks. For example, Ref. [7] found that the degree of traffic concentration on links is heavily dependent on the global structure of the topology. Actually, the Internet topology suffers from traffic congestion more than a random network [41]. It is important to understand the global structure related to the spatial dynamics of traffic flow to develop a new evolution process that avoids the current and future traffic concentration suffered by the Internet topology.

In Ref. [13], Shavitt et al. analyzed changes in topological structure, such as betweenness centrality and link density, by focusing on large content providers, also referred to as Hyper Giants [15,16]. From this analysis, it was found that the structure of the Internet topology has changed from a hierarchical to a flat structure. This is because large content providers construct links with a lot of small ISPs. Because they have influenced the Internet topology, considerable attention is currently focused on these Hyper Giants. However, Hyper Giants do not contribute to the moderation of traffic concentration over certain parts of the links, because the traffic flow between two ASes does not traverse the Hyper Giants, i.e., the traffic is not aggregated at the links controlled by the Hyper Giants. Thus, the Hyper Giants are not relevant to an evolution process to reduce traffic concentration at these links. In this chapter, we focus on the structure of traditional links, such as those between ISPs.

2.3 The flow hierarchy

2.3.1 Concept of the flow hierarchy

We use the flow hierarchy to reveal where and how traffic is aggregated. The structure of the flow hierarchy is the hierarchical structure based on containment relationship of modules. We note that the flow hierarchy is not a hierarchy of "tier" based on the ISP's business scale but the structure indicating a gradual traffic aggregation in the Internet topology. Such the containment relationship has appeared in the history of the Internet evolution, and then the traffic is aggregated in accordance with the flow hierarchy. This makes the flow hierarchy be useful for analyzing degree of traffic aggregation. In the late 1960s, some academic organizations deployed network equipment and connected with all other organizations. This is the origin of the Internet, and the organizations became to be called ASes later. To participate in the early Internet, new ASes needed to connect with all other ASes. However, as the scale of the Internet became larger, it was increasingly difficult to sustain the full mesh network. Because the construction and maintenance costs of long or high-capacity links are high, new ASes tend to connect with only a few “senior” ASes that have long or high-capacity links. As a result, sets of ASes centered on senior ASes, i.e., modules, were generated. However, as the number of ASes connecting to senior ASes increases, the amount of traffic aggregated at senior ASes and global links increases, and the risk of suffering traffic congestion increases. To reduce the traffic load at senior ASes, some ASes have locally aggregated traffic. Because a hierarchical structure has appeared in the Internet under this process of traffic aggregation, the flow hierarchy reflects the hierarchical nature of traffic aggregation. Therefore, we use the flow hierarchy to reveal where and how traffic is aggregated.

2.3.2 Extraction of the flow hierarchy

We now extract and investigate the flow hierarchy in the Internet topology. First, we obtain the topology data of ASes and links in the Internet topology (Sec. 2.3.2). We then extract the hierarchical structure based on containment relationship of modules from the Internet topology (Sec. 2.3.2). We finally give the traffic demand to the hierarchical structure because the flow hierarchy is derived by adding the traffic amount on each link to the hierarchical structure (Sec. 2.3.2).

Obtaining topology data

We obtain the topology data of ASes and links in the Internet topology. We extract the topology data from the BGP routing tables that have been recorded in the gateway routers of large ISPs and have been gathered. Various organizations, such as UCLA [42] and CAIDA [39], create the Internet topology data and these topology data include more links [43, 44]. However, these topology data are not suitable for a longitudinal topological analysis because the number of monitors that observe

Table 2.1: Number of ASes, links, and AS paths in the Internet topology.

	2000/6/15	2004/6/15	2008/6/15	2013/11/15
# of ASes	8,162	18,015	29,320	45,980
# of links	17,533	40,205	64,305	105,540
# of AS paths	299,434	1,108,704	1,901,745	3,136,820

BGP tables and traceroute results that are used to create topology data has greatly increased. That is, we cannot distinguish between actual evolution of the topology is contributed by the real change of the topology and changes caused by the increase of monitors. Instead of the data provided by UCLA and CAIDA, we use the BGP tables gathered by a part of servers of RouteViews Project and RIPE NCC. The part of servers have been gathering the BGP tables from almost the same ISPs after starting up of their projects. Although the number of links observed is fewer than the topology data of UCLA and CAIDA, the BGP tables from RouteViews Project and RIPE NCC are suitable for a longitudinal topological analysis because they are consistently comparable over time. BGP tables contain AS paths, which are the routes between two ASes. The AS path is described as a list of ASes that the traffic traverses. From the AS paths in the BGP tables, we obtain the ASes and links in the Internet topology. We use BGP routing tables stored in `route-views.route-views.org`, which is a RouteViews Project server, and `rrc00.ripe.net`, which is a RIPE NCC server. The reason why we use these servers is that they are the oldest ones that are still working. Table 2.1 shows the number of ASes and links that we can extract. Unfortunately, Refs. [11, 45] reported that this method cannot capture over 40% of the peering links on which traffic is exchanged without a transit fee. Since a huge amount of traffic traverses peering links through IX, missing of peering links decreases the accuracy of estimated amount of traffic traversing each link. However, the use of BGP routing tables is not a problem for this study because the purpose of this study is to reveal the impact of the global structure of the Internet on the traffic concentration rather than to show the actual traffic amount.

Table 2.2: Definition of notation for modularity.

Notation	Definition
m	Number of links
i, j	Node
A_{ij}	Element of adjacency matrix.
k_i	Degree of node i
S_i	Module that contains node i
$\delta_{S_i S_j}$	Kronecker delta. If S_i and S_j are the same, $\delta_{S_i S_j}$ is 1, otherwise 0.

Extracting the hierarchy of modules based on containment relationship

The structure of the flow hierarchy is the hierarchical structure based on containment relationship of modules. We extract the hierarchical structure from the Internet topology. The hierarchical structure based on containment relationship of modules is extracted by repeating the division of modules into submodules. Several methods for division of modules have been proposed such as the Infomap method [46], the OSLOM method [47], and the Louvain method [48]. Since our main concern is the traffic aggregation, we select the Louvain method for our analysis. The Infomap method uses the probability flow of random walks on a network as a proxy for information flows in the real system and divide the network into modules by compressing a description of the probability flow [46]. However, since the traffic flow of the Internet is not random walk, we cannot capture links where the traffic is aggregated from the Infomap method. The OSLOM method uses a measure indicating how obvious module structure there is in the network against a random null model graph. Therefore, the OSLOM method can detect the obvious module structure against the random null model graph. However, the traffic concentration is expected to be observed in also the random null model graph and the OSLOM method cannot capture the traffic concentration. Unlike the Infomap and the OSLOM methods, the Louvain method derives modules so that the number of inter-module links relative to that of the intra-module links is minimized. The traffic originated inside a module is first conveyed and aggregated by the intra-module links, and then transfered by the intra-module links. The Louvain method incrementally merges modules into a module, so we can gradually capture links where the traffic is aggregated by using the Louvain method.

In the Louvain method, the topology is divided in such a way as to maximize the modularity. The modularity is a measure of the strength of interconnection among modules when a particular division P of a topology is given, and is defined by,

$$M(P) = \frac{1}{2m} \sum_{ij} [A_{ij} - \frac{k_i k_j}{2m}] \delta_{S_i S_j}. \tag{2.1}$$

Descriptions of the variables in Eq. (2.1) are shown in Table 2.2. Here, we regard the maximum of $M(P)$ for all divisions as the modularity of the topology. The modularity of a topology ranges from 0 to 1. The modularity is high in case that links between ASes in the same module are densely connected and links between ASes in different modules are sparsely connected. The modularity of a complete graph and a star graph is 0, because these graphs do not consist of sets of nodes densely connected to each other.

After dividing the Internet topology into modules as described above, we divide each module into smaller submodules. Furthermore, we divide these submodules into even smaller submodules. By repeating this dividing process, the hierarchical structure based on the containment relationship is extracted. If the modularity of a module is 0, it cannot be divided into submodules because the module does not consist of sets of densely connected nodes. All modules are repeatedly divided until their modularity is 0. We define the "containment level" (CL) as the level of the hierarchical structure. As shown in Fig. 2.1, CL1 modules are modules that are extracted in the first division of the Internet topology. Submodules of CL1 modules are CL2 modules, and submodules of CLn modules are CL$n+1$ modules, where n is a non-negative integer.

Assigning traffic demand

We assign traffic demand to the hierarchical structure of the containment relationship of modules. Since the actual traffic amount on most paths is closed information, we give the traffic demand based on the gravity model [49]. The gravity model is a simple method for estimating the traffic demand [49, 50] and is used in some studies [17, 51]. The traffic demand of AS i is proportional to the degree of AS i since the business scale of AS i is related to its degree [7, 52]. Note that, as discussed in [53], the gravity model does not capture self-similarity and long-range dependence

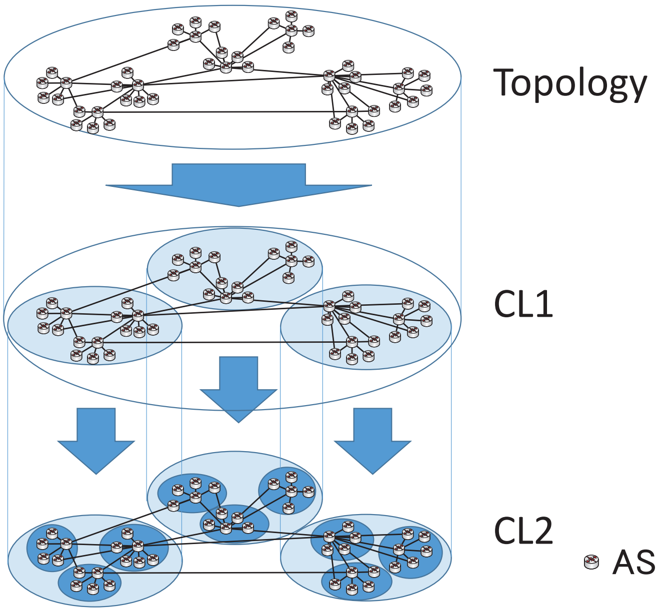


Figure 2.1: Extraction of hierarchical structure based on the containment relationship of modules.

of traffic. However, we use the gravity model for assigning traffic demand since our study focuses on the increase in the degree of traffic concentration rather than short-term traffic fluctuation. The gravity model is represented by the following expression;

$$e_{ij} \quad = \quad \gamma \cdot x_i \cdot x_j, \tag{2.2}$$

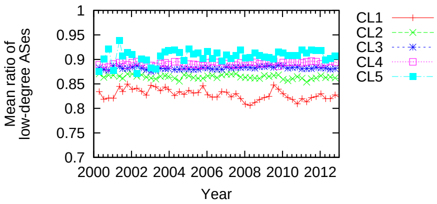
where e_{ij} is traffic amount on the path between AS i and AS j. x_i and x_j are the traffic demand of AS i and AS j, respectively, and γ is a scaling factor and is set to 1 hereafter. Note that this setting may not reflect actual traffic amount. However, our focus here is to reveal the traffic concentration on some links rather than actual traffic amount on each link.

Note that Hyper Giants send huge amounts of traffic compared with the other ASes. In particular, Google and Akamai are defined as Hyper Giants by some studies [7, 15]. We check names of organizations managing ASes in CIDR report [54], and we regard ASes whose names contain "Google", "Akamai" as Hyper Giants. Then, γ is set to 1 if both of AS i and AS j are not Hyper Giants, otherwise γ is set to 895. These values are determined based on a Cisco report [55, 56] that quantifies the traffic amount on the Internet. Cisco reported the traffic over the whole of the Internet to be 369 exabytes in 2011, and that between users and data centers to be 116 exabytes. The number of ASes registered by the Internet Registry is 60538, and the number of famous content providers is about 30. Therefore, the average amount of traffic at each AS is 4.18 petabytes ($= (369 - 116)/(60538 - 30)$ exabytes), and the average amount of traffic sent by a large content provider is 3.74 exabytes ($= 116/30$ exabytes). Thus, we set γ to 895 ($= 3.74 \cdot 1000/4.18$) for the Hyper Giants. The value of γ may not reflect actual traffic amount. However, our focus here is to reveal the traffic concentration on some links rather than actual traffic amount on each link. Note that Microsoft is also called as Hyper Giants in some studies [7, 15], however, we regard only Google and Akamai as Hyper Giants because the degree of Microsoft (AS number is 8075) has greatly changed.

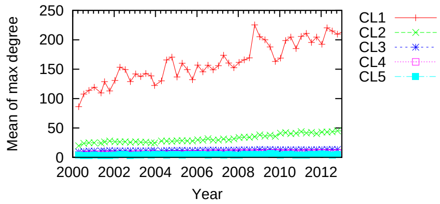
When we derive the amount of traffic that traverses each link from the amount of traffic between AS pairs, the path between two ASes is required. Unfortunately, most paths between AS pairs are undocumented. Thus, we assume that the path between two ASes is a minimum hop path, although this is not always the case for actual BGP routings [57]. This assumption is sufficient to observe the change in traffic aggregation, because Ref. [13] reported that the number of minimum hop paths that traverse an AS is similar to the actual amount of traffic that traverses that AS. Thus, we consider minimum hop paths to be useful for analyzing the changes in traffic aggregation.

2.4 Long-term change of the flow hierarchy

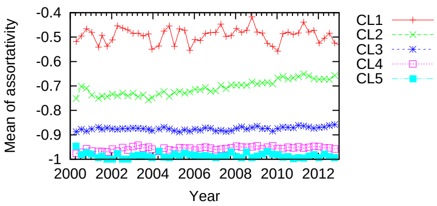
The traffic concentration at links between modules is dependent on the structure within modules and the structure between modules. An investigation of the change in the flow hierarchy is important for discussing the future evolution of the Internet topology. Therefore, in this section, we first analyze the internal structure of modules. Through this analysis, we investigate ASes that have a lot of links between modules to confirm where traffic is aggregated in the module. We then analyze the between-module structure. In particular, we investigate the structure between CL1 modules, which are top-level modules in the flow hierarchy, because it is thought that large amounts of traffic are aggregated in the links between CL1 modules. Finally, we investigate the long-term change in the



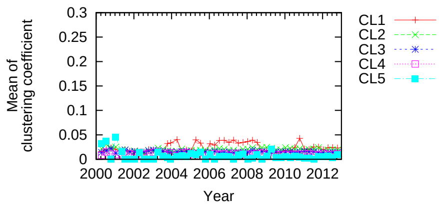
(a) Mean ratio of the number of one- or two-degree ASes to the number of all ASes in a module



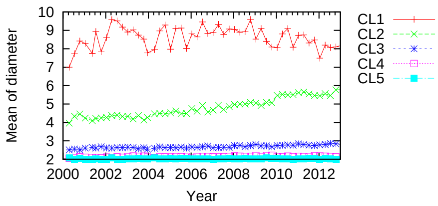
(b) Mean of max degree



(c) Mean of assortativity



(d) Mean of clustering coefficient



(e) Mean of diameter

Figure 2.2: Mean value of graph metrics of modules in each CL.

structure of each level in the flow hierarchy to reveal the trend of traffic aggregation at links between modules at each level.

2.4.1 Internal structure of modules

In this section, we reveal the internal structure of modules using various graph metrics. Here, we do not divide CL5 modules even when some CL5 modules can be divided to CL6 modules. The reason is that the number of CL6 modules and the size of CL6 modules are too small to see the change of internal structure of the CL5 module. Figure 2.2 shows the longitudinal change in the graph metrics of modules. From the analyses in Fig. 2.2, we confirm that the internal structure of modules gives a star-like graph. Figure 2.2(a) shows the mean ratio of ASes that have degree one or two. For the modules in most CLs, the ratio of these ASes is over 80%. Figure 2.2(b) shows the mean of the maximum degree in the modules. Whereas over 80% of ASes in a module have only one or two links, the degree of hub ASes in CL1 modules is over 100, and that in CL2 modules is over 30. Furthermore, the degree of hub ASes in these CLs has been increasing. Although the degree of hub ASes in CL4 and CL5 is less than 10, they connect to most of the ASes in the module. Thus, it is found that the degree of most ASes in a module is small, but the degree of some ASes is large. To reveal where the links are constructed in a module, we now investigate the assortativity of modules. Assortativity is an index indicating that a node in a network connects with ASes that have the similar degree [58]. If all links are constructed between nodes that have the same degree, the assortativity of the network is 1. On the contrary, the assortativity is 0 when there is no correlation between the degrees of two nodes that are connected with each other. When the nodes with small degrees are likely to be connected to the nodes with large degrees, the assortativity is close to -1. As shown in Fig. 2.2(c), the assortativity of modules in all CLs is small, which means that ASes that have a small degree connect to hub ASes. Figure 2.2(d) shows the clustering coefficient of modules in each CL to investigate the connection between neighbor ASes. The clustering coefficient of an AS is an index indicating the ratio of connected pairs to all neighbor nodes' pairs of an AS, and ranges from 0 to 1. As shown in Fig. 2.2(d), the clustering coefficient of each module is small. This means that neighbor ASes of a given AS do not connect with each other. The result suggests that hub ASes link to a lot of ASes that have a small degree, and ASes with a small degree are not connected to each other. Finally, Fig. 2.2(e) shows the mean diameter of modules. As the CL increases, the module diameter approaches 2. To summarize the points in Fig. 2.2, it is obvious that the internal structure of each module is a star-like graph.

Table 2.3: Ratio of inter-module links of hub ASes and ratio of inter-module links of low-degree ASes.

	Hub ASes	Low-degree ASes
CL1	0.244	0.137
CL2	0.396	0.269
CL3	0.476	0.293
CL4	0.463	0.267
CL5	0.406	0.093

2.4.2 ASes with a number of links between modules

The large amount of traffic that is generated within a module is aggregated at links between modules. We reveal the relationship between the degree of ASes and the number of links between modules. We first investigate whether a hub AS or an AS that has a small degree have more links between modules. Here, we define hub ASes as those having a degree that is more than half of the maximum in the module. Table 2.3 shows the average ratio of links between modules to all links of an AS in the Internet topology on 15 July 2013. This shows that hub ASes have a higher ratio than low-degree ASes. This means that low-degree ASes tend to connect to only the hub ASes belonging to the same module. The hub ASes link to both ASes in the same module and ASes in other modules. Therefore, the traffic between modules is aggregated at the hub ASes, and then transferred to ASes in other modules.

Next, we examine which types of ASes have many links between modules. In the Internet, there are various types of ASes. ISPs are classified into four types, Tier-1 to Tier-3 and sub-Tier-1. We define sub-Tier-1 as ISPs for which there is no consensus as to whether they should be categorized as Tier-1 or Tier2. The other ASes are classified as Hyper Giants or Academic. In this study, ASes are ranked based on two types of links: transit links and peering links. A transit link is one in which traffic is exchanged with a transit fee. A peering link is one where traffic is exchanged without a transit fee. Unfortunately, information about the type of link is generally unknown. The method of Ref. [39] can infer the link type with an accuracy rate of 99.1%, and so we use this approach. We classify ASes based on the following steps. First, we extract “peering links” and ASes that have peering links. We regard a connected component consisting of peering links as one tier, because two

Table 2.4: Average number of links between modules.

	e_1	e_2	e_3	e_4	e_5	e_6
Tier-1	989.54	158	624.31	0.54	22.77	0
sub-Tier-1	191.03	75.23	160.82	2.31	14.31	0
Tier-2	52.76	29.39	52.63	0.93	7.74	0.03
Tier-3	16	11.33	33.08	0.58	2.42	0.17

ASes connected with a peering link generally process the same amount of traffic. Next, we check the commercial name of the AS in each connected component, and determine the tier of each connected component from six types. Finally, we regard the tier of the connected component that contains the AS to be the type of AS. There is a hierarchy in the Internet based on link types [9, 36, 37]. Note that a hierarchy based on AS types is different from the flow hierarchy. The hierarchy based on link types shows the difference in the amount of traffic exchanged by two connected ASes. The flow hierarchy describes the amount of traffic aggregated at ASes or links based on the global structure of the topology.

Table 2.4 shows the average number of links between modules for each AS type. e_x is the average number of links between modules of an AS in CLx. Table 2.4 shows that e_x decreases as x increases. This means that Tier-1 ASes have more links between modules than other ASes, because most Tier-1 ISPs have a global network spanning multiple continents and connected with many ISPs all over the world.

According to our findings, the flow hierarchy can be illustrated as in Fig. 2.3. In Fig. 2.3, the number of ASes, number of links between ASes in different tiers, and number of links between ASes in the same tier are 1/5 of those in the actual Internet topology in 2012. In Fig. 2.3, ISPs are arranged from top to bottom in descending order of amount of traversing traffic, and the triangles represent modules. As shown in Fig. 2.3, there is a hierarchy in the Internet based on AS type. Note that this hierarchy is different from the flow hierarchy. The major difference is that the hierarchy based on AS type is not reflected by the structure of the topology. Each module contains ASes in different tiers, and ASes in higher tiers have more links between modules. A module in the flow hierarchy is a part of a vertically divided Internet topology. From the structure in Fig. 2.3, we can see that Tier-1 ISPs exchange traffic traversing from/to other modules. The traffic concentrates at

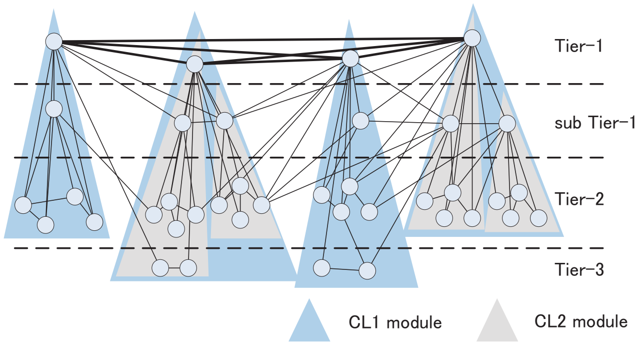


Figure 2.3: The the flow hierarchy appeared in the Internet topology.

Tier-1 ISPs, because they aggregate the traffic that is generated in the modules.

2.4.3 Long-term change in structure of top-level modules in the flow hierarchy

A hub AS connects links to a lot of ASes in other modules. Thus, a hub AS aggregates traffic generated in the module, and relays the traffic to the other modules. Therefore, it is considered that an immense amount of traffic generated in CL1 modules is aggregated at the links between top-level (CL1) modules. In the future, when traffic concentrates at links between CL1 modules, an evolution process is needed that avoids traffic concentration, allowing the Internet topology to accommodate this increase in traffic amount. Thus, the change of traffic concentration at links between CL1 modules must be clarified. For this purpose, we analyze the long-term change in the structure between CL1 modules, because the degree of traffic concentration at the links depends on the connections between CL1 modules.

We first investigate the long-term change in modularity of the Internet topology to investigate the structure between CL1 modules. Since the value of modularity itself is not suitable measure to investigate the modular structure [59–61], we compare the modularity between the ER random model, hierarchical scale-free graph, and the Internet topology. Figure 2.4 shows the long-term change in modularity of these graphs. For the hierarchical scale-free graph, a module having a scale-free degree distribution is first generated, and this is incrementally added into the graph until the number of nodes and links exceed those of the Internet topology. We create the hierarchical scale

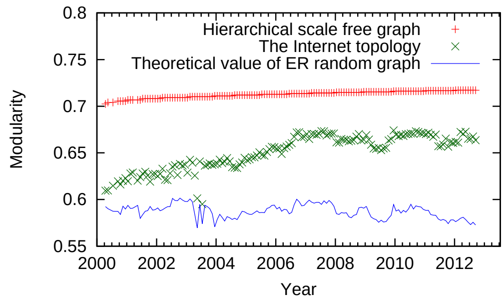
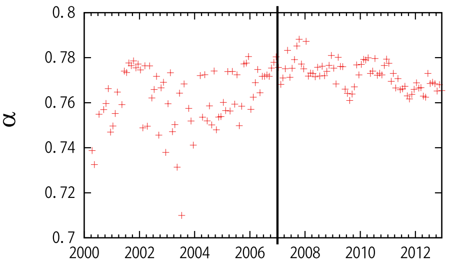


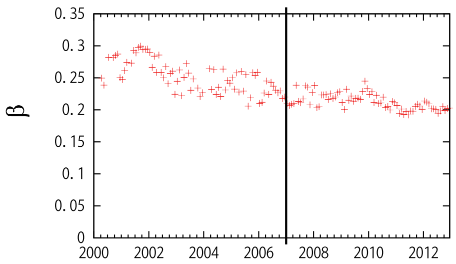
Figure 2.4: Long-term change in modularity.

free graph that have the same number of nodes and links as the Internet topology. In Fig. 2.4, we use Eq. (19) in [59] for calculating the modularity of the ER random model. Eq. (19) is an equation to analytically calculate the maximum modularity of the ER random model without the module detection, and the modularity derived by the Eq. (19) in [59] is close to the modularity derived by the simulated annealing method [59]. There is another approach to calculate the maximum modularity [61]. However, the modularity derived by the equation in [59] is slightly closer to the modularity derived by the simulated annealing method in case that the average degree is fewer than 10 (see Fig. 12 in Ref. [61]). Since the average degree of the Internet topology is also fewer than 10, we use the equation in [59].

As shown in Fig. 2.4, the hierarchical scale-free graph has the largest modularity, and the ER random graph has the smallest. In the hierarchical scale-free graph, a large amount of traffic tends to be aggregated at the links between modules, because the large modularity indicates a low density of links between modules. In Fig. 2.4, the modularity of the hierarchical scale-free graph and the ER random graph remains constant. On the other hand, the trend in modularity of the Internet topology changed sometime around 2007. This suggests that the overall structure started to change at this time. The dashed line in Fig. 2.4 denotes 1 January 2007. Until this point, the modularity of the Internet topology had been increasing. This suggests that new links had tended to be locally constructed between two ASes in a module. It is thought that, when new ASes are created in the Internet topology, they connect to ASes having links between higher-level modules. Since 2007, the modularity of the Internet topology has remained constant. However, the number of links between



(a) Ratio of links between nodes in a module to all links.



(b) Probability that a link exists between node i and node j in a module when links are randomly deployed on the topology.

Figure 2.5: Ratio of links between nodes in a module to all links and expected probability to connect link between ASes in the same module.

modules has increased since 2007.

To clarify the factors affecting the change in the modularity trend around 2007, we investigate the long-term change of variables in the definition of modularity (Eq. (2.1)). The modularity depends on the ratio of links between nodes in a module to all links and the node degree in each module. The key terms in Eq. (2.1) are

$$\alpha = \frac{1}{m}\sum_{ij} A_{ij}\delta_{S_iS_j}, \tag{2.3}$$

and

$$\beta = \frac{1}{m}\sum_{ij} \frac{k_ik_j}{2m}\delta_{S_iS_j}. \tag{2.4}$$

α is the ratio of links between two nodes in a module to all links, and β is the probability of drawing a link between nodes that are in the same module when the link is randomly deployed on the topology. The higher the degree of node i and node j, the higher the value of β. α and β are normalized by the number of links in the Internet topology. Figure 2.5 shows the long-term change in these terms. Figure 2.5(b) shows that β has decreased continuously since 2000. As there is no change in this trend around 2007, β is not considered to be a factor in the change in modularity.

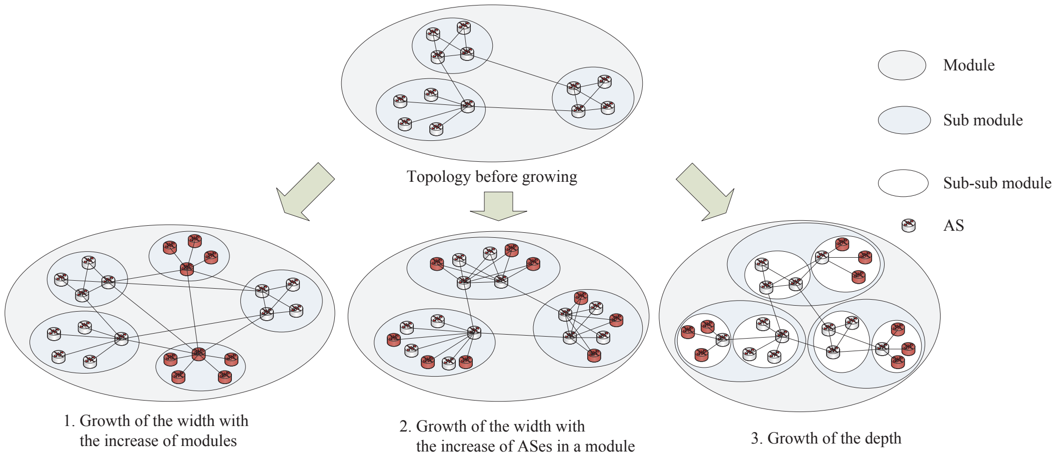


Figure 2.6: Three possible scenario for the evolution of flow hierarchy.

On the other hand, Fig. 2.5(a) shows that the trend of α changed around 2007. α was increasing until 2007, with minor fluctuations, and decreases after 2007. Thus, we assert that the change in the trend of α affected the modularity of the Internet topology. Even though the scale of the Internet topology has increased since 2007, the ratio of links between nodes in a module has decreased; i.e., the number of links between top-level modules has increased. We believe that the factors behind the increase in links between top-level modules are the reduction in the price of constructing links and the increase in IXes (Internet eXchanges), which are relaying points for traffic between two connected ASes. These factors lead to an increase in inter-module links between ASes that do not have a lot of links between top-level modules. As a result, the modularity of the Internet topology has decreased.

2.4.4 Long-term change of each level in the flow hierarchy

More links between modules are needed to avoid an increase in traffic concentration at links between top-level modules. New links between modules should be constructed between two ASes that locally aggregate traffic. This is because a part of the traffic that traverses the existing links between top-level modules will traverse links between two ASes that locally aggregate traffic. We investigate the traffic aggregation at links between modules in each CL to reveal where the ASes

Table 2.5: Number of modules in each CL.

Year	CL1	CL2	CL3	CL4	CL5	CL6
2000	26	255	812	529	71	0
2002	37	384	1215	881	131	6
2004	43	462	1526	1173	208	6
2006	40	479	1883	1562	299	4
2008	40	508	2437	2088	389	6
2010	42	490	2795	2641	438	2
2012	51	578	3153	3181	638	12

that locally aggregate traffic are located. The degree of traffic aggregation at the links between modules in each level of the flow hierarchy depends on the structure between the modules in each level. Therefore, in this section, we investigate the long-term change in the structure of each level in the flow hierarchy.

There are two ways in which the flow hierarchy can evolve: by expanding in depth and by expanding in width. There are two further subcategories for the expansion of the width. One is to increase the number of modules in each CL, and the other is to increase the number of ASes in each module. Figure 2.6 illustrates these expansions of the flow hierarchy. White nodes indicate ASes that exist before the growth, and red nodes indicate those added after the expansion. In the left-hand growth pattern in Fig. 2.6, the number of modules in each CL increases as the topology grows. In this case, the links between modules also increase in number. By increasing the links between modules, the concentration of traffic at existing links is relaxed. In the center growth pattern in Fig. 2.6, a star-like graph in each module becomes larger because additional ASes connect to the hub ASes in each module. As a result, the amount of traffic aggregated at hub ASes and on links between modules increases. In the right-hand growth pattern in Fig. 2.6, submodules are generated in each module. The generation of submodules increases the maximum number of CLs, which corresponds to the depth of the flow hierarchy. If the depth of the flow hierarchy in the Internet topology grows, the amount of traffic aggregated on the links between top-level modules will decrease. This is because the paths between ASes belonging to the same module do not traverse the links between modules in the upper CL.

We first investigate whether the depth of the flow hierarchy has been expanding or not. The

Table 2.6: Mean number of ASes contained in one module.

Year	CL1	CL2	CL3	CL4	CL5	CL6
2000	224.97	24.78	8.41	4.01	3.22	2
2002	424.32	35.73	9.81	4.32	3.35	2.75
2004	414.07	37.84	10.41	4.67	3.59	3.5
2006	528.33	43.54	11.25	5.43	3.59	2
2008	695.98	57.18	12.20	6.20	3.71	2
2010	841.98	69.16	12.26	5.71	3.81	2.17
2012	915.93	73.31	12.93	6.36	3.74	2.89

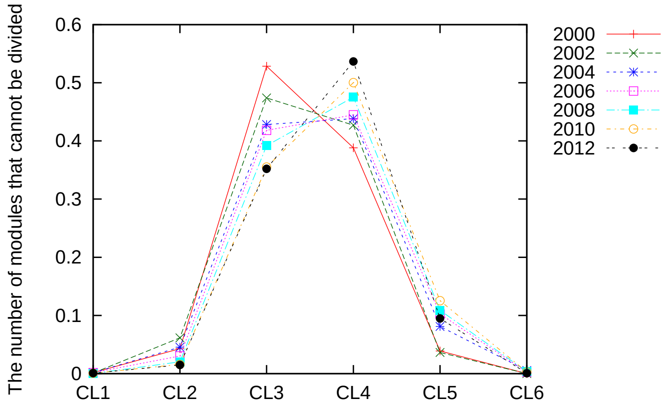


Figure 2.7: Containment level at which a module cannot be divided anymore.

depth of the flow hierarchy is defined by the containment level where a module at the level cannot be divided into sub modules. Hereafter, we call modules that do not have sub modules as terminal modules. Figure 2.7 shows the number of terminal modules at each CL. The value of Y-axis is normalized by the total number of terminal modules. We observe that most of terminal modules are located at CL3 and CL4, and the depth of these modules has increased from 2000 to 2012. However, the increase in terminal modules in CL4 is only 10 %. Moreover, the average depth of terminal modules is slightly increased; from 3.42 to 3.71. The depth of the deepest terminal module remains steady at six from 2003 to 2013. Therefore, we conclude that the depth of the flow hierarchy has not changed greatly.

We next investigate whether the growth in the flow hierarchy has followed the left-hand pattern or the center pattern in Fig. 2.6. Table 2.5 shows the number of modules in each CL. The number of modules in CL3 and CL4 is greater than that in other CLs. Furthermore, the number of modules at CL3 and above has increased more rapidly than the number at CL1 and CL2. This means that the structure in CL3 and above has grown in similar fashion to the left-hand pattern in Fig. 2.6. Table 2.6 shows the average number of ASes in a module. From 2000 to 2012, the average number of ASes in CL1 modules increased by a factor of 4.07, and that in each CL2 module increased 2.96 times. The number of ASes in modules in these CLs increased at a faster rate than in the other CLs. This suggests that the structure in CL1 and CL2 has expanded by increasing the number of ASes within a module. That is, the structure of these CLs has expanded according to the center pattern in Fig. 2.6. The expansion in width with the increase of ASes in a module leads to an increase in the amount of traffic aggregated at links between modules. Therefore, more traffic has been concentrated at links between CL1 modules and links between CL2 modules. Note that it is known that the Louvain method suffers from a resolution limit. The resolution limit is the characteristic scale of the smallest size of a module that the method can detect. We checked the effect of the resolution limit by comparing divisions by the Infomap method, which is known to mitigate the resolution limit better than the Louvain method [62]. We found that the division by the Louvain method is affected by the resolution limit: the number of small size (< 10 ASes) modules is about ten times fewer than that by the Infomap method. However, we also found that the impact of the resolution limit on analyzing the evolution of flow hierarchy is marginal (see Appendix A. for detail). The main reason is that the evolution of the flow hierarchy depends on the relation between the large-size module at the CL and the large-size module at lower-level CL. That is, the evolution of flow hierarchy indicates how the large size module at a CL can be divided into sub modules at lower-level CL. Our result shows that the resolution limit of the Louvain method is enough to capture the large-size module and is enough to understand the way of traffic aggregation in the flow hierarchy. Another reason is that, although the Infomap method can detect some “periphery nodes” (which in turn form a small-size module), such the small-size modules are detected at each CL. Thus, the relation between the large-size module at the CL and the large-size module at lower-level CL is less suffered from the resolution limit.

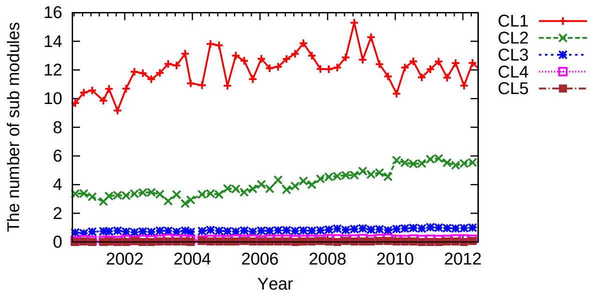


Figure 2.8: Average number of submodules contained in a module.

2.5 Long-term change in traffic aggregation

Section 2.4 showed that the structure within a module can be represented as a star-like graph. It was also revealed that the structure in higher CLs has expanded by increasing the number of ASes within a module, whereas the structure in lower CLs has expanded with an increase in the number of modules. In this section, we use this structural analysis to investigate where the traffic will become concentrated. In particular, we focus on the traffic amount over inter-module links where large amounts of traffic are exchanged.

2.5.1 Relationship between inter-module links and traffic aggregation

The traffic concentration on links between modules is dependent on the structure of the Internet topology. In particular, the number of submodules influences the amount of traffic aggregated on the links between modules. This is because traffic aggregated inside each submodule is aggregated at an AS in a higher-level module, and the traffic aggregated at this AS is relayed via links between modules. We therefore investigate the number of submodules contained in a module. Figure 2.8 shows the average number of submodules contained in a module in each CL. The average number of submodules contained in a CL1 module increased until 2007, after which it can be seen to have slightly decreased. In levels below CL2, the average number of submodules has remained almost constant. In CL2, the average number of submodules has increased. The reason for this increase is that the number of CL3 modules has increased more than the number of CL2 modules, as shown in

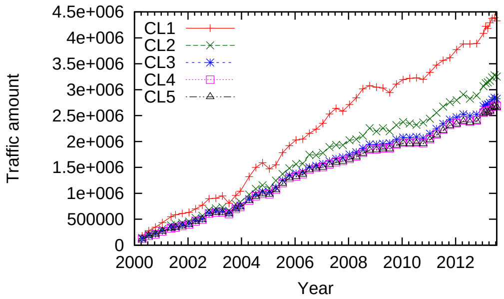


Figure 2.9: Normalized average traffic amount on inter-module links.

Sec. 2.4.4. Thus, more traffic has become concentrated on the links between CL2 modules.

2.5.2 Amount of traffic traversing links between modules

We now investigate the traffic concentration on links between modules. Figure 2.9 shows the increase in the average amount of traffic traversing links between modules in each CL. The average amount of traffic on links between CL1 modules has increased more than in other CLs. If this trend continues, more traffic will become concentrated on links between CL1 modules. The amount of traffic traversing links between CL2 modules also increased compared to the other CLs. In particular, the amount of traffic traversing links between CL2 modules in Fig. 2.9 has slightly accelerated since 2011. The reason for the shift in 2011 may relate to the change of structure in CL2 modules. In Fig. 2.2(c) and Fig. 2.2(e), we can see that the increase in the assortativity and diameter of CL2 modules stopped around 2011. This implies that ASes having few links have tended to connect to an AS with the highest degree in a CL2 module after 2011. This trend leads to the increase in traffic aggregated on links between CL2 modules, and the acceleration in the amount of traffic on links between CL2 modules prevents the Internet from accommodating the overall increase in traffic. We also examined by changing the value of γ from 238 at year 2004 to 3804 at year 2012, and the similar tendency of traffic concentration was observed. By the traffic concentration, the operating and investment costs of routers increase. For example, the increase in processing cost leads to heatings problem and the power cost to cool routers, which is the primary contributor to an energy footprint, exponentially increases [63]. Moreover, an expansion of network equipment is needed according to the increase in the traffic volume. However, the transit fee that an AS receives from the other ASes does not increase more largely than the increase of traffic traversing the AS [7]. The traffic concentration will prevent ASes from continual maintenance and expansion of network equipment. Therefore, a new evolution process is needed to slow down the traffic concentration on links between CL1 modules and links between CL2 modules.

2.6 Evolution to accommodate the increase in traffic amount

Our analysis of the flow hierarchy shows that traffic is concentrated on links between CL1 modules and links between CL2 modules. Therefore, an evolution process that considers the global structure of the Internet topology is needed to slow down this increase in concentration. In this section, we examine a new evolution process that attempts to increase the number of links between lower-level modules to reduce the traffic concentration among higher-level modules. We explain our evolution process in Sec. 2.6.1, and then evaluate its performance in Sec. 2.6.2.

2.6.1 Evolution process to slow down traffic concentration

The results presented in Sec. 2.5 show that traffic has become increasingly concentrated on links between CL1 modules and links between CL2 modules. This is mainly because the number of ASes within CL1 and CL2 modules has increased, leading to an increase in the traffic generated in these modules. To continually accommodate the increase in traffic amount, the Internet topology requires a new evolution process to reduce this concentration at the links. Because the degree of traffic concentration on the links depends heavily on the global structure of the topology, our focus here is a global structure that can accommodate more traffic without increasing the concentration. For this purpose, we apply our evolution process in a centralized manner, rather than in the autonomous manner currently employed by ASes.

The basic approach of our evolution process is to construct more links between modules at lower CLs. With the links between lower CL modules, the traffic concentration in the current Internet can be relaxed, as some of the traffic will no longer have to traverse links between higher-level modules. On the one hand, our evolution process is necessary to avoid traffic concentration among higher-level modules associated with the increase in traffic amount. On the other hand, our evolution process relies to some extent on the current topological characteristic that attempts to aggregate many paths into one link. In fact, the Internet topology has evolved such that a hub AS attracts more intra-module links (see discussion of Fig. 2.2(b)). The hub AS aggregates and exchanges traffic from/to other modules. In the proposed evolution process, we must avoid traffic concentration among higher-level modules while retaining the characteristic of traffic aggregation used in the past. We therefore introduce a parameter w to represent the threshold of the number of links between hub ASes in different modules. As we increase w, the number of links between modules increases, which will lead to a relaxation in traffic concentration at higher-level modules. By changing the value of w, we are able to examine how the number of links between modules slows down the traffic concentration in links between higher-level modules. Formally, w is defined as follows. Let $E_v(CLx)$ be the set of links between a hub AS and another AS in a CLx module, and $E_h(CLx)$ be the set of links between CLx modules. We define the ratio $R(CLx)$ of links in $E_h(CLx)$ to both $E_v(CLx)$ and $E_h(CLx)$ at CLx as:

$$R(CLx) = \frac{|E_h(CLx)|}{|E_v(CLx)| + |E_h(CLx)|}. \tag{2.5}$$

Then, our evolution process increases the links in $E_h(CLx)$ until $R(CLx)$ exceeds the threshold w. Figure 2.10 illustrates how $R(CLx)$ is calculated. A red node denotes a hub AS, which we call the gateway AS hereafter, in a module. A link between two red nodes is a link in $E_h(CLx)$, which is shown as a blue line. A link between a red node and a white node is a link in $E_v(CLx)$, which is shown as a red line. By increasing w, links in $E_h(CLx)$ are constructed between blue nodes. We then evolve a topology T using the following evolution process.

Step 1 Add new ASes to T.

Step 2 Add only one link for each new AS in T such that the new AS connects links to T.

Step 3 Calculate the flow hierarchy of T.

Step 4 Repeat the following steps from CL6 to CL1.

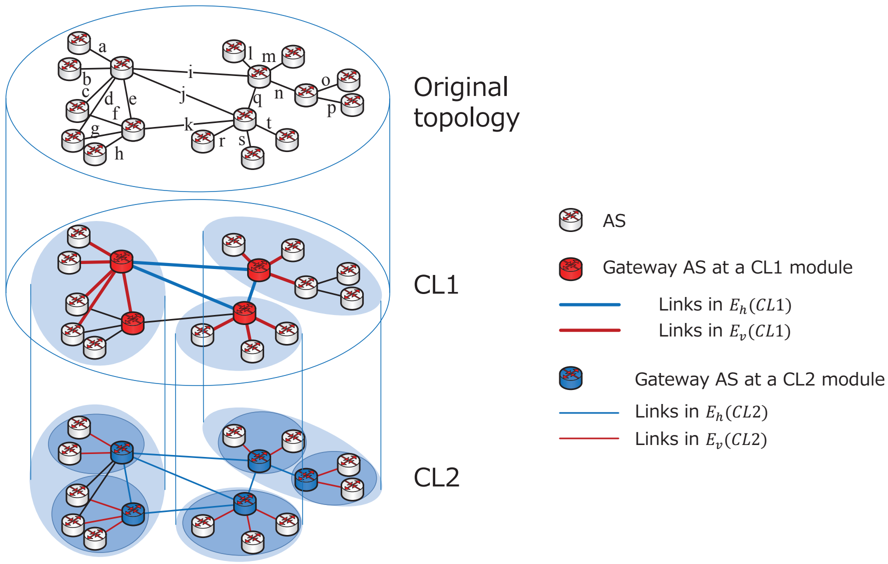


Figure 2.10: Illustrative example for $E_v(CLx)$ and $E_h(CLx)$.

Step 4.1 Add a link between modules at the same CL.

Step 4.2 Calculate $R(CLx)$.

Step 4.3 If $R(CLx) < w$ and the connection among CLx modules is not a full mesh, return to Step 4.1.

In Step 4.1, the link is constructed between gateway ASes, because a certain degree of traffic aggregation should be retained to preserve its characteristics.

Note that the current Internet does not have a mechanism which lets an AS know the location and the CL of the other gateway ASes. However, each AS can estimate whether an AS is a gateway from the AS paths in BGP tables. When most AS paths traverse a specific AS, the AS is considered as a gateway AS. Since the amount of traffic on links between modules in the same CL differs according to CL, as shown in Fig. 2.9, the traffic amount on links connecting to gateway ASes also varies with the CL. By investigating the number of AS paths that traverse the gateway AS, the CL of the gateway AS can be estimated.

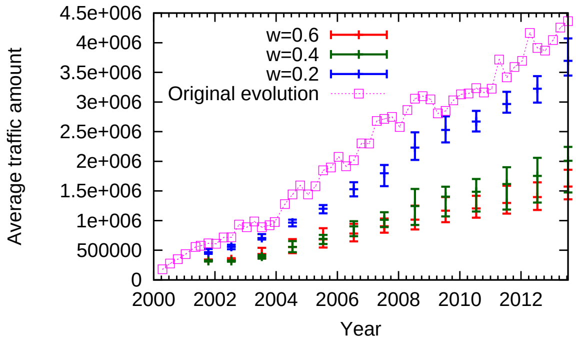
2.6.2 Effect of the evolution process

Backtracking the Internet topology

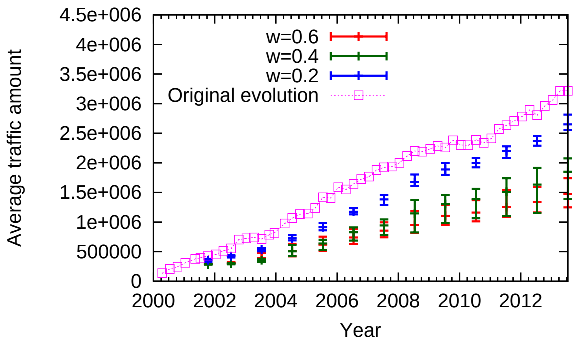
We examine the effect of our evolution process in terms of slowing down the traffic concentration. For this purpose, we apply our evolution process to the Internet topology in the year 2000, and evolve the topology until 2013. Then, we compare the degree of traffic concentration in the evolved topology with that of the actual Internet topology in 2013.

To apply our evolution process, we first check the ASes and links added from year y to year $y+1$ from $G(y)$ and $G(y+1)$. Here, $G(y)$ represents the actual Internet topology at year y. We then evolve the topology such that the ASes are the same as those in the Internet topology in the next year. Links between ASes are constructed by the proposed evolution process described in Sec. 2.6.1. The evolution process is repeatedly applied 13 times, that is, the topology $T(y)$ is evolved to $T(y+13)$. Note that when some ASes vanish at $G(y+1)$, we remove them and their links from $T(y+1)$ just after Step 1. If the topology $T(y+1)$ becomes unconnected by this removal process, we select the largest connected component for further evolution. Selecting the largest connected component leads to a decrease in the number of ASes and links. However, we can confirm that the number of ASes in unselected connected components is less than 1% of all ASes, so the impact of this decrease is negligible.

At Step 3, we re-calculate the flow hierarchy after adding links in Step 2 such that the flow hierarchy reflects the change of traffic aggregation altered by the link addition. At Step 4.1, we randomly select a pair of gateway ASes to construct a link on $E_h(CLx)$. Instead, we could calculate the optimal pair that minimizes the amount of traffic traversing links between higher-level modules. However, such a calculation is difficult in practice, because it requires complete information about the Internet topology and AS paths. Therefore, we randomly select a pair of gateway ASes, and estimate the change in the amount of traffic traversing links. In this chapter, we evolve the Internet 10 times with different random seeds, and present the average change in the amount of traffic traversing links. After Step 4.1, when the number of links in $T(y+1)$ is the same as the number of links in $G(y+1)$, we stop applying our evolution process. After Step 4.3, we ensure that the number of links in $T(y+1)$ is equal to that of $G(y+1)$ for the purpose of comparison. We randomly



(a) Average traffic amount at CL1 inter-module links.



(b) Average traffic amount at CL2 inter-module links.

Figure 2.11: Average traffic amount at CL1 and CL2 inter-module links in the topology grown by the proposed evolution process.

select links from a set that is not included in $T(y+1)$ but is included in $G(y+1)$, and add the selected links to $T(y+1)$. Finally, y is set to $y+1$, and our evolution process is again applied until y becomes 2013.

Evaluation results of the proposed evolution process

To investigate how the number of links in $E_h(CLx)$ should be increased in the Internet topology, we evaluate the amount of traffic at links between higher-level modules in the topology evolved by our evolution policy. Figure 2.11 shows the average and the range of traffic amount on CL1 and CL2 inter-modules links of 10 evolutions with different random seeds. The vertical axes in Fig. 2.11(a) and Fig. 2.11(b) are normalized by the average traffic amount on links between CL1 modules and between CL2 modules, respectively, on 15 July 2000. The figures show results for $w = 0.2$, 0.4, and 0.6. Note that the evolved topology has more links in $E_h(CLx)$ as we increase w. Figure 2.11 shows that the evolution policy slows down the increase in traffic at links between higher-level modules. When w is 0.2, this slow down is small, because the size of $E_h(CLx)$ is small. In contrast, when the threshold w is set to 0.4 or 0.6, the slow-down effect is high. This is because traffic no longer needs to traverse links between higher-level modules. More importantly, the increase in traffic on links between CL2 modules has accelerated since 2011 in the original evolution, but this trend is not observed in Fig. 2.11(b). We observe that the traffic concentration given by our evolution policy with $w = 0.6$ is not significantly different from that when $w = 0.4$. This suggests that, when the size of $E_h(CLx)$ is above some threshold, the slow-down effect is not enhanced. We consider the traffic aggregated at links between higher-level modules to be adequately reduced when w is set to 0.4.

These results mean that a suitable structure is derived when the threshold w is 0.4. Although our evolution policy with $w = 0.4$ slows down the traffic concentration, the volume of traffic on links between higher-level modules increases slightly. Therefore, there is a possibility that the traffic concentration will become a problem in the distant future. To further reduce the traffic concentration on these links, each AS exchanges information about which AS is a gateway in the modules at each CL. Thus, some feedback mechanism is required to achieve a suitable global structure and global performance. Under such a feedback mechanism, more suitable pairs of gateway ASes can be selected to construct links in $E_h(CLx)$. This evolution process may be difficult to realize in the current mechanism of link construction of ASes because this evolution process does not include the economic incentive for ASes. Our focus is not to develop a rigid evolution policy, but investigate how the principles of evolution policy lead to the difference of the evolution of the global structure and whether it is possible to relax the future traffic concentration or not. Results show that our proposed evolution process can relax the traffic concentration on links between top level modules by a half of the traffic concentration in the original evolution as shown in Fig. 2.11. In practice, some economic incentives for promoting ASes toconstruct links based on the evolution process are necessary to optimize the performance of the global Internet, which is left for our future work.

2.7 Are Hyper Giants necessary for the evolution of the Internet?

Recently, the appearance of Hyper Giants, such as Google and Akamai, has impacted the traffic flow and evolution of the Internet topology. They generate huge amounts of traffic and send this across the Internet. Ref. [15] found that the traffic amount sent by Hyper Giants is about 30% of the whole amount across the Internet, and the traffic amount generated and sent by Hyper Giants is expected to increase [7]. The appearance of Hyper Giants has influenced the structure of the Internet topology [7, 11, 13, 15, 64]. Hyper Giants construct peering links to ASes that use services provided by Hyper Giants, so that traffic sent by Hyper Giants does not traverse large ISPs. The primary reason that Hyper Giants construct a lot of peering links is to reduce the transit cost of traffic traversing large ISPs.

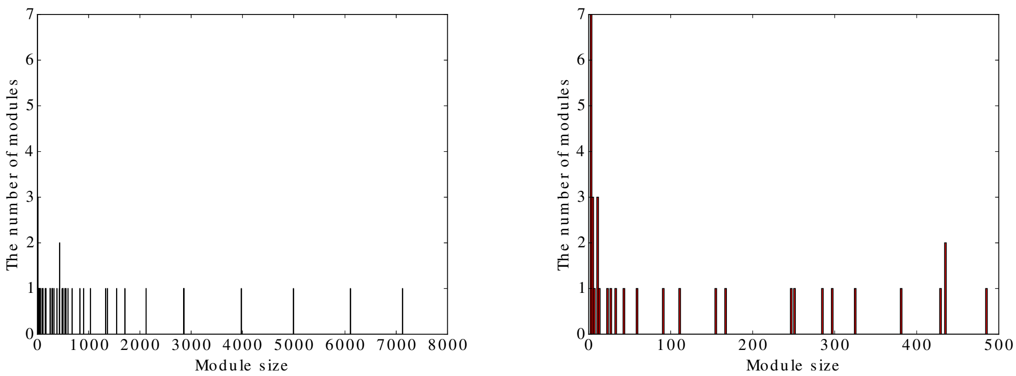
The increased number of peering links partly helps the Internet topology to achieve a suitable structure to continually accommodate an increase in traffic amount. This is because peering links are connected between modules, which are links in $E_h(CLx)$. However, the appearance of Hyper Giants alone will not allow the Internet topology to evolve sufficiently to accommodate the increase in traffic amount, because only traffic between a Hyper Giant and an ISP can be exchanged over the peering links. To accommodate the increase in traffic amount, some of the traffic aggregated at links suffering from overconcentration must traverse the other links. The peering links of Hyper Giants do not exchange traffic, but links between ISPs can. Therefore, it is important to consider not only the peering links of Hyper Giants, but also the connection among ISPs.

2.8 Conclusion

An evolution process that considers the global structure of the Internet topology is needed to accommodate future traffic amount. An analysis of the structure in the topology reveals where the traffic is concentrated, which enables us to develop an evolution policy to relax the overconcentration. Many works have shown that the Internet has a hierarchical structure [9, 36, 37]. Within this hierarchical structure, an AS aggregates traffic from lower-level ASes, and relays the traffic to higher-level ASes. To identify the hierarchical nature of traffic aggregation, we investigated the long-term change in the structure of the Internet topology by analyzing the flow hierarchy. By examining the internal structure of a module, we found that each hub AS in a module is a gateway that aggregates and exchanges traffic from/to other modules. Furthermore, when the traffic demand is given by the gravity model, we showed that the amount of traffic traversing links between top-level modules and link between second-level modules has been rapidly increasing.

We considered a new evolution policy to avoid traffic concentration, and then examined how this policy could slow down the traffic concentration compared with the actual evolution of the Internet topology. The basic approach behind our evolution policy is to construct more links between gateway ASes in different modules at the same level of the flow hierarchy, particularly at lower levels. While the topology retains the characteristic of traffic aggregation, a new policy is needed to avoid traffic concentration. To retain this characteristic, links between a gateway AS and other ASes in the same module should be preserved. We therefore introduced a threshold that determines the ratio of links between gateway ASes in different modules to the links between a gateway AS and other ASes. By varying this threshold, we examined how many links between gateway ASes are needed to slow down the traffic concentration. In evaluating the effect of our evolution policy, we found that the traffic concentration at links between higher-level modules decreased noticeably when the threshold was 0.4 or 0.6. We thus considered the traffic aggregated at links between higher-level modules to be adequately reduced when $w = 0.4$.

In future work, we will develop an evolution policy that considers the merits of each AS. Because the evolution of the Internet topology is not centrally controlled but an ensemble of individual link construction by each AS, the evolution policy should be applied to each AS. Indeed, Refs. [7, 65] investigated the evolution of the Internet topology from the viewpoint of game theoretic behavior by each AS. Future evolution policies must consider both the merit to individual ASes and the merit for the global structure of the Internet.



(a) All modules.

(b) Modules that contains smaller than 500 nodes.

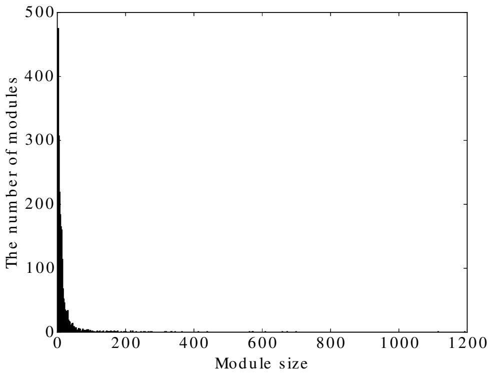
Figure 2.12: The size of CL1 modules that are divided by the Louvain method.

Appendix 2.A - The impact of resolution limit on analysis of the evolution of the flow hierarchy

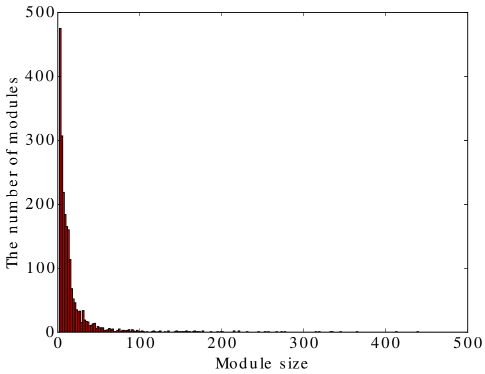
In Sec. 2.4, we analyzed the evolution of the Internet topology by investigating the evolution of the flow hierarchy. In the investigation, we used the Louvain method to exploit the flow hierarchy from the Internet topology. However, it is known that the Louvain method suffers from a resolution limit. The resolution limit is the characteristic scale of the smallest size of a module that the method can detect. To determine the effect of resolution limit on the analysis of the evolution of the flow hierarchy as shown in Table 2.5 and Fig. 2.6, we analyze the evolution of each CL with the Infomap method [46], which does not much suffer from the resolution limit [62].

Analysis of the size of module by Infomap method

We first investigated the size of module derived by the Louvain method and the Infomap method. Figure 2.12 shows the size of CL1 modules derived by the Louvain method at 15th November 2013. X axis indicates the size of a module and Y axis indicates the number of modules. The width of a bar is 2 in both of Fig. 2.12(a) and Fig. 2.12(b). The number of modules containing fewer than



(a) All modules.



(b) Modules that contains smaller than 500 nodes.

Figure 2.13: The size of CL1 modules that are divided by the Infomap method.

Table 2.7: The number of modules in each CL derived by the Infomap method

Year	CL1	CL2	CL3
2000	445	573	4
2002	752	950	19
2004	887	1313	53
2006	1127	1625	25
2008	1379	2221	42
2010	1757	2604	49
2012	1991	3177	64

10 ASes is only about 10 and there is a few large modules containing more than 5000 ASes. Figure 2.13 shows the size of CL1 modules derived by the Infomap method at 15th November 2013. X axis and Y axis show the same as them of Fig. 2.12. By the Infomap method, much more amount of small size modules appear compared to the Louvain method. This means that there is the effect of resolution limit on our analysis of the modular structure.

Analysis of the evolution of the flow hierarchy by Infomap method

We next clarify whether our analysis of Table 2.5 and Fig. 2.6. Table 2.7 shows the number of modules in each CL derived by the Infomap method. The depth of the deepest module is always

Table 2.8: The average number of ASes in a module derived by the Infomap method.

Year	CL1	CL2	CL3
2000	18.34	10.33	4
2002	18.1	9.16	5.95
2004	20.31	10.56	7.66
2006	20.34	10.87	4.52
2008	21.26	10.74	4.83
2010	20.26	10.91	17.67
2012	21.1	10.67	6.03

3 from 2000 to 2012, i.e., the depth has not changed. This result is the same as the result with the Louvain method. The number of modules in middle or bottom level such as CL2 and CL3 has more greatly increased than CL1 modules which is top level. This result also agrees with the result with the Louvain method.

Table 2.8 shows the average number of ASes in a module derived by the Infomap method. The increase of ASes in a CL1 module is slight. The reason is that there are much more number of small size CL1 modules as shown in Fig. 2.13. Nevertheless, the number of ASes in CL1 modules has increased compared to CL2 and CL3. This suggests that the number of ASes in large size CL1 modules has greatly increased. From Table 2.7 and Table 2.8, we consider that the structure in top level has expanded with the center pattern in Fig. 2.6 since the structure in top level has expanded by increasing the number of ASes within a module. The structure in low level has expanded with the left pattern in Fig. 2.6 since modules has more increased than top level. This result agrees with the result of analysis with the Louvain method.

Chapter 3

A provider and peer selection policy for the future sustainable Internet

3.1 Introduction

The Internet is currently the largest network system in the world, and is rapidly becoming a social infrastructure as the number of network devices, users, and content increases. As of November 2014, there were at least 46,120 autonomous systems (ASes) and 172,271 interconnected links. The number of ASes and links has been increasing in response to the rising volume of traffic on the Internet. This volume has increased fivefold since 2012, and Cisco forecast an annual growth rate of 21% from 2013 to 2018 [1]. This rise is partly due to the current increase in mobile traffic [2], as well as traffic from new and emerging applications, e.g., sensor devices with a communication function [3]. Such increases will lead to a significant concentration of traffic on existing network equipment and links. Ideally, the Internet should be able to accommodate future increases in traffic volume without congestion. For this purpose, all Internet service providers (ISPs) must continually improve their network equipment in response to traffic increases. However, such improvements cost money, so it is crucial that the ISPs extract sufficient benefits. That is, each ISP should attain some economic utility through the traffic exchange with other ASes. With this economic utility, ISPs can improve their network equipment to ensure it can handle further traffic increases. This is an important foundation for wholesome growth in the Internet, and we refer to this characteristic as "sustainability": as the Internet becomes more sustainable, it is better able to meet its requirement as our social infrastructure.

Whereas most of other social infrastructures are provided by monopolistic or oligopolistic organizations, the Internet is a decentralized system that consists of thousands of independent ASes of various business types such as ISPs, contents providers and enterprise networks. Within the Internet, each AS selfishly selects ASes to connect with in an effort to increase its own economic utility.

The economic utility of an AS is determined by subtracting outcome from income. The income includes the total transit fees received from other ASes. The transit fee is a charge incurred for the offer by one AS to transfer traffic to the other AS on a link. The outcome includes transit fees to pay to other ASes, peering costs, and the maintenance cost of the AS's network. The peering cost is the cost of maintaining a peering link. The maintenance cost of an AS is a cost incurred for operations, staff, and equipment needed to exchange traffic. The income and outcome are dependent on the amount of traffic traversing the AS or links connecting with the AS. The economic utility of an ISP may change through link constructions between other ASes because traffic flow within the Internet is affected by link constructions. Since the Internet is not a centralized system, it is impossible to optimally manage link constructions for all ISPs and thus obtain sufficient economic utility to improve network equipment. Therefore, each AS has to consider the effect of its link construction on the economic utility of and traffic on other ISPs from information that the AS can know, and coordinately constructs links such that the Internet is sustainable.

In this chapter, we first reveal whether the future Internet is sustainable even if the Internet topology evolves according to the current policies of ASes. For this purpose, we investigate the variation in the economic utility of ASes from past to present. Our result shows that about 20% of ISPs have seen their economic utility reduce from 1998 to 2013. We then discuss the reason for and the mechanism behind the emergence of ISPs with reduced economic utility, revealing that ISPs with insufficient economic utility have been unable to adequately construct new links. We next investigate quantitatively whether the Internet is sustainable. For this purpose, we introduce a metric that can be used to characterize the sustainability of an ISP. The metric is defined as the rate of increase in an ISP's economic utility against the rate of increase in the amount of traffic handled by the ISP. The metric captures whether the ISP can obtain economic utility to improve its network equipment in response to an increase in traffic. Our results show that around half of ISPs do not obtain sufficient economic utility in response to a traffic increase, and the ratio has tended to increase in recent years. We then develop and evaluate evolution policy that selects ASes with which to connect such that the sustainability of an unsustainable ISP is improved.

This chapter is organized as follows. Section 3.2 gives an overview of related work on the analysis of the Internet topology and the current policy for selecting an AS to connect links with. Section 3.3 shows the sustainability of the Internet under the current policy. In Section 3.4, we present a policy that can improve the sustainability of ISPs and we evaluate the variation in sustainability of each ISP under the policy. Finally, conclusions are presented in Section 3.5.

3.2 Related work

The global structure of the Internet topology affects the traffic flow. Thus, various performance properties of the Internet, such as the amount of traffic that can be accommodated within the Internet and reliability against network failures, are dependent on the structure of the Internet topology. For the past dozen years, various structural properties of the Internet topology have been widely investigated. Faloutsos et al. [8] revealed that the degree distribution of the Internet topology has power-law attributes, and Satorras et al. [9] showed that the distribution of betweenness centrality also follows a power law. These analyses are needed for a network operator of an AS to add new links and network equipment according to a design that considers the properties of the topology. In addition, determining properties of the Internet topology is vital to the evaluation of the performance of new applications and protocols on a topology reflecting structural properties of the Internet. For example, a topology reflecting properties of the Internet is required to evaluate the scalability of the Border Gateway Protocol [14]. However, these studies revealed only the current properties and their variation in the evolution of the Internet topology, and did not sufficiently discuss the future evolution of the Internet topology so as to improve the performance of the Internet.

In discussing the future evolution of the Internet topology, the focus should be on an AS's policy for constructing a link since the Internet topology has evolved by decentralized link constructions of ASes according to their own policies. Some studies have analyzed which features of policies have led to the current structural properties of the Internet topology. Reference [4] showed that the power-law degree distribution of the Internet topology results from link constructions made by each AS to improve its economic utility. Reference [6] proposed a simple dynamic model that captures salient features of the provider selection process, and revealed that most ASes today select a provider according to price, rather than performance or other criteria. Some studies proposed policies that improve an AS's economic utility. Ref. [17] proposed a framework that can be used to decide whether a transit link or a peering link with a neighboring AS is better improving economic utility. Reference [18] proposed a model of an ISP's peering strategy that increases economic utility according to the amount of traffic on the ISP and the amount of traffic generated by content providers. However, these studies focused on a local decision based only on the amount of traffic at the time when a link is constructed. Furthermore, they do not consider whether each ISP within the Internet can continually obtain economic utility.

Nowadays, the study of mechanisms that can optimize the performance of the global Internet is one of main research directions in the study of the future Internet architecture [66–68]. For example, Ref. [66] proposed an incentive mechanism that encourages ASes to implement the outbound filtering of spam traffic on the Internet, and Ref. [67] proposed a mechanism of controlling the growth of Internet routing tables. In addition to improvement of these network performances, the sustainability of the increase in traffic should be considered for the future evolution since the Internet is a social infrastructure. Therefore, it is necessary to consider a future mechanism by which ASes select an AS to connect links with such that ISPs continually improve their network equipment for the increase in traffic. We thus study what information is needed and how ASes should use such information in a future mechanism by presenting policies that improve the sustainability of each ISP.

Some studies analyzed behaviors in link constructions of ASes from the view point of game theory since each AS selects ASes to connect links by a competition principle. For example, Ref. [7] proposed a link construction model based on a game theoretic approach, and addressed that the structure of the Internet topology depends on the amount of traffic generated by large content providers. Ref. [69] proposed a link construction method to maximize the economic utility of each AS from the view point of game theory. However, these game-theoretic approaches are not available for the actual link construction because link construction methods provided in these studies use the information that each AS cannot obtain in practice. In the model of Ref. [7], each AS uses the global information about the Internet topology for selection of ASes to connect links with. In Ref. [69], it is assumed that the information about traffic flow after link constructions is available although each AS cannot estimate the traffic flow after link constructions. Therefore, policies that we provide in this chapter do not include a game-theoretic approach.

3.3 Sustainability of the Internet topology

For the Internet to be sustainable, each ISP has to continually improve its network equipment for the increase in traffic. However, since the expansion of network equipment has a cost, an ISP that does not obtain sufficient economic utility for the traffic amount on the ISP cannot continually improve its network equipment. To consider policies of ASes for sustainable evolution of the Internet, it is necessary to clarify the reason for and the mechanism behind the emergence of such ISPs. In this section, we first investigate the evolution of the economic utility of each AS in response to the evolution of the Internet topology to find the sustainability of the current Internet. We then show features of ASes that cannot improve network equipment and thus reveal the process by which such ASes emerge. Finally, we define a sustainable ISP as an ISP that can obtain sufficient economic utility for the increase in traffic handled by the ISP, and show to what degree ISPs are sustainable.

3.3.1 Evolution of each AS's economic utility

In this section, we show the variation in the economic utility of ASes in response to the evolution of the Internet topology. For this investigation, we first obtain topology data from CAIDA's web site [70]. These topology data are derived from AS paths included in routing table snapshots from 1998 to the present day collected by the RouteViews project [32] and RIPE [33]. An AS path is described as a list of ASes that the traffic traverses between end ASes of the AS path. The Internet topology is then extracted from the AS paths. Furthermore, the RouteViews project proposed a method of inferring a type of a link (i.e., a transit link or peering link) and which AS is a provider on a transit link. The topology data we obtain include this information.

The economic utility of an AS is determined by the amount of traffic passing through its links. However, information concerning the actual amount of traffic on most paths is unavailable. Therefore, we simulate the traffic demand on the Internet topology based on the gravity model [49]. This is a simple method for estimating traffic demand [49, 50], and has been used in various studies [17, 51]. The traffic demand of AS i is proportional to its degree, because the business scale of an AS is known to be related to this characteristic [7,52]. Note that, as discussed in [53], the gravity model does not capture self-similarity and the long-range dependence of traffic. However, we use the gravity model to assign traffic demand, as our study is focused on the evolution of economic utility calculated from traffic volume, rather than short-term traffic fluctuations. The gravity model is represented by the following expression:

$$e_{ij} = \lambda \cdot x_i \cdot x_j, \tag{3.1}$$

where e_{ij} is the amount of traffic on the path between AS i and AS j. x_i and x_j denote the traffic demand of AS i and AS j, respectively, and λ is a scaling factor, which is set to 1 hereafter. Note that this setting may not reflect the actual traffic amount. However, our focus here is to reveal the evolution, rather than the actual amount, of traffic passing over certain links. Google, Akamai, Microsoft, and Yahoo! are defined as Hyper Giants by some studies [7, 15]. These Hyper Giants send huge amounts of traffic compared with other ASes. We therefore checked the names of organizations managing ASes in the CIDR report [54], and regard ASes whose names contain "Google", "Akamai", "Microsoft", and "Yahoo" to be Hyper Giants. Then, λ is set to 1 if neither AS i nor AS j are Hyper Giants; otherwise, λ is set to 895. These values were determined based on a Cisco report [1, 55] that quantifies the amount of traffic on the Internet. Cisco reported the total volume of traffic across the whole of the Internet to be 369 exabytes in 2011, with that between users and data centers constituting 116 exabytes. According to the Internet Registry, there are a total of 60538 ASes, and only around 30 famous content providers. Therefore, the average amount of traffic handled by each AS is 4.18 petabytes (= $(369 - 116)/(60538 - 30)$ exabytes), and the average sent by each large content provider is 3.74 exabytes ($= 116/30$ exabytes). Thus, we set λ to 895 ($= 3.74 \cdot 1000/4.18$) for the Hyper Giants. Although this value may not reflect the actual amount of traffic, it allows us to examine the traffic concentration on certain links.

The economic utility of an AS is derived using cost models [7, 71, 72]. In these cost models, the economic utility is calculated from the traffic amount handled by links and the types of the links. In particular, Ref. [7] used realistic values of parameters in its cost model by taking values from another study and an investigation conducted by network consultant companies. Therefore, we believe that the cost model in Ref. [7] can derive more realistic economic utility when the topology and the traffic amount handled by each link are given. Thus, we use this cost model to calculate the economic utility. The economic utility of an AS i, f_i, is expressed as

$$f_i \quad = \quad C_i + I_i - P_i - R_i - L_i, \tag{3.2}$$

where C_i is total revenue from customers of AS i, I_i is the revenue from users in AS i, P_i is the total transit fee paid to providers of AS i, R_i is the total cost of peering links connected to AS i, and L_i is the total cost for operating and maintaining a network in AS i. Each term in Eq. 3.2 is calculated as follows:

$$\begin{aligned}
C_i &= \sum_{c \in S_{i,c}} T(v_{ic}), &(3.3)\\
I_i &= T(v_{ii}), &(3.4)\\
P_i &= \sum_{p \in S_{i,p}} T(v_{ip}), &(3.5)\\
R_i &= \sum_{r \in S_{i,r}} R(v_{ir}), &(3.6)\\
L_i &= L(v_i), &(3.7)
\end{aligned}$$

where $S_{i,c}$, $S_{i,p}$, and $S_{i,r}$ are sets of customers of AS i, providers of AS i, and ASes constructing peering links with AS i, respectively. v_{xy} is the amount of traffic on a link between AS x and AS y, v_{ii} is the total amount of traffic generated and consumed by AS i, and v_i is the total amount of traffic generated, consumed, and transmitted by AS i. T, R, L are functions to calculate the transit fee, cost of peering links, and maintenance cost of a network in an AS based on a traffic volume of v. These are defined as follows:

$$T(v) = m_t \cdot (v)^{e_t}, \tag{3.8}$$

$$R(v) = m_r \cdot (v)^{e_r}, \tag{3.9}$$

$$L(v) = m_l \cdot (v)^{e_l}. \tag{3.10}$$

The parameters in Eqs. (3.8)–(3.10) are constants. In [7], these values were calculated based on a previous study [17] and an investigation by network consultant companies. They were given as follows:

$$m_t = 20, \tag{3.11}$$

$$e_t = 0.75, \tag{3.12}$$

$$m_r = 300, \tag{3.13}$$

$$e_r = 0.25, \tag{3.14}$$

$$m_l = 100, \tag{3.15}$$

$$e_l = 0.5. \tag{3.16}$$

Although these settings are relatively realistic, this cost model cannot derive accurate values for the revenue and cost of each AS. This is because the transit fee and cost of peering links are different in each agreement between two ASes and each contract with an Internet exchange (IX). However, our main focus is not to derive accurate economic utility, but to analyze the variation in economic utility of each AS with an increase in traffic. Thus, we use the cost model in [7].

Figure 3.1 shows the economic utility of each AS in 1998 and 2013. The X axis indicates the economic utility of each AS in 1998, and the Y axis indicates that in 2013. The dashed line shows $y = x$, and a plot above the dashed line means that the economic utility of the AS increased from 1998 to 2013. There are ASes that existed in either 1998 or 2013 but not both. In Fig. 3.1, the economic utility of an AS at a time when the AS did not exist is regarded as zero. In 1998,

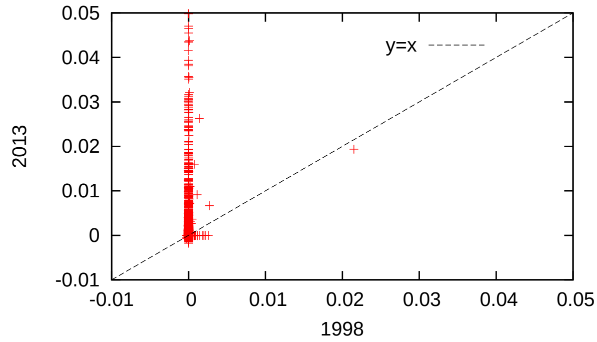


Figure 3.1: The economic utility of each AS in 1998 and 2013.

the economic utility was almost the same and close to zero for most ASes. In 2013, however, the economic utility differed greatly among ASes. The total number of ASes plotted in Fig. 3.1 is 46,136, and the number of ASes that increased their economic utility from 1998 to 2013 is 7085; i.e., the ratio of ASes that increased their economic utility is only about 12%. If the difference in economic utility of each AS increases in the future, most ASes will not be able to continually improve their network equipment and the Internet will not be sustainable in the face of an increase in traffic.

To reveal which features of ASes decrease their economic utility, we investigate various types of ASes. In this chapter, we classify these as top-level ISPs, middle-level ISPs, stub ASes, IXes, and Hyper Giants. Table 3.1 gives a definition of each type, and Table 3.2 lists the number of each AS type who suffered a decrease in economic utility from 1998 to 2013. The proportion of top- and middle-level ISPs whose economic utility decreased is small (about 21% and 23%, respectively). This is because the main revenue stream of an AS is transit fees from its customers. As the traffic on the Internet topology has increased, the transit fees received by each ISP have also increased, and so the economic utility of each ISP increases in response to the evolution of the Internet topology. ASes that are not ISPs have seen their economic utility decrease, because they do not place their customers on transit links. However, some 1547 middle-level ISPs have seen a decline in economic utility, the second highest number behind stub ASes.

Table 3.1: Definition of AS types.

Type	Definition
Top-level ISP	An AS that has no higher-level AS providers.
Middle-level ISP	An AS that has both providers and customers.
Stub AS	An AS that has no customers.
IX	An AS whose links are all peering links.
Hyper Giants	An AS whose organization name includes “Google”, “Yahoo”, “Microsoft”, or “Akamai”.

Table 3.2: Number of ASes whose economic utility decreased from 1998 to 2013.

Type	# of ASes with decreased economic utility	# of ASes
Top-level ISPs	13	61
Middle-level ISPs	1547	6721
Hyper Giant	82	99
IX	140	195
Stub AS	37199	37534

3.3.2 Mechanism of the appearance of ASes decreasing their economic utility

In considering policies that will ensure ASes are sustainable, it is necessary to clarify the process in which an ISP’s economic utility decreases. We first consider how an ISP obtains economic utility by exchanging traffic on neighbor links. On transit links, each ISP transmits traffic from its customers to its provider. By the definition of the cost model in Section 3.3.1, when an ISP receives traffic from its customer and transmits it to its provider, the transit fee that the ISP receives from its customer is the same as the transit fee that the ISP pays to its provider. The main revenue of an ISP is the transit fee for traffic that the ISP receives from a customer and transmits to another customer. This is because the ISP does not have to pay a transit fee to any provider. Therefore, the feature of top-level and middle-level ISPs that have sufficient economic utility is that the ratio of customers to all neighboring ASes is high. In Fig. 3.2,3.3, ISP i and ISP j are examples of middle-level ISPs that have more economic utility and have less economic utility, respectively. AS i has more customers

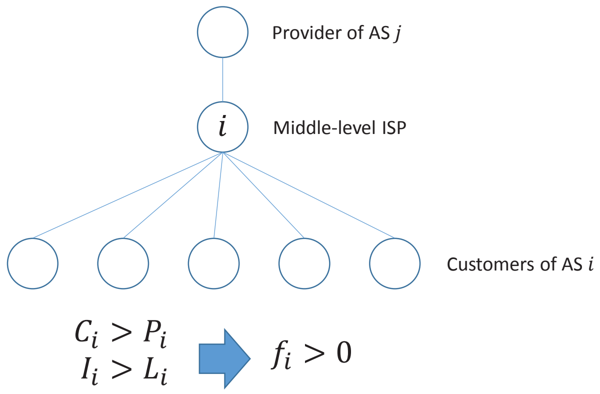


Figure 3.2: Features of middle-level ISPs that do and do not have sufficient economic utility.

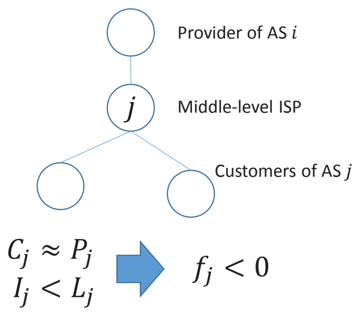


Figure 3.3: Process of decreasing economic utility in middle-level ISPs that transmit little traffic.

and more traffic between its customers traverses AS i. In contrast, since AS j has few customers, the amount of traffic through AS j between customers of AS j is small. Most traffic traversing AS j is traffic for communication between customers and providers of AS j. Thus, the transit fee that AS j receives from its customers is close to the transit fee that AS j pays to its providers. In this case, the main factor affecting the economic utility of AS j is the revenue from users in AS j and the maintenance cost of the network of AS j. When the traffic generated and consumed at AS j is small, the maintenance cost is dominant. This results in the decrease in economic utility of AS j.

We now discuss which types of AS can attract more customers on transit links. ASes that do not attain sufficient economic utility cannot apply a transit and/or peering strategy to improve their economic utility, because they cannot construct new links. Therefore, ASes that have less economic

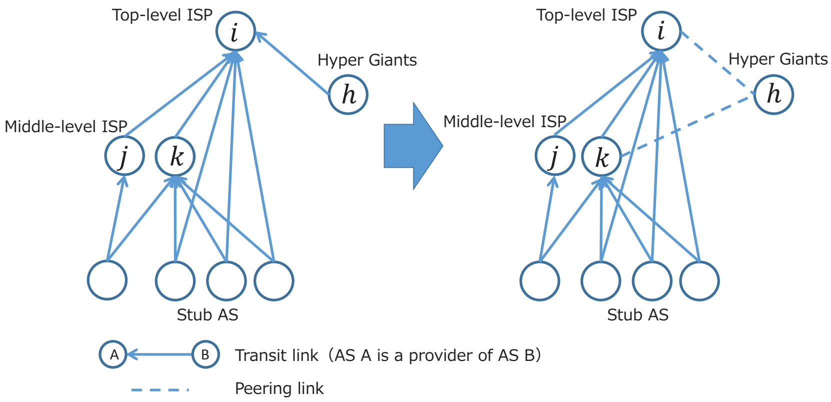


Figure 3.4: Process of decreasing economic utility of middle-level ISPs that transmit few traffic.

utility will see further decreases. Figure 3.4 illustrates the process whereby an ISP sees a decrease in its economic utility. In this figure, AS j is a middle-level ISP that has few customers. AS j cannot construct new peering links, because it does not get sufficient economic utility for new link constructions. Even if AS j constructed a new peering link, not much traffic would traverse it because the total amount of traffic traversing AS j is currently small. Thus, AS j cannot attract traffic by link construction. In contrast, AS i and AS k can increase their economic utility by link construction, because the amount of traffic traversing these ASes is large before the links are constructed. By constructing these peering links, traffic between the Hyper Giants and Stub ASes traverses AS i or AS k. This further decreases the amount of traffic traversing AS j. In practice, the average amount of traffic traversing middle-level ISPs that have increased their economic utility is about 1.5 times that of middle-level ISPs whose economic utility has decreased. Thus, an ISP that handles a greater volume of traffic can attract more traffic, and the economic utility gap among ISPs becomes wider.

3.3.3 Sustainability of the Internet with the current evolution

We define the sustainability of an AS to allow a quantitative investigation of how many unsustainable ASes there are within the Internet. The sustainability of AS i at time t, $S_i(t)$, is defined

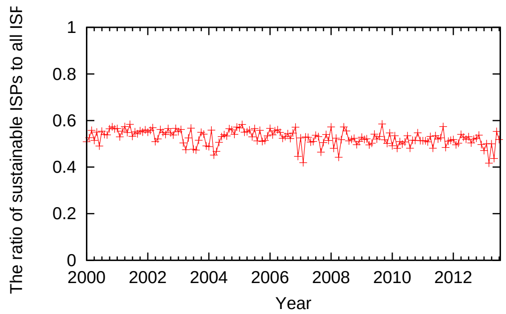


Figure 3.5: Ratio of sustainable ISPs to all ISPs.

as

$$S_i(t) \;=\; \frac{\Delta U_i(t)}{\Delta F_i(t)}, \tag{3.17}$$

where $U_i(t)$ is the economic utility of AS i at time t, and $F_i(t)$ is the amount of traffic generated, consumed, and transmitted by AS i at time t.

$$\Delta U_i \;=\; \begin{cases} -\frac{U_i(t)-U_i(t-\Delta t)}{U_i(t-\Delta t)}, & (U_i(t-\Delta t) < 0) \\ \frac{U_i(t)-U_i(t-\Delta t)}{U_i(t-\Delta t)}, & (U_i(t-\Delta t) >= 0) \end{cases} \tag{3.18}$$

$$\Delta F_i \;=\; \frac{F_i(t) - F_i(t-\Delta t)}{F_i(t-\Delta t)}, \tag{3.19}$$

where $U_i(t)$ is the economic utility of AS i at the time t, and $F_i(t)$ is the amount of traffic generated, consumed and transmitted by AS i at the time t. The sustainability of AS i, $S_i(t)$, is the rate of increase in the economic utility against the rate of increase in traffic handled by AS i. In the case that $S_i(t)$ is more than 1, AS i is sustainable in the face of an increase in traffic.

Figure 3.5 shows the ratio of sustainable ISPs to all ISPs. In Fig. 3.5, Δt is a month and the sustainability of an ISP is calculated each month. We found that the ratio of sustainable ISPs is less than 60%. In addition, the ratio of sustainable ISPs has decreased since 2005. The reason why the ratio of ISPs that have enough economic utility decreases is that the increase in the ISP's economic utility is smaller than the increase in traffic handled by the ISP. Figure 3.6 shows the average economic utility of ISPs and the average amount of traffic handled by the ISPs. Since the

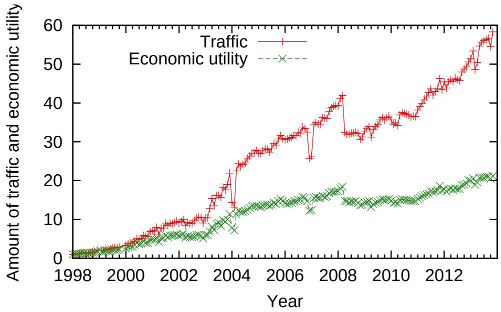
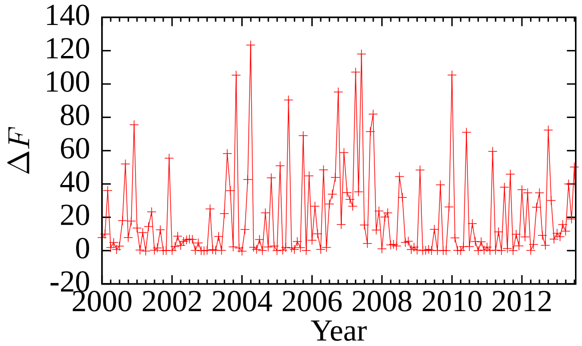


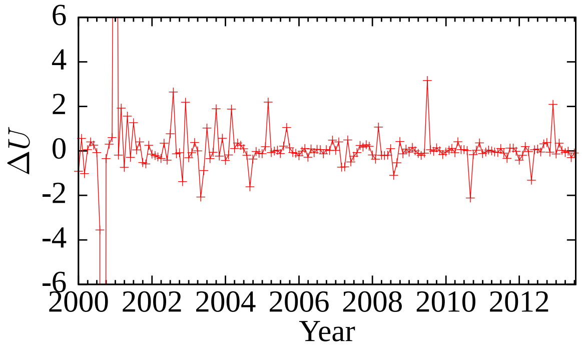
Figure 3.6: Normalized total traffic volume and revenue of all ISPs in 1998.

absolute values are not comparable, these values are normalized by the values in 1998. From Fig. 3.6, we find that the increase in traffic handled by ISPs is more than the increase in the economic utility of ISPs. In addition, this gap has become wider over time. The economic utility of ISPs decreases even more because the transit fee is falling by about 30% per year owing to pricing competition among ISPs [73]. It is thus expected that the gap between the increase in traffic and the increase in economic utility will widen further. Therefore, the number of ISPs that can continually improve network equipment in response to an increase in traffic will become small according to the current evolution of the Internet topology.

Figure 3.7(a) shows the variation in the average rate of increase in traffic handled by an ISP and the average rate of increase in the economic utility of an ISP. We found that the average rate of increase in traffic greatly fluctuates. In addition, a more important point is that the average rate of increase in traffic has increased since 2013, whereas the rate of increase in economic utility has remained between 0 and 1. Since the rate of increase in economic utility is much smaller than the rate of increase in traffic, most ISPs are not sustainable. It is considered that unsustainable ISPs will become more common in the future because the rate of increase in traffic has outpaced that of economic utility since 2013.



(a) Average increase in rate of traffic on ISPs.



(b) Average increase in rate of economic utility of ISPs.

Figure 3.7: Average increase in rate of traffic and economic utility of ISPs.

3.4 Evolution for the sustainable Internet topology

As shown in Section 3.3.3, the number of ISPs that do not have sufficient economic utility has increased in the current evolution of the Internet topology. However, since the Internet is a social infrastructure, it has to be sustainable. The Internet topology evolves by the decentralized link constructions of each AS. Therefore, we present a new policy of selecting ASes to connect links with such that all ISPs obtain sufficient economic utility, and then reveal what kind of information is needed and how each ISP should use such information to improve the sustainability of the Internet.

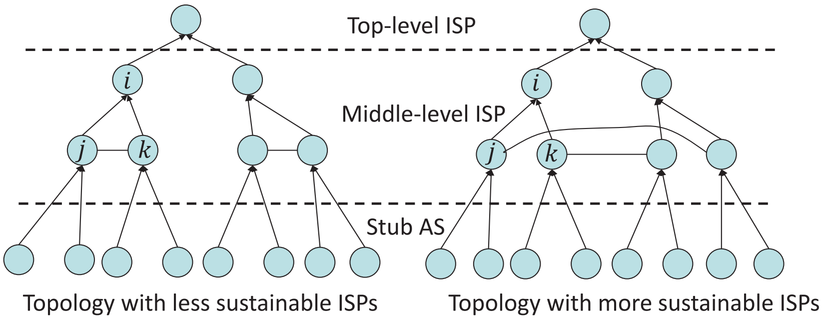


Figure 3.8: A topology including ISPs that get less economic utility and a topology including ISPs that get more economic utility.

3.4.1 Concept of evolution policies

Global structure of a topology including more sustainable ISPs

The traffic amount handled by an ISP and the economic utility of the AS are dependent on the global structure of the Internet topology. Therefore, we first consider what structure is better for the sustainable evolution of the Internet. As we discussed in Section 3.3.2, ISPs that connect links among more of their customers can increase their economic utility. The reason for this is that more traffic between the customers traverses the ISPs. However, when customers of ISPs connect with each other via peering links, the traffic between customers does not traverse the ISPs. This reduces the economic utility of the ISPs. Figure 3.8 shows an example of this scenario. In both of left and right topologies in Fig. 3.8, ISP i has the same number of customers. However, since AS j and AS k, which are customers of ISP i, connect with each other via a peering link in left topology, traffic between AS j and AS k does not traverse ISP i. In the right topology, although AS j and AS k connect to peering links, traffic between AS j and AS k traverses ISP i since AS j and AS k do not connect with each other via a peering link. Although top-level ISP decreases its economic utility by construction of this peering link, the decrease of the sustainability of the top-level ISP is marginal. This is because large amount of traffic traverses top-level ISP before constructing the peering link. Therefore, the global structure of the Internet topology should evolve to become the structure of the right topology in Fig. 3.8.

Types of ASes applied the evolution policy

In general, policies differ greatly depending on the type of AS because factors of revenue and cost differ depending on the type of AS. It is therefore necessary to understand the purpose of policies of ASes, and we present various policies for each type of AS.

A top-level ISP typically constructs links in response to link requests from ASes. Therefore, top-level ISPs do not select ASes to connect links with. Thus, we do not consider a policy for top-level ISPs. Middle-level ISPs select ASes with which to connect transit links and peering links. The purpose of constructing transit links is to achieve connectivity to all other ASes, while the purpose of constructing peering links is to reduce transit fees that are paid to providers. Stub ASes select ASes with which to construct transit links to achieve connectivity to all other ASes. Hyper Giants and IX also construct links, but do not typically select ASes because they construct links after other ASes request to construct links with them. Thus, we do not consider policies for Hyper Giants and IX. In addition to types of ASes, the purpose of constructing links differs between newly participating ASes within the Internet and existing ASes. New ASes construct transit links to achieve connection to all other ASes, while existing ASes connect peering links to reduce costs. Therefore, we consider policies for new middle-level ISPs, new stub ASes and existing middle-level ISPs.

Selection of ASes for improved sustainability

In our provided policy, when existing middle-level ISPs construct peering links, they do not select a customer of an ISP that is one of their providers. In this way, traffic between customers of providers of the middle-level ISPs still traverses providers of the middle-level ISPs. Thus, the economic utility of providers of middle-level ISPs is retained, and the sustainability does not decrease.

When unsustainable ISPs are selected as providers of new stub ASes and new middle-level ISPs, the sustainability of unsustainable ISPs improves. In addition, the sustainability of unsustainable ISPs improves when they are selected to construct peering links by existing middle-level ISPs. For these link constructions, it is necessary to open information about the sustainability of each ISP. Therefore, we assume that the rate of increase in traffic handled by each ISP and the rate of increase in the economic utility of each ISP are open information in showing how the sustainability of each

ISP improves when each AS can recognize the sustainability of other ASes. In practice, such information is not open; however, our main concern is not proposing realistic policy but revealing how different the evolution of the topology is by the difference of policy, and whether all ISPs can be sustainable or not. Therefore, we assume these information is available and provide policies.

3.4.2 Algorithm of the provided policy

Policy for new ASes

New stub ASes and new middle-level ISPs construct transit links with existing ISPs. On constructed transit links, existing ISPs are providers for new ASes. The following is proposed policy for a new AS i.

Step 1 AS i determines the number of links l to be constructed.

Step 2 AS i selects the first to l-th ISP in increasing order of $\Delta U_j(t)/\Delta F_j(t)(j \in S_N - i)$, where S_N is the set of all ASes in the topology.

Step 3 AS i constructs transit links with the ISPs selected in Step 2 as providers of AS i.

In the case of the current Internet, the average number of transit links through which a stub AS connects with its providers is about 1.5 [74]. Thus, when AS i is a stub AS, l is set to 1 or 2 with a probability of 50%. The average number of transit links through which a middle-level ISP connects with its providers is about 2. Therefore, when AS i is a middle-level ISP, l is set to 2.

Policy for existing middle-level ISPs

The existing middle-level ISPs construct peering links to save transit fee to pay their providers. A policy for the existing middle-level ISP i is as follow.

Step 1 When $\Delta U_i(t)/\Delta F_i(t) < 1$, a middle-level ISP i attempts the following steps.

Step 2 ISP i determines candidates with which to construct a peering link.

Step 2.1 The set of candidates S_i includes all ISPs in the topology.

Step 2.2 ISPs that construct links with ISP i are removed from S_i.

Step 2.3 If a path between AS j ($\in S_i$) and ISP i passes through customers of the providers of ISP i, AS j is removed from S_i.

Step 2.4 ISP i picks up ISPs with similarly sized customer cones, which are the set of ASes that are reachable by transit links in the provider-to-customer direction. These picked-up ISPs remain in S_i, and other ASes are removed from S_i.

Step 3 If S_i is not the empty set, ISP i constructs a peering link with a selected ISP. Otherwise, ISP i constructs a peering link with the ISP with the smallest $\Delta U_j(t)/\Delta F_j(t)$ in S_i.

At Step 2.4, we focus on the size of the customer cone as a measure of the scale of each ISP. ISPs with large customer cones will allow more traffic to traverse. Because peering links are constructed between two ISPs that handle a similar amount of traffic, the size of the customer cone is used to select appropriate ISPs with which to construct a peering link. In a typical ISP peering policy, the volume of traffic exchanged must be within about a factor of 2 for a peering link to be constructed. For example, the acceptable gap in AT&T's peering policy is 2:1 [75], and that of Verizon is 1.8:1 [76]. In this chapter, we assume that a peering link can be constructed when the ratio of customer cone sizes is less than 2:1. Note that an AS cannot calculate customer cone sizes of other ASes since an AS does not know the global knowledge about the Internet topology. In this study, each AS estimates the customer cone sizes of the other AS as the number of paths to other ASes through the AS.

3.4.3 Evaluation of the sustainability of each ISP

We evaluate the variation in sustainability of each ISP in the evolution of the topology according to link constructions based on our proposed policies. We first add a new AS into the topology. The added AS constructs links according to our policy. Since the amount of traffic handled by each AS and the economic utility of the ISP change in response to the link construction, we recalculate them after the new AS constructs links. Next, all existing middle-level ISPs attempt to construct peering links according to our policy. After a middle-level ISP constructs a link, we recalculate the amount

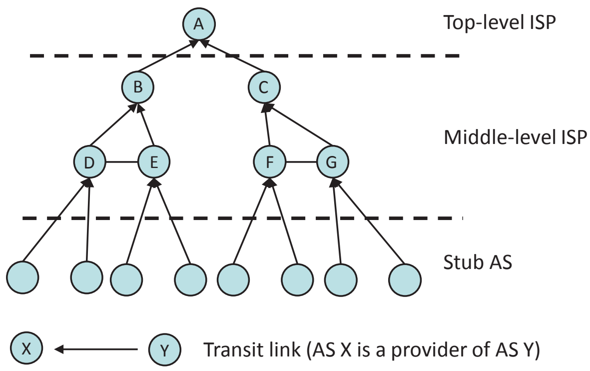
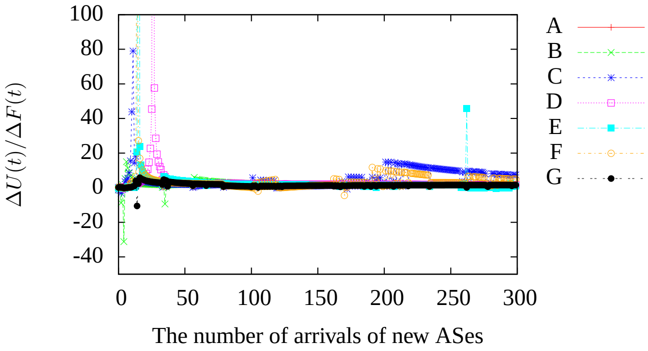


Figure 3.9: An initial topology for evolution based on our policies.

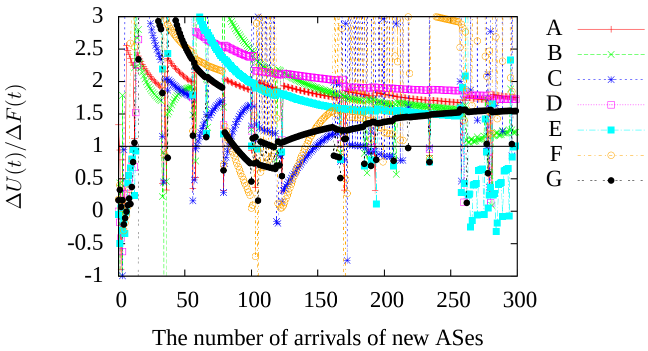
of traffic handled by each ISP and the economic utility of the ISP. When the sustainability of all middle-level ISPs exceeds 1 or no middle-level ISP can find an ISP with which to connect a link, no middle-level ISPs construct more links. After the link constructions of middle-level ISPs, the sustainability of each ISP is calculated. The link constructions of new ASes and existing middle-level ISPs are regard as one cycle of this evaluation, and 300 cycles are operated in this evaluation. We evaluate the variation in the sustainability of each ISP in this evolution of the topology.

Figure 3.9 shows the initial topology that evolves. The type of new AS is decided according to the ratio of stub ASes and middle-level ISPs in the current Internet topology. In 2014, there are 1547 middle-level ISPs and 37,199 stub ASes within the Internet. Therefore, the type of new AS is decided as a middle-level AS with a probability of 1547/38,746 and as a stub AS with a probability of 37,199/38,746. In this evaluation, the number of added stub ASes is 289 and the number of added middle-level ISPs is 11. The number of added transit links is 311 and the number of peering links is 71.

Figure 3.10 shows the variation in the sustainability of each ISP. In the initial topology, the sustainability of only ISP A exceeds 1. As the topology evolves according to our policies, the sustainability of other ASes increases whereas the sustainability of ISP A decreases. When a new middle-level ISP is added in the topology, the sustainability of some existing ISPs greatly decreases. The reason is that the traffic that once traversed an ISP from its customer may not traverse the ISP with the addition of the new middle-level ISP. However, the sustainability of such an ISP increases



(a) Variation in the sustainability of existing ISPs. The Y axis ranges from -50 to 100.



(b) Variation in the sustainability of existing ISPs. The Y axis ranges from -1 to 3.

Figure 3.10: Sustainability of existing ISPs.

with the addition of new stub ASes. Figure 3.11 shows the ratio of sustainable ISP to all existing ISPs. Green circles indicate the time when a new middle-level ISP is added. From the Fig. 3.11, we find that the sustainability of all ISPs that were in the initial topology exceeds 1 when 300 ASes are newly added to the topology. Figure 3.12 shows the variation in the sustainability of the added middle-level ISPs. When a middle-level ISP is added, its sustainability is low. Since the added middle-level ISPs are preferentially selected as the provider of new sub ASes, the sustainability of

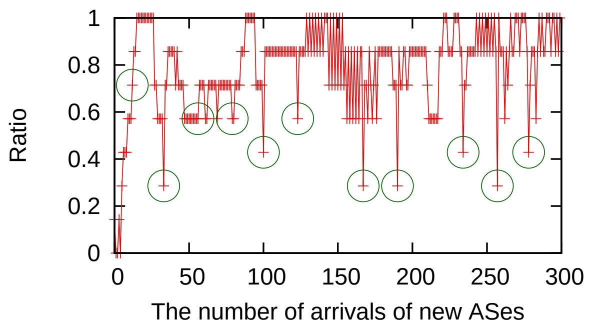


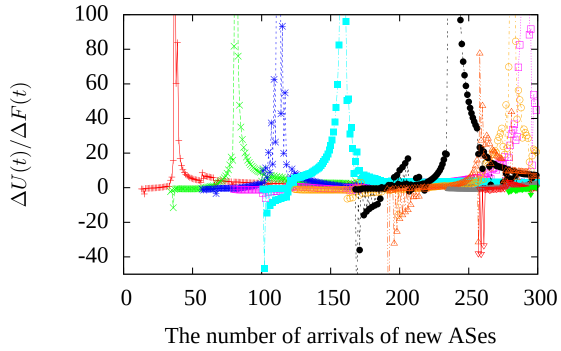
Figure 3.11: Ratio of sustainable ISPs to all existing ISPs.

the new middle-level ISPs gradually increases. When 300 ASes are added, although the sustainability of the last-added ISP and that of the second-last-added ISPs are less than 1, the sustainability exceeds 1 for other ISPs. There are peaks in the sustainability of added ISPs because an added ISP is selected as a provider by subsequently added ISPs, and the traffic from the subsequently added ISPs rapidly increases. After the peaks, the sustainability of added ISPs converges to an equilibrium value that exceeds 1.

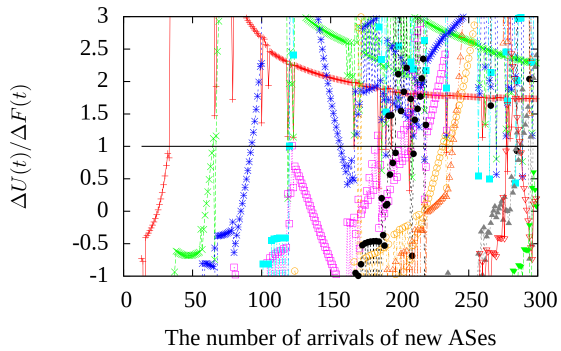
Simulation of the implementation of our policies revealed that cooperative link construction with information about sustainability, such as the rate of increase in the amount of traffic handled by an ISP and the rate of increase in economic utility of an ISP, are important for the sustainable evolution of the Internet. Note that clear financial incentives for each AS are required for the future implementation of a mechanism for sustainable evolution, and we will study policies with incentives in future work.

3.5 Conclusion

The amount of traffic on the Internet is rapidly increasing owing to an increase in network applications and content. Since the Internet is social infrastructure, it has to be sustainable in the face of an increase in traffic. For the Internet to be sustainable, each ISP has to continually improve its network equipment in response to the increase in traffic. ASes construct links according to their own policy to optimize their economic utility in what is a local decision made by two ASes considering



(a) Variation in the sustainability of newly arriving ISPs. The Y axis ranges from -50 to 100.



(b) Variation in the sustainability of newly arriving ISPs. The Y axis ranges from -1 to 3.

Figure 3.12: Sustainability of newly arriving ISPs.

the traffic flow at the time when a link is constructed. However, optimal economic utility cannot be maintained since the traffic flow is affected by the evolution of the Internet topology.

We first showed that each ISP does not have enough economic utility to expand network equipment in response to an increase in traffic handled by the ISP in the current evolution of the Internet topology. This means that the current Internet is not sustainable in the face of an increase in traffic. We then provided policies by which ASes select ASes to construct links with such that each ISP has sufficient economic utility for improvement of its network equipment. Simulation of the implementation of these policies revealed that cooperative link construction with information about sustainability, such as the rate of increase in the amount of traffic handled by an ISP and the rate of increase in the economic utility of an ISP, are important for the sustainable evolution of the Internet. This result means that cooperative link construction and relevant information are required to realize a future mechanism by which ASes select ASes to connect links with such that the Internet becomes more sustainable. Note that clear financial incentives for each AS are required in the future mechanism for sustainable evolution, and the study of policies with incentives remains as our future work.

Chapter 4

Analyzing and utilizing the collaboration structure for reliable router-level networks

4.1 Introduction

As the Internet has become a social and economic infrastructure, its reliability is essential if we are to survive failures. Many approaches to improving its reliability have been investigated either at the network layer [19] or higher layers [20] in OSI model. The reliability of optical communication systems has also been improved through protection/restoration techniques [21].

While these approaches have greatly improved the reliability of networks, physical connectivity of networks is more essential to characterize their reliability. That is, if physical connectivity of networks is easily disrupted by network failures, approaches to improving reliability at the network layer will no longer be effective. In fact, the physical topologies used in the previous studies have inherently assumed that physical connectivity is retained after network failures occur. It is important to make the physical topology reliable against network failures to design reliable networks. It is also necessary to investigate the topological characteristics and topological structures that make the physical topology more reliable to achieve this purpose.

Regular topologies have also been studied to construct reliable networks. One example is a hypercube structure [77] where each node has an identical number of out-going links that are interconnected through a regulated wiring rule. Failure-tolerant characteristics of regular topologies have recently been intensively studied to enhance the reliability of data center networks [78, 79]. However, unlike regular topologies, the degree distribution of router-level topologies of ISPs on the Internet exhibits power-law attributes, meaning that the existing probability, $P(k)$, of a degree k node that has k links is proportional to $k^{-\gamma}$ [8]. This means that we have to make drastic changes to the topology from the current router-level topology to benefit from the failure-tolerant characteristics of these regular topologies, which is an unrealistic approach to enhancing reliability.

The main objective of this research is to investigate topological structures that should be embedded to make router-level topologies more reliable on the basis of knowledge in biological systems. More precisely, we evaluate the topological structure of a transcriptional regulatory network for several species that have a much longer evolutional history than information networks, and investigated what effect introducing its topological structure into router-level topologies would have.

Transcriptional regulatory networks are biological system where transcription factors regulate the genes in cells, and control the expression of genes to produce the proteins necessary for biological activities [22, 23]. The degree distribution of these networks also exhibits power-law attributes like router-level topologies [80]. Balaji et al. [22] explains that transcriptional regulatory networks have many collaboration structures where two or more transcription factors co-regulate other transcription factors (see the definition in Section 4.2.2). The collaboration structures contribute to making the topologies reliable because they introduce multiple paths between nodes, and are therefore generally more reliable against failures in transcription factors. As we will see in Section 2, connectivity after multiple failures in *E. coli*, taking an average degree of 1.55, is higher than that in an ISP router-level topology, taking an average degree of 1.87. That is, the transcriptional regulatory network is more reliable than the ISP router-level topology. Bhardwaj et al. [23] classified nodes into top-level, middle-level, and bottom-level layers of a hierarchy, and they investigated the degree of collaboration between these three layers. Their results indicated that the transcription factors of the middle level are co-regulated the most, and complex organisms like humans collaborate more than other organisms such as *E. coli* or yeast. The results obtained by Balaji et al. and

Bhardwaj et al. [22, 23] are significant from the biological point of view. However, our interest here is the reliability of router-level networks. That is, it is important to analyze the difference in the collaboration structures between router-level topologies and transcriptional regulatory networks.

We investigated topological structures that made router-level topologies more reliable based on an analysis of transcriptional regulatory networks with collaboration structures, which is discussed in this chapter. We particularly focused our attention on collaboration structures related to robustness and analyzed the difference in collaboration structures between router-level topologies and transcriptional regulatory networks by using comparative investigations. We first investigated whether the router-level topologies of ISPs had already obtained the topological structures that appeared in living organisms. As we will see in Section 4.3, there is a clear difference in the collaboration structures between transcriptional regulatory networks and router-level topologies; there are much fewer collaboration structures between top-level and middle-level nodes in router-level topologies. To check what effect such structures had on reliability, we examined rewiring to increase the collaboration between top-level and middle-level nodes in router-level topologies, and observed the differences in reliability before and after rewiring was carried out. Note that we did not intend to actually rewire the links in router-level topologies. Rewiring did not retain the number of links in the physical topology, but changed the topological structures of router-level topologies.

This chapter is organized as follows. Section 4.2 describes transcriptional regulatory networks and similarities between the networks and router-level topologies. Section 4.3 presents a definition of collaboration structures in biological networks and router-level topologies. We evaluated the number of collaboration structures by using a metric called the degree of collaboration, which is explained in Section 4.4. We then investigated the effects of collaboration structures on reliability by changing the physical topology through the rewiring process explained in Section 4.5. Finally, we conclude the chapter in Section 4.6.

4.2 Reliability of transcriptional regulatory networks and router-level topologies

4.2.1 Analogies between transcriptional regulatory networks and router-level topologies

Transcriptional regulatory networks represent biological systems where transcription factors regulate the genes in cells, and control their expression. Each gene generates its corresponding protein, which is necessary for biological activity in cells. Transcription factors in transcriptional regulatory networks are collaborated each other and co-regulate other transcription factors or genes.

There are various analogies between transcriptional regulatory networks and router-level topologies. For example, the degree distributions of both networks exhibit power-low attributes. Another similarity is their hierarchical structures. There are three levels of hierarchy in transcriptional regulatory networks, i.e., top-level, middle-level, and bottom-level layers [23]. Router-level topologies also have a hierarchy in a network, e.g., a core network is connected with several regions and / or states, regional networks, and access networks. The collaboration structures in transcriptional regulatory networks correspond to load balancing and / or alternate paths in router-level topologies. That is, the collaboration structures contribute to the reliability of topologies because they introduce multiple paths between nodes, and are therefore generally more reliable against failures in transcription factors.

We evaluate the reliability of transcriptional regulatory networks and router-level topologies, which are discussed in the following subsection. We also investigate and analyze the hierarchies and collaboration in router-level topologies and transcriptional regulatory networks, which are explained in Section 4.3.

4.2.2 Reliability

In this section, we compare the reliability of router-level topologies and the transcriptional regulatory networks. Note that transcriptional regulatory networks are directed networks, and router-level topologies are undirected networks. Nevertheless, the reliability of both transcriptional regulatory

Table 4.1: Numbers of nodes and links in *E.coli*, human, mouse, rat, and yeast transcriptional regulatory networks.

	E.coli	Human	Mouse	Rat	Yeast
Nodes	80	88	78	30	127
Links	124	327	160	39	421
Links/Nodes	1.55	3.72	2.05	1.3	3.31

Table 4.2: Numbers of nodes and links in eight router-level topologies of AT&T, Ebone, Exodus, Level3, Sprint, Telstra, Tiscali, and Verio.

	AT&T	Ebone	Exodus	Level3	Sprint	Telstra	Tiscali	Verio
Nodes	523	140	157	623	467	329	240	839
Links	1304	261	283	5298	1280	616	403	1889
Links/Nodes	2.49	1.86	1.80	8.50	2.74	1.87	1.68	2.25

networks and router-level topologies should be evaluated by the same measure. Therefore, we replace undirected links in router-level topologies to directed links by following procedures.

Since the traffic is usually aggregated at a regional network and then forwarded to the backbone networks in router-level topologies, the backbone network is located at the "center" (in terms of hop-counts) of network and the top-level nodes defined by modularity analysis are backbone routers. In addition, nodes that are apart from "center" of network are regarded as bottom-level nodes because these nodes do not relay the traffic. Thus, our approach to define the direction of links is valid under the condition that router-level topologies aggregate the traffic at their backbone network. We suspect that our approach does not work when the router-level topologies do not have a hierarchical structure and traffic aggregation is not intended. However, we believe that such the situation merely occurs in the router-level topologies, and we actually observe that the hierarchical structure and the traffic aggregation by looking at Fig. 6 and Fig. 9 of Ref. [81].

In the transcriptional regulatory networks, top-level nodes receive stimuli from the external environment. For the router-level topologies, we regard the stimuli as the traffic from top-level nodes to bottom-level nodes. We therefore introduce the reachable node ratio for investigating reliability of directed networks, and evaluate the number of nodes that receive stimuli or traffic from top-level nodes after node failures.

We consider the random node failures in each network, and we evaluate the ratio of nodes that can be reached from top-level nodes to the number of nodes in the network. After this, we will call the ratio the *reachable node ratio*. We use the transcriptional regulatory networks of five species, i.e., *E.coli*, human, mouse, rat, and yeast [23]. The original data on transcriptional regulatory networks in Bhardwaj et al. [23] does not guarantee connectivity between any nodes. We have only considered the largest connected components to compare transcriptional regulatory networks with router-level topologies in this chapter. The numbers of nodes and links for five transcriptional regulatory networks are summarized in Table 4.1. For purposes of comparison, we also use the eight router-level topologies of AT&T, Sprint, Ebone, Exodus, Level3, Telstra, Tiscal, and Verio [82]. These topologies are obtained from trace-route-based measurements of networks, which may require alias resolution. The rocketfuel in Ref. [82] extended the Mercator project's method [83] and relaxed the possibility of IP aliasing of routers to some extent.

Figure 4.1 shows the reachable node ratio, which is dependent on the failure ratio. The failure ratio is defined as the number of failed nodes normalized by the number of nodes in the original network. Nodes to fail are selected randomly from a set of nodes in the top or middle levels to obtain the figure since bottom-level nodes are located at the edge of the network and removing them does not have an impact on the reachable node ratio. Figure 4.1 indicates the reachable node ratios when the failure ratios are 0.04 and 0.08. We can observe from this figure that human, mouse, and yeast transcriptional regulatory networks are the most reliable of the organisms that we investigate. As this figure shows, *E.coli* and rat networks are not more reliable than the other organisms, and even lower than some router-level topologies. Looking at Table 4.1, the reason for this is that the link density of *E.coli* and rat networks is much lower than that of other networks. When we compare the *E. coli* and Telstra networks whose average degrees are almost the same, the reachable node ratio for *E. coli* is higher than that for Telstra. This indicates that transcriptional regulatory networks are generally more reliable than router-level topologies.

We will focus on the collaboration structures of route-level topologies and investigate the difference in collaboration structures between router-level topologies and transcriptional regulatory networks from the beginning of the next section.

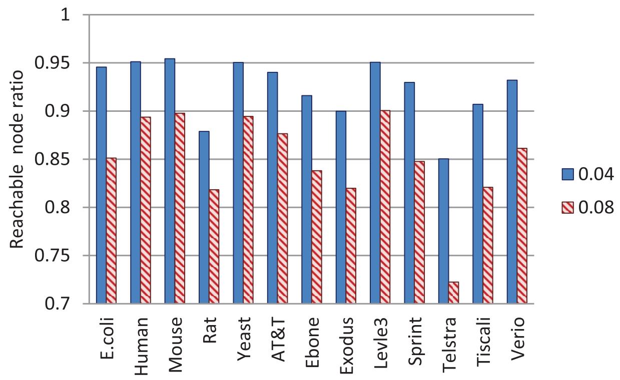


Figure 4.1: Ratio of reachable nodes where failure node ratios are 0.04 and 0.08.

4.3 Collaboration in Networks

4.3.1 Collaboration in Biological Networks

The collaboration structure in transcriptional regulatory networks was investigated by Bhardwaj et al. [23]. The collaboration structure in transcriptional regulatory networks is a co-regulation relationship where two transcription factors regulate a transcription factor. According to the results obtained by Bhardwaj et al. [23], more complex organisms such as those of humans have more collaboration structures.

A key to identifying collaboration structures is to find a hierarchy, i.e., top, middle, and bottom levels in router-level topologies and transcriptional regulatory networks. We therefore investigate the collaboration structures in router-level topologies and find differences in the collaboration structures of router-level topologies and transcriptional regulatory networks. We then examine changes in the collaboration structures to discover future directions in designing a reliable router-level topology.

4.3.2 Definition of Hierarchy in Transcriptional Regulatory Networks

Top-level nodes in transcriptional regulatory networks do not have any incoming links, and middle-level nodes have both incoming links and outgoing links [23]. The other nodes are categorized into bottom-level nodes that are only regulated by other nodes.

4.3.3 Definition of Hierarchy in Router-level Topologies

We define top, middle, and bottom-level nodes in router-level topologies as follows. Top-level nodes are determined through modularity analysis [38]. We divide the topologies into modules, and a node having one or more links that are connected with other modules is classified as a top-level node. Note that top-level nodes in transcriptional regulatory networks receive stimuli from the external environment. External stimuli can be regarded as traffic from other modules in the current case for router-level topologies.

We next calculate H_i as the average hop count from node i to other nodes. Then, we set a directed link from node i to node j when H_i is lower than H_j if undirected link (i, j) exists in the router-level topology. That is, when node i is located at the "center" of the network, the node tends to become a higher-level node. When the node is located at the "edge" of the network, the node tends to become a lower-level node. However, when there is a directed link toward the top-level node, we reverse the direction of the link so that we do not have links from the lower level layer to the top-level layer. When there is a directed link between top-level nodes, we change the directed link to become a bidirectional link. The link between a node pair whose nodes have the same average hop count is also regarded as being a bi-directional link. In this way, we construct a directional network from the router-level topology. Nodes in a directed network that have both incoming and outgoing links are classified into middle-level nodes, and nodes that only have incoming links are classified into bottom-level nodes.

4.3.4 Comparison of Hierarchical Structures in Transcriptional Regulatory Networks and Router-level Topologies

We investigate the characteristics of the hierarchical structures of transcriptional regulatory networks and router-level topologies. Figure 4.2 shows the ratio of nodes in each level of hierarchy. We can observe that the number of bottom-level nodes is greater than the number of top-level or middle-level nodes in router-level topologies. In contrast, the ratio of middle-level nodes is large in transcriptional regulatory networks.

The ratio of links between levels of hierarchy is shown in Fig. 4.3. Transcriptional regulatory

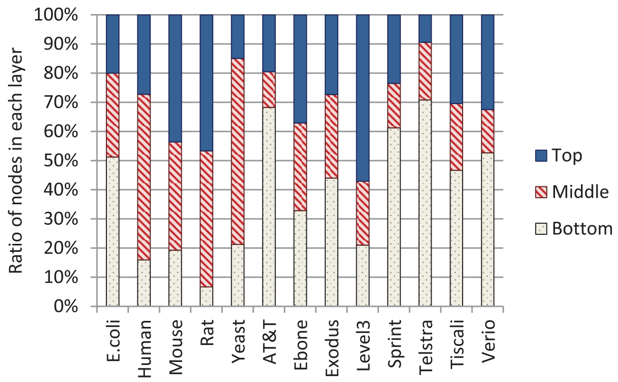


Figure 4.2: Ratio of top-level, middle-level, and bottom-level nodes in each topology.

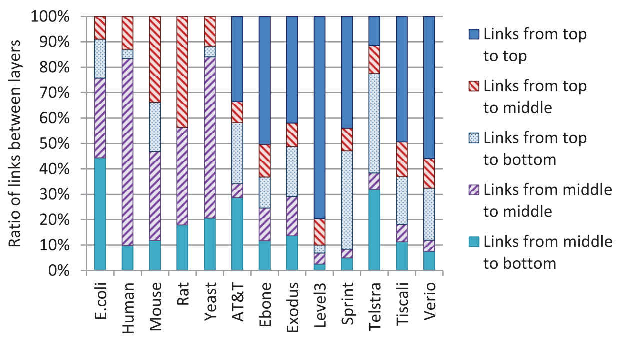


Figure 4.3: Ratio of links between each level in hierarchy.

networks have numerous links between middle-level nodes but have few links from top-level nodes to bottom-level nodes. There are comparatively more links from top-level nodes to bottom-level nodes in router-level topologies. Since top-level nodes in transcriptional regulatory networks are not regulated by other top-level nodes, there is no link from top-level nodes to top-level nodes.

4.3.5 Definition of collaboration

The collaboration structures in directed networks are structures where multiple higher-level nodes are connected with lower-level nodes. The collaboration structures contribute to the reliability of topologies because it introduces multiple paths between nodes, i.e., topologies that have many collaboration structures tend to be reliable. Here, we explain a metric, called the degree of collaboration, to compare it with the number of collaboration structures in topologies.

The degree of collaboration has been defined by Bhardwaj et al. [23]. It is the fraction of transcription factors or genes that are regulated by multiple transcription factors. We adjusted the definition in this chapter to investigate the collaboration structures inside a topology, i.e., the degree of collaboration is the fraction of nodes that are regulated by multiple nodes. The degree of collaboration does not depend on the numbers of nodes and links. Bhardwaj et al. [23] introduced two types of degrees of collaboration. The first was the degree of collaboration in each layer D^{L}_{collab} and the second was the degree of collaboration between layers $D^{L_1,L_2}_{betw-level-collab}$.

Degree of collaboration in each layer

The degree of collaboration in each layer D^{L}_{collab} represents the average of D^{i}_{collab} for all nodes i at the L-level, where D^{i}_{collab} is the number of nodes that are co-regulated by node i and another node (A, for instance) divided by the nodes that are regulated by node i. The formal definition of D^{i}_{collab} and D^{L}_{collab} is:

$$\begin{aligned} D^{i}_{collab} &= \frac{\sum_{A \in N} |N_i \cap N_A|}{|N_i|}, & (4.1) \\ D^{L}_{collab} &= \langle D^{i}_{collab} \rangle_i \quad \forall i \in L, & (4.2) \end{aligned}$$

where N is a set of nodes in the network, and N_i is a set of nodes that are regulated by node i. Then, $|N_i \cap N_A|$ represents the number of nodes that are regulated by both nodes i and A shown in Fig. 4.4. $\langle\ \rangle$ represents the arithmetic average.

Degree of collaboration between layers

The degree of collaboration between layers $D^{L_1,L_2}_{betw-level-collab}$ indicates the fraction of nodes that are co-regulated by the node at the L_1-level and the node at the L_2-level, and is defined by:

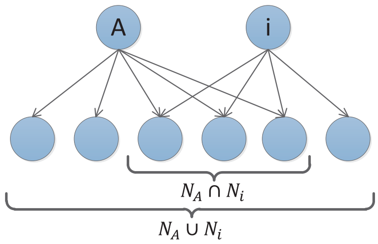


Figure 4.4: The collaboration structures between nodes i and A.

$$D^{L_1,L_2}_{betw-level-collab} = \frac{\sum_{A\in L_1}\sum_{B\in L_2}\frac{|N_A\cap N_B|}{|N_A\cup N_B|}}{|L_1|\cdot|L_2|}, \tag{4.3}$$

where $|N_A \cup N_B|$ is the number of nodes regulated either by node A or by node B (see Fig. 4.4 for illustrative example). $|L|$ is the number of nodes including in L-level. However, the degree of collaboration between layers in Ref. [23] is affected by structures other than the collaboration structure, which we illustrate in Fig 4.5. Both of topologies (upper and bottom) have the same number of nodes / links and the same number of collaboration structures, but have one difference: In the upper graph of Fig. 4.5, each two nodes co-regulate one node, whereas specific two nodes co-regulate two nodes in the bottom graph. In this case, the original definition (Eq. 3) differs for two topologies. We therefore modified the definition of the degree of collaboration between layers and introduce Eq. 4 such that the number of collaboration structures is directly counted in order to compare several router-level topologies that have different numbers of nodes / links.

$$D^{L_1,L_2}_{collab-betw} = \frac{|S_{L_1}\cap S_{L_2}|}{|S_{L_1}\cup S_{L_2}|}, \tag{4.4}$$

Figure 4.6 outlines $S_{L_1} \cap S_{L_2}$ and $S_{L_1} \cup S_{L_2}$. S_{L_1} is the number of nodes regulated by nodes in L_1 level. The S_{L_1} is the number of nodes regulated by nodes at the L_1 level. The $|S_{L_1} \cap S_{L_2}|$ is the number of nodes regulated by both a node included in the L_1-level and another node included in the L_2 level. The $|S_{L_1} \cup S_{L_2}|$ is the number of nodes regulated by nodes included in the L_1-level

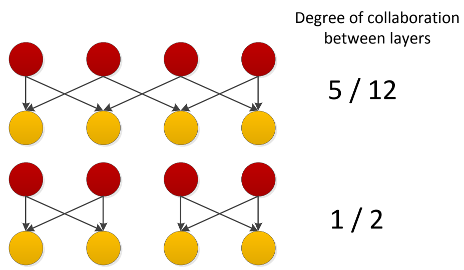


Figure 4.5: Illustrative example of how the degree of collaboration between layers differs even when it has the same number of the collaboration structure.

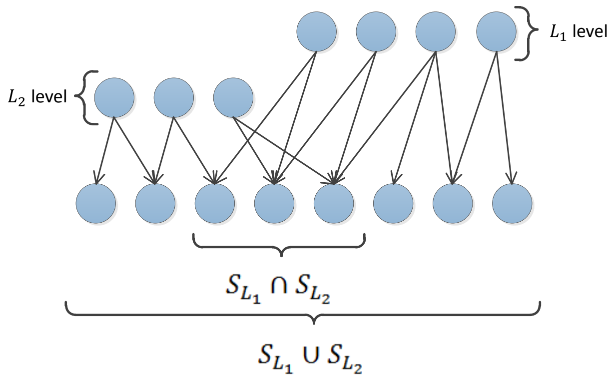


Figure 4.6: Modification to the definition of degree of collaboration between layers.

or nodes included in the L_2-level.

To compare several ISP topologies that have different numbers of nodes / links, we modified the definition of the degree of collaboration between layers to represent the number of collaboration structures:

Definition 4.4 does not depend on the numbers of nodes / links. To compare several ISP router-level topologies that have different numbers of nodes / links, we calculate:

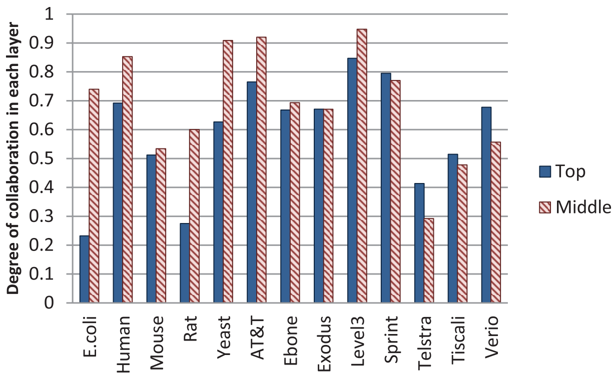


Figure 4.7: Degree of collaboration in each layer.

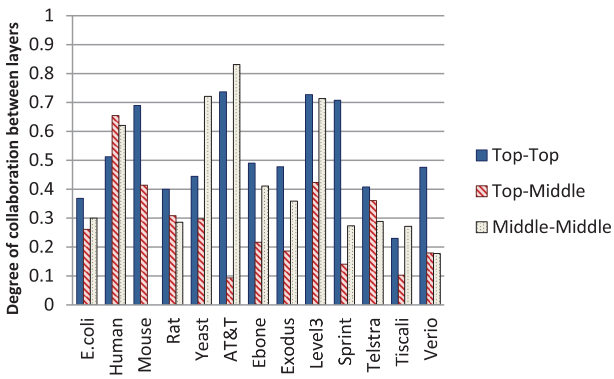


Figure 4.8: Degree of collaboration between layers.

4.4 Collaboration structures and reliability of router-level topologies

We first evaluate the collaboration structures in eight router-level topologies of AT&T, Sprint, Ebone, Exodus, Level3, Telstra, Tiscal, and Verio [82]. For purposes of comparison, we compare the results obtained from the router-level topologies and the five transcriptional regulatory networks of *E. Coli*, human, mouse, rat, and yeast. We calculate the hierarchy for each topology, and then obtain the degree of collaboration in each layer and the degree of collaboration between layers. Note that we do not calculate the degree of collaboration related to the bottom-level layer since nodes at the bottom level do not regulate other nodes according to our definition of hierarchy.

We have presented the degree of collaboration in Figs. 4.7 and 4.8. From the results of router-level topologies in Fig. 4.7, we can observe that the difference between the degree of collaboration at the top level and the degree of collaboration at the middle level is less than 0.1. In contrast, the difference in transcriptional regulatory networks is generally large. More distinctive characteristics of router-level topologies can be seen from Fig. 4.8. The collaboration structures between top-level nodes and middle-level nodes are marginal in router-level topologies, whereas these are not in transcriptional regulatory networks. One possible reason for such marginal collaboration structures is the functionality of middle-level nodes in router-level topologies. That is, traffic is first aggregated at middle-level nodes and then forwarded to top-level nodes. Thus, no consideration is given to load-balancing between top-level nodes and middle-level nodes. Although degree of collaboration between top-level and middle-level nodes is comparatively high in Telstra, reliability of it is worst in Fig 4.1. The reason is that the number of top-level nodes in Telstra is much fewer than that in other topologies, and there is less degree of collaboration in top and middle layers. With this case and only at the Telstra, the reliability is low because the primal bottleneck (in terms of reliability) is the connectivity between top-level nodes.

Looking at the Fig. 4.7, we observe that most of router-level topologies have high degree of collaboration in each layer. However, the results of Fig. 4.1 indicate that the reachability from top-level nodes is not high. The reason of decreasing reliability is lacks of collaboration structures between layers. Therefore, it is expected that increasing the collaboration structure between top-level and middle-level nodes improves the reliability. Again referring to Fig. 4.1, note that these organisms are very reliable. That is, more reliable networks are expected to be constructed by incorporating such collaboration structures. In the next section, we will discuss the effect of collaboration structures on reliability in detail.

4.5 Effects of collaboration structures on reliability

The previous section explained that the human, mouse, and yeast transcriptional regulatory networks were the most reliable of the organisms we investigated, and we found that these organisms exhibited higher degrees of collaboration between top-level and middle-level nodes, while the router-level topologies exhibited lower degrees of collaboration between them.

This section describes our investigations into what effects collaboration structures have on reliability. More specifically, we increase the collaboration structures between top-level and middle-level nodes by rewiring links in the router-level topologies, and evaluated the differences in reliability before and after the links were rewired. Note that an actual ISP network may increment links or their capacity rather than rewiring them. However, we still consider rewiring links because our prime concern here is whether increasing the number of collaboration structures will improve reliability or not.

4.5.1 Rewiring to increase number of collaboration structures

Here, we explain how we rewired links to increase the collaboration structures between top-level and middle-level nodes. The operation consisted of the four steps described below. Each step in rewiring has been outlined in Fig. 4.9.

Step 1 Find node X regulated by three or more nodes on the same level. If several nodes are found, a node is randomly selected.

Step 2 Randomly select node Y from several nodes that regulate node X and that are at the same level.

Step 3 When node Y is a middle-level node, find node Z that is only co-regulated by top-level nodes. Otherwise, i.e., when node Y is a top-level node, find node Z that is only regulated by a middle-level node. If there are several candidates for node Z, randomly select one of them as node Z.

Step 4 Rewire a link between nodes Y and X; remove the link from node Y to node X, and wire a link from nodes Y and Z.

Note that if node X in Step 1 is selected from nodes only regulated by two nodes, rewiring the link leads to decreased collaboration in the layer (middle-level layer in Fig. 4.9) that node Y belongs to.

This rewiring is continued until either of the following termination conditions is satisfied.

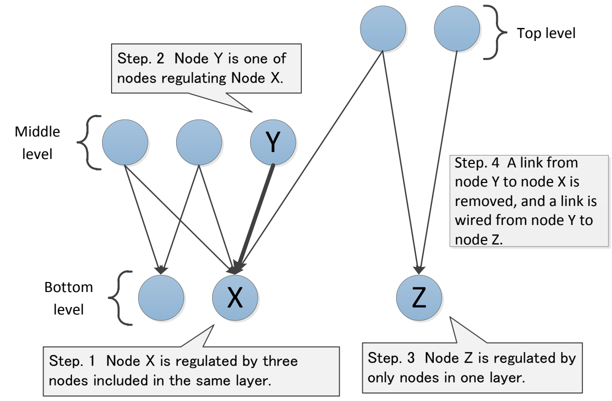


Figure 4.9: Algorithm for the link rewiring.

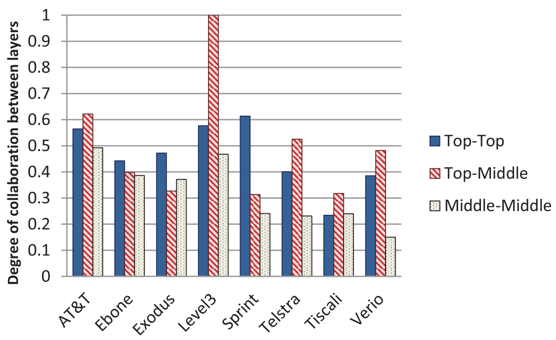


Figure 4.10: Degree of collaboration between layers after rewiring.

Condition A When there is no candidate for node X.

Condition B When there are some candidates for node X, but there are no candidates for node Z

Condition C When all nodes are connected to top-level nodes and middle-level nodes, i.e., rewiring is not necessary.

The degree of collaboration between layers after rewiring is summarized in Fig. 4.10, and it shows that this operation certainly increases the numbers of collaboration structures between top-level and middle-level nodes. Table 4.3 summarizes the number of rewirings carried out until the algorithm reaches either of the termination conditions. As Table 4.3 indicates, the number of rewirings until termination conditions are reached differs for the topologies. The reason for this

Table 4.3: Number of rewirings until termination condition is reached and reached termination conditions for each ISP topology.

Topology	AT&T	Ebone	Exodus	Level3	Sprint	Telstra	Tiscali	Verio
Number of rewirings	222	15	15	154	59	48	36	170
Types of termination conditions	A	A	A	C	B	A	A	B

is not only the size of topologies but also the number of candidates for nodes X and Z in Fig. 4.9. That is because the number of rewirings depends on the number of candidates for nodes X and Z. The types of termination conditions for each topology are also listed in Table 4.3. The type of termination condition in most router-level topologies, except for Level3, Sprint, and Verio, is condition A, i.e., there are a few candidates for node X in these topologies. For Level3, all the middle-level and bottom-level nodes are connected to top-level and middle-level nodes after rewiring. Since most nodes are connected to higher level nodes before rewiring for Sprint and Verio, there are more candidates for node X and less for node Z.

4.5.2 Reliability of topologies after links are rewired

Last, we investigate the reliability of topologies after links were rewired, which increased the degree of collaboration between top-level and middle-level nodes. Unlike Fig. 4.1, which shows the connectivity of directed networks after node failures, we investigate connectivity after random node failures by using the undirected links instead of directed links, and evaluate the difference between the original router-level topologies and topologies after links were rewired. We particularly use the *cover ratio* as the measure of reliability, which is defined as $\frac{S_i}{N}$. The S_i is the number of nodes in the largest connected component after failure in the i-th node, and N is the number of nodes in the original topology. That is, $\frac{S_i}{N}$. The S_i means the ratio of remaining nodes to the number of nodes in the original topology when i nodes have failed. In Sec. 2.2, we used the reachable node ratio for investigating the reliability on a directed network because the transcriptional regulatory networks are directed. However, since router-level topologies are undirected networks, our concern here is the connectivity between nodes. Thus, we use the cover ratio that is defined on undirected networks

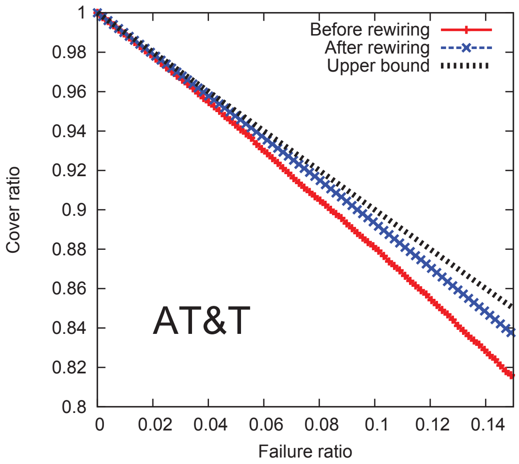


Figure 4.11: Difference in reliability between topologies before and after rewiring: AT&T

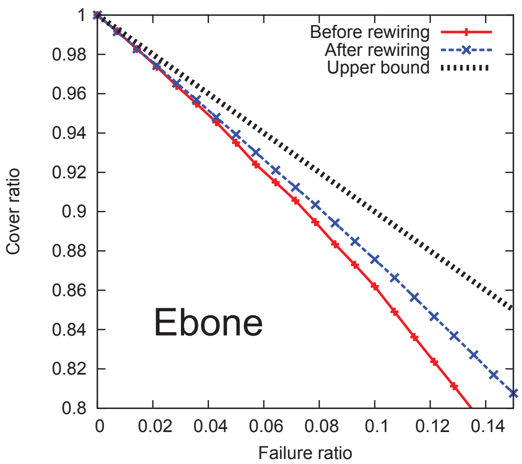


Figure 4.12: Difference in reliability between topologies before and after rewiring:Ebone

here.

Figures 4.11 to 4.18 plot the cover ratios for each topology after the links were rewired. We randomly rewired the links for each router-level topology until the algorithm reached terminal conditions. We obtained three topologies for each router-level topology by applying the rewiring algorithm, and examined 300 trials of random node failures for each of the topologies we obtained.

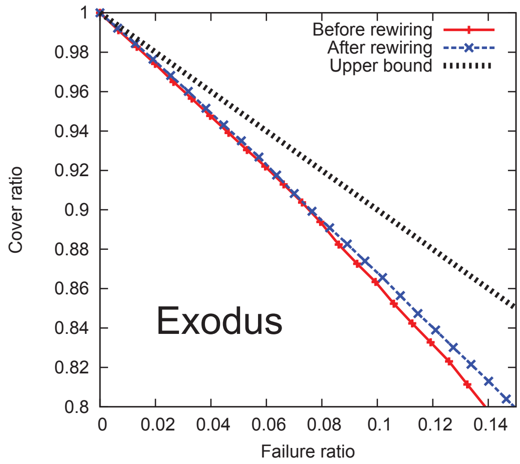


Figure 4.13: Difference in reliability between topologies before and after rewiring:Exodus

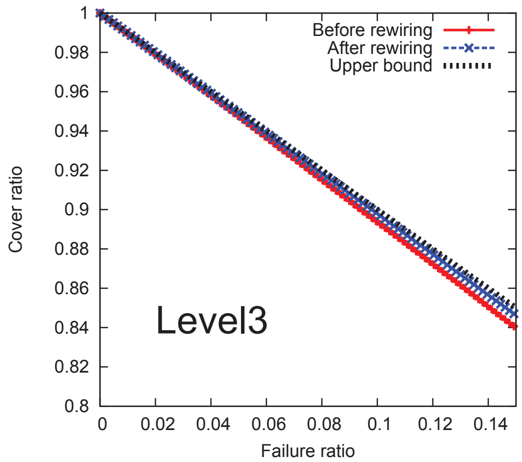


Figure 4.14: Difference in reliability between topologies before and after rewiring:Level3

The average of the cover ratios is plotted in the figure, where *Upper bound* represents the maximum cover ratio.

We can see that the cover ratios improve for most router-level topologies, except for Sprint, Exodus, and Level3, which demonstrate little improvement. However, there is no topology where the cover ratio decreases.

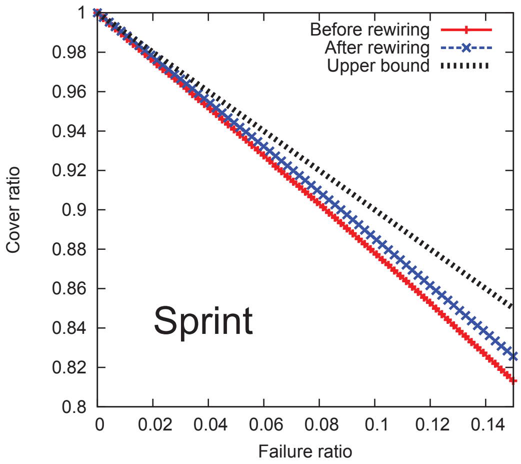


Figure 4.15: Difference in reliability between topologies before and after rewiring:Sprint

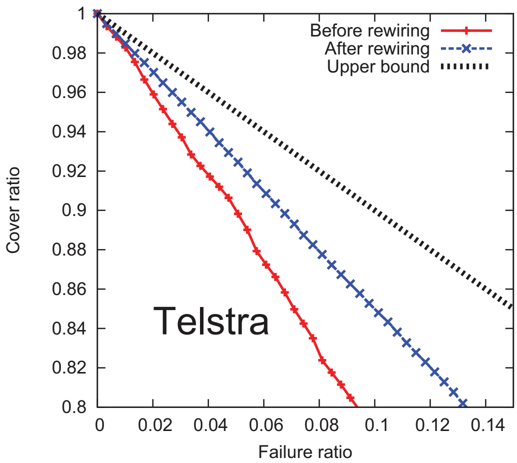


Figure 4.16: Difference in reliability between topologies before and after rewiring:Telstra

We can see that the cover ratios improve in all the router-level topologies. However, the improvements in the cover ratios for Level3, Sprint, and Exodus are marginal. The reasons for this are as follows. The original Level3 topology has numerous links and already has a high cover ratio. That is, it offers little room for improvement. The marginal improvements in the Sprint and Exodus topologies are caused by the poor opportunities for rewiring. A few nodes in the Sprint topology

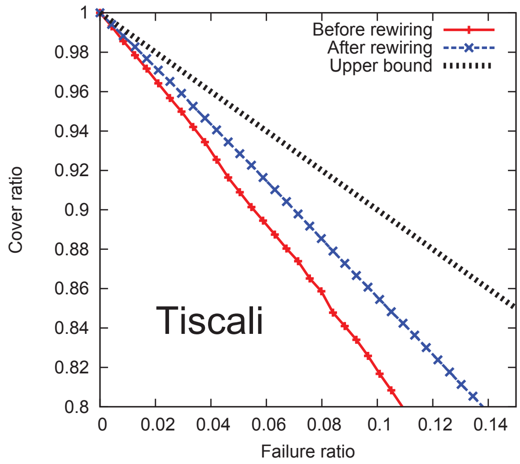


Figure 4.17: Difference in reliability between topologies before and after rewiring:Tiscali

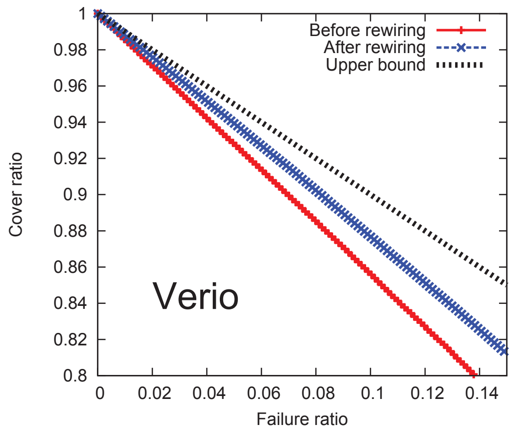


Figure 4.18: Difference in reliability between topologies before and after rewiring:Verio

are only connected to middle-level nodes. Hence, the Sprint topology has few candidates for node Z in Fig. 4.9. There are few candidates for node X in Fig. 4.9 in the Exodus topology because most nodes do not have three or more links connected to top-level nodes and they do not have three or more links connected to middle-level nodes. Note that, the cover ratio in the Ebone topology improves more than that in the Exodus topology even though the number of rewirings is the same for both topologies. This is because the degree of collaboration in Ebone increases more through rewiring than that in Exodus. As summarized in Table 4.1, the number of nodes and links in Ebone is less than that in Exodus, but the number of rewirings is the same as that in Ebone and Exodus. Thus, the degree of collaboration in Ebone increases more. Because Ebone obtains more collaboration structures under the given number of nodes and links compared with Exodus through rewiring, the cover ratio in Ebone is improved more than that in Exodus. The results in this section indicate that the collaboration structures of topologies characterize reliability, and reliability improves to some extent by increasing the number of collaboration structures.

4.6 Conclusion

We investigated collaboration structure in router-level topologies, and found that there were fewer collaboration structures between top-level and middle-level nodes in router-level topologies than those in transcriptional regulated networks. Because of this, the connectivity of router-level topology easily deteriorated when node failures occurred. We demonstrated that the reliability of several topologies improved when the collaboration structures between top-level nodes and middle-level nodes increased to find a possible evolutionary path to improve the reliability of router-level topologies. However, the improvements to reliability were limited in Level3, Sprint, and Exodus topologies. These topologies were extremely reliable before rewiring. In other words, if original router-level topologies are not reliable, this is more likely to improve reliability.

The main contribution of this study is to reveal how the reliability improves by increase in collaboration structures between top-level and middle-level nodes. We believe that this contribution is useful for a design of highly reliable network under geographical and financial constraints. In addition, it may be used for network construction with clean slate.

Our future work is to establish network designs based on collaboration structures for large-scale and reliable router-level topologies. We investigated the relationship between collaboration structures and the reliability of networks by rewiring links in this research. However, link rewiring may be impractical for network design because ISPs do not need to remove old links. Incorporating the property of collaboration structure to evolving strategies, such as [84, 85] may be important, but it is left for future investigations.

Chapter 5

Conclusion and future work

In this chapter, we summarize the discussion in each of the previous chapters and describe future research works.

Chapter 1 mentioned research background and overview of our studies. As the Internet has become a social and economic infrastructure, it is essential that the Internet continually accommodate the future traffic increase. Remaining challenges for the purpose are relaxing the traffic concentration, continual improving of network equipment by each of ISPs and improving reliability of router-level topology against router failures.

In Chapter 2, we investigated the evolution of the Internet topology to relax the traffic concentration. We focused on the hierarchical structure that associate with the hierarchical nature of traffic aggregation, and first identified links where more traffic is concentrated. The results showed that more traffic concentrates on links between ASes aggregating vast amount of traffic, and the amount of traffic on the links has rapidly increased. We then considered a new evolution process to avoid traffic concentration, and then examined how this process could slow down the traffic concentration compared with the actual evolution of the Internet topology. Since costs for exchanging traffic, such as cooling costs of a router, increase exponentially corresponding to traffic increase, this relaxing traffic concentration greatly contributes to cut of costs and sustainable traffic accommodation.

In Chapter 3, our next concern was whether each of ISPs can continually improve network equipment against the increase of traffic or not. With the economic utility through traffic exchange with other ASes, ISPs can improve the network equipment against the traffic increase. The economic utility is heavily depending on the traffic flow which changes based on the evolution of the Internet topology. The Internet topology evolves by link constructions of ASes with their own policies to select ASes to connect links with. We therefore first investigate whether each of ISPs can continually get a sufficient economic utility against the traffic increase on the ISP or not even if the Internet topology will evolve with the current policies of ASes. Our results show that half of ISPs does not obtain sufficient economic utility against traffic increase, and the ratio tends to increase in recent years. We then develop and evaluate the policy to select ASes to connect links with for relaxing unsustainable state of an ISP, and showed that all ISPs can improve economic utility against the traffic increase by our policy. Therefore, this policy enables each of ISPs to continually improve its network equipment against the traffic increase.

In Chapter 4, we investigated topological structures that should be embedded to make router-level topologies more reliable on the basis of knowledge in biological systems. In particular, we focused on transcriptional regulatory networks because transcriptional regulatory networks have the same topological properties as router-level topologies, and a flow of stimuli in transcriptional regulatory networks is comparable to a flow of traffic from gateway routers to other routers. In addition, we focused on a collaboration structure where two or more transcription factors co-regulate other transcription factors. The collaboration structures contribute to making the topologies reliable because they introduce multiple paths between nodes, and are therefore generally more reliable against failures in transcription factors. We embedded the characteristics of collaboration structure in transcriptional regulatory networks into eight router-level topology, and showed that all of them became more reliable. In addition, we found that the improvement of reliability increases corresponding to increase of the number of failure routers.

As our future work, we will analyze the sustainability of the Internet and provide the evolution policy by considering link capacities. The analysis with consideration of link capacities can show that how amount of traffic has to be distributed on links where traffic heavily concentrates. As a result, it is revealed that where links have to be added and how amount of links are required for the Internet to accommodate the future traffic increase. Furthermore, we will develop an evolution process and policies that consider the merits of each AS. Because the evolution of the Internet topology is not centrally controlled but an ensemble of individual link construction by each AS, the evolution policy should be applied to each AS. Indeed, Refs. [4, 7, 65] investigated the evolution of the Internet topology from the viewpoint of game theoretic behavior by each AS. Future evolution policies must consider both the merit to individual ASes and the merit for the global structure of the Internet. Therefore, we will study how collaboration is needed between ASes for link constructions in the future evolution that satisfies both merits.

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