A provider and peer selection policy for the future sustainable Internet

Abstract: For the Internet to be sustainable for rapidly increasing traffic, each ISP must improve its network equipment in response to this increase in traffic. For this improvement, ISPs require a sufficient level of economic utility, which is derived from network interconnections. However, the evolution of the Internet topology may degrade economic utility of each ISP because the traffic flow changes with the evolution of the Internet topology. In this study, we first investigate whether each ISP can obtain sufficient economic utility with an increase in traffic. From this investigation, we show that the increase in the rate of traffic through each ISP greatly outstrips the increased economic utility of each ISP. This means that the Internet topology is not sustainable for such an increase in traffic. We then develop policies by which autonomous systems can construct links such that each ISP continually achieves sufficient economic utility for increase in traffic.

Keywords: Internet topology; Autonomous System; Sustainability; Economic utility; Link construction policy.

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 study, 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 paper is organized as follows. Section 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 shows the sustainability of the Internet under the current policy. In Section 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 5.

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. (4) revealed that the degree distribution of the Internet topology has power-law attributes, and Satorras et al. (5) 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 (6). 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 (7) 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 (8) 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. (9) 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 (10) 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 (11; 12; 13). For example, Ref. (11) proposed an incentive mechanism that encourages ASes to implement the outbound filtering of spam traffic on the Internet, and Ref. (12) 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.

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.

3.1 Evolution of economic utility in each AS

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 (14). These topology data are derived from AS paths included in routing table snapshots from 1998 to the present day collected by the RouteViews project (15) and RIPE (16). 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 (17). This is a simple method for estimating traffic demand (17; 18), and has been used in various studies (9; 19). 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 (20; 21). Note that, as discussed in (22), 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:

$$e_{ij} = \lambda \cdot x_i \cdot x_j, \tag{1}$$

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 (20; 23). 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 (24), 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 (25; 1) 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 (20; 26; 27). 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. (20) 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. (20) 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

$$f_i = C_i + I_i - P_i - R_i - L_i, \tag{2}$$

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. 2 is calculated as follows:

$$C_i = \sum_{c \in S_{i,c}} T(v_{ic}), \tag{3}$$

$$I_i = T(v_{ii}), \tag{4}$$

$$P_i = \sum_{p \in S_{i,p}} T(v_{ip}), \tag{5}$$

$$R_i = \sum_{r \in S_{i,r}} R(v_{ir}), \tag{6}$$

$$L_i = L(v_i), \tag{7}$$

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:

$$T(v) = m_t \cdot (v)^{e_t}, \tag{8}$$

$$R(v) = m_r \cdot (v)^{e_r}, \tag{9}$$

$$L(v) = m_l \cdot (v)^{e_l}. \tag{10}$$

The parameters in Eqs. (8)–(10) are constants. In (20), these values were calculated based on a previous study (9) and an investigation by network consultant companies. They were given as follows:

$$m_t = 20, \tag{11}$$

$$e_t = 0.75, \tag{12}$$

$$m_r = 300, \tag{13}$$

$$e_r = 0.25, \tag{14}$$

$$m_l = 100, \tag{15}$$

$$e_l = 0.5. \tag{16}$$

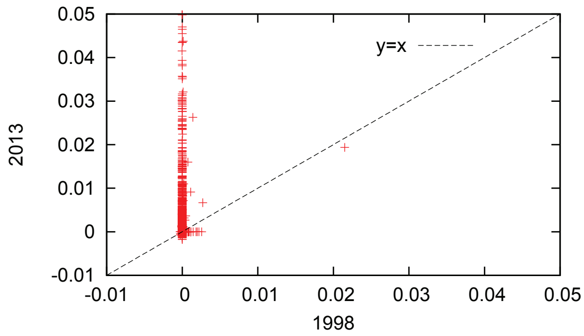


Figure 1 The economic utility of each AS in 1998 and 2013.

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 (20).

Figure 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. 1, the economic utility of an AS at a time when the AS did not exist is regarded as zero. In 1998, 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. 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 paper, we classify these as top-level ISPs, middle-level ISPs, stub ASes, IXes, and Hyper Giants. Table 1 gives a definition of each type, and Table 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 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 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

3.2 Mechanism by which an AS suffers decreased 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 3.1, 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. 2,3, 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 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.

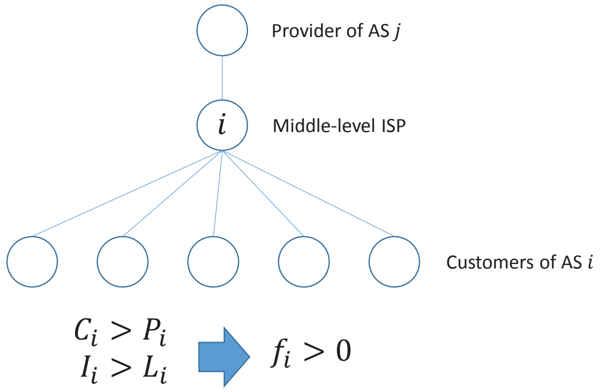


Figure 2 Features of middle-level ISPs that do and do not have sufficient economic utility.

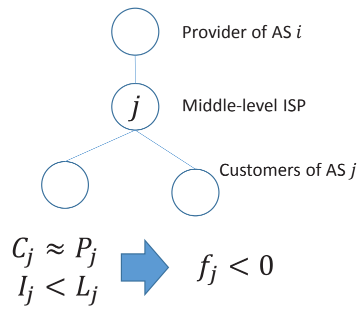


Figure 3 Process of decreasing economic utility in middle-level ISPs that transmit little traffic.

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 utility will see further decreases. Figure 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.

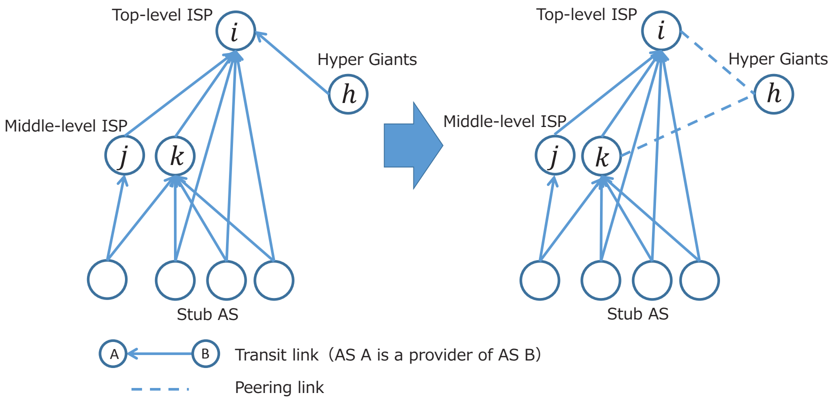


Figure 4 Process of decreasing economic utility of middle-level ISPs that transmit few traffic.

3.3 Sustainability of the Internet with its 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 as

$$S_i(t) = \frac{\Delta U_i(t)}{\Delta F_i(t)}, \tag{17}$$

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.

$$\Delta U_i = \begin{cases} -\frac{U_i(t)-U_i(t-\Delta t)}{U_i(t-\Delta t)}, & (U_i(t-\Delta t) < 0) \\ \frac{U_i(t)-U_i(t-\Delta t)}{U_i(t-\Delta t)}, & (U_i(t-\Delta t) >= 0) \end{cases} \tag{18}$$

$$\Delta F_i = \frac{F_i(t) - F_i(t-\Delta t)}{F_i(t-\Delta t)}, \tag{19}$$

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 5 shows the ratio of sustainable ISPs to all ISPs. In Fig. 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 6 shows the average economic utility of ISPs and the average amount of traffic handled by the ISPs. Since the absolute values are not comparable, these values are normalized by the values in 1998. From Fig. 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

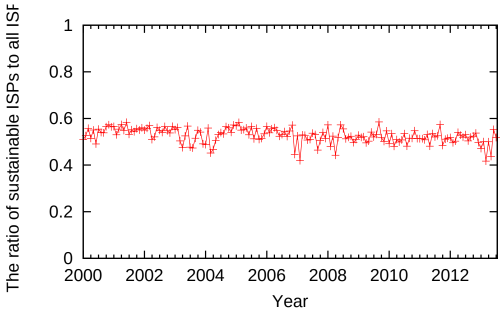


Figure 5 Ratio of sustainable ISPs to all ISPs.

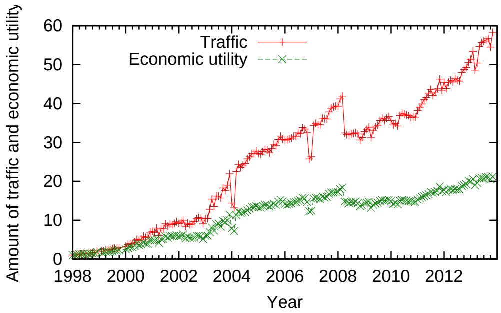


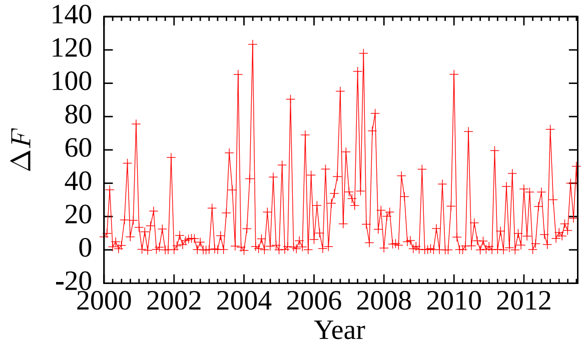
Figure 6 Normalized total traffic volume and revenue of all ISPs in 1998.

by about 30% per year owing to pricing competition among ISPs (28). 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.

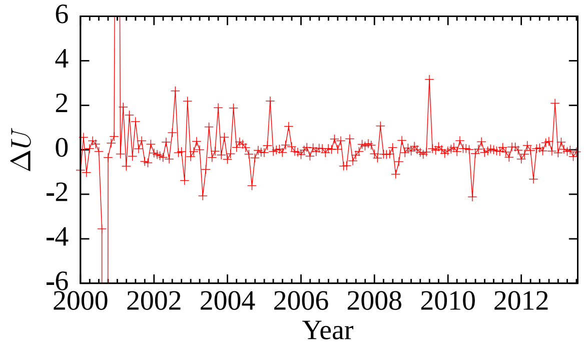
Figure 7(a) shows the variation in the average rate of increase in traffic handled by an ISP and the average rate of increase in the economic utility of an ISP. We found that the average rate of increase in traffic greatly fluctuates. In addition, a more important point is that the average rate of increase 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.

4 Evolution for a sustainable Internet topology

As shown in Section 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



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



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

Figure 7 Average increase in rate of traffic and economic utility of ISPs.

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.

4.1 Concept of evolution policies

4.1.1 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 3.2, 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 8 shows

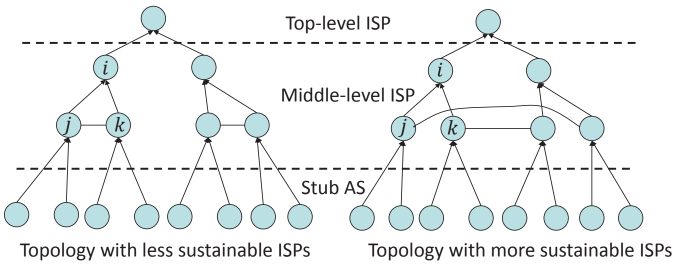


Figure 8 A topology including ISPs that get less economic utility and a topology including ISPs that get more economic utility.

an example of this scenario. In both of left and right topologies in Fig. 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. Therefore, the global structure of the Internet topology should evolve to become the structure of the right topology in Fig. 8.

4.1.2 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.

4.1.3 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.

4.2 Algorithm of the provided policy

4.2.1 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 (29). 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.

4.2.2 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.

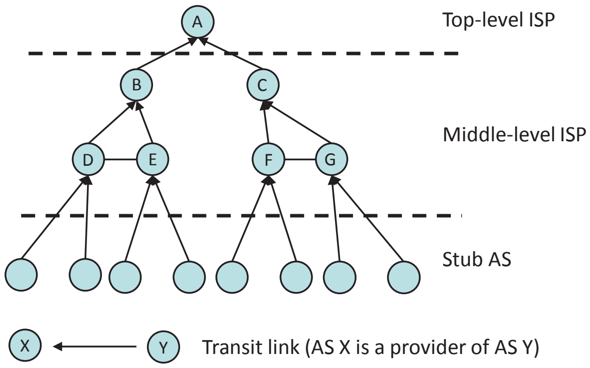


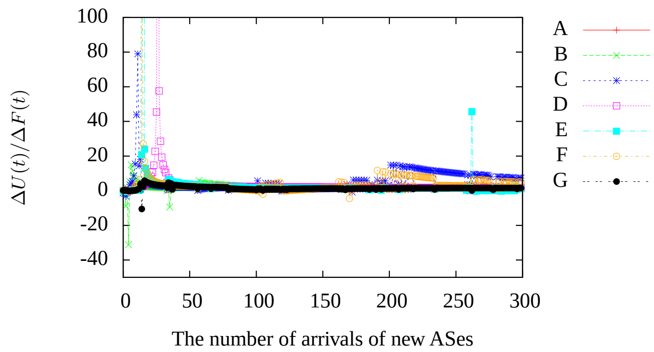
Figure 9 An initial topology for evolution based on our policies.

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 (30), and that of Verizon is 1.8:1 (31). In this paper, 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.

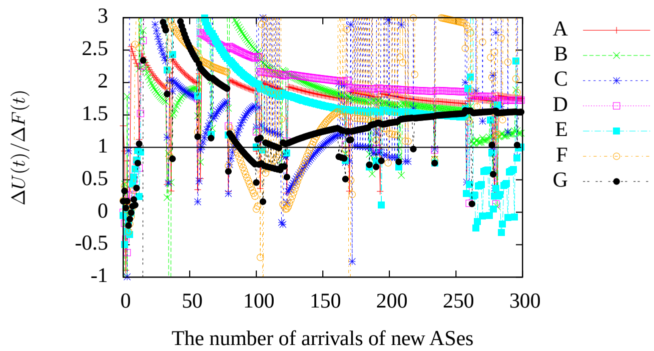
4.3 Evaluation of the sustainability of each ISP

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 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 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



(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 10 Sustainability of existing ISPs.

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 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 with the addition of new stub ASes. Figure 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. 11 , we find that the sustainability of all ISPs

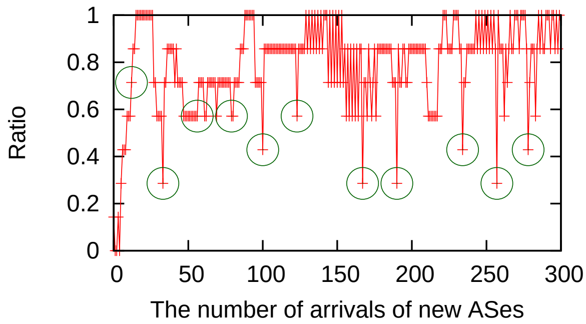


Figure 11 Ratio of sustainable ISPs to all existing ISPs.

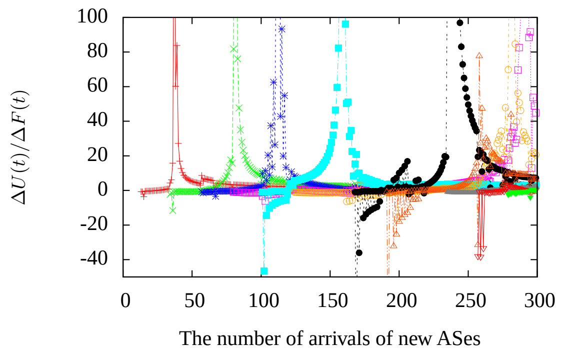
that were in the initial topology exceeds 1 when 300 ASes are newly added to the topology. Figure 12 shows the variation in the sustainability of the added middle-level ISPs. When a middle-level ISP is added, its sustainability is low. Since the added middle-level ISPs are preferentially selected as the provider of new sub ASes, the sustainability of 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.

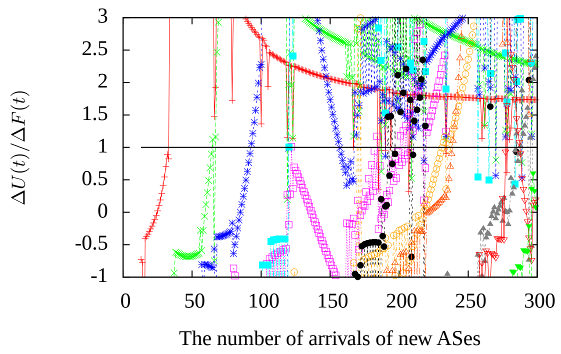
5 Conclusion

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 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



(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 12 Sustainability of newly arriving ISPs.

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.

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