Understanding the evolution of the Internet topology through hierarchical analysis

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***Abstract*—Understanding how the topology has been changing is important for analyzing performance of applications and protocols. In this paper, we investigate a process of evolution of AS-level topology in the Internet by analyzing hierarchy of modules. We first investigate how top-level modules in the hierarchy are connected in the AS-level topology. Our results show a trend that the amount of traffic aggregated in the module before forwarding to other modules had increased until about 2006. We then investigate the hierarchy of modules. The result shows the amount of traffic that passes through Tier-1 ASes increase as the AS-level topology evolves.**

I. INTRUDUCTION

The Internet is the largest network system in the world. The traffic demand in the Internet is increasing as the increase of communication devices. To accommodate the increase of traffic demand, a lot of network equipment and physical links are deployed in the Internet. The size of the topology in the Internet is becoming larger.

The Internet topology, which is called AS-level topology, consists of huge number of ASes (Autonomous System) and links between ASes. AS is a kind of network that company, research institution or contents provider has and manages. Internet is constructed by individual ASes. When operators of ASes deploy network equipments, they decide where to deploy the network equipment and which AS to connect based on their own policy. As the traffic demand increase and the Internet has a role as the social infrastructure, new ASes is constructed and AS-level topology is becoming larger and evolving. In 2012, there are 42,009 ASes and 93,470 links. AS-level topology becomes a large and complex topology. However, the structure and properties of AS-level topology is not clear since there is no network operator that manages the whole Internet.

Understanding and analyzing the structure of AS-level topology is important. One of reasons is to evaluate performance of new applications and protocols on a topology reflecting the structure and properties of the Internet. For this purpose, understanding only the current structure is not enough. The investigation of the longitudinal evolution of AS-level topology over time is required, which will lead to understand future AS-level topology and can be applied to performance evaluations.

Some studies challenge to visualize AS-level topology from observing topology map to capture structural properties intuitively [1, 2]. However, it is hard to capture structural properties from pictures of AS-level topology that are generated by the methods of these studies because AS-level topology is a too large and complex topology. Some of studies investigate structural properties by using various graph metrics. Faloutsos et al. revealed that the degree distribution of AS-level topology exhibits power-law attribute [3], and Satorras et al. showed that the distribution of betweenness centrality also exhibits power-law attribute [4]. However, these studies analyze structural properties from only single point in the evolution of AS-level topology. Dhamdhere et al. investigated the evolution of AS-level topology, and showed that the path length is almost constant though the number of ASes or links increases [5]. Furthermore, the authors of [5] quantified the ability of an AS to attract and retain customer ASes which pay transit fee for traversing traffic by using metrics called attractiveness and repulsiveness, and found that ISPs connecting a lot of customer ASes acquire more customers ASes. Shavitt et al. analyzed the evolution by focusing on large content providers, also known as "Hyper Giants" in other papers [6, 7], and they revealed that the structure of AS-level topology is changed from hierarchical structure to mesh structure [8]. This is because large content providers tend to have links with a lot of small ISPs. These studies analyzed the evolution of AS-level topology by the graph metrics of topology. However, graph metrics do not directly relate 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 is different depending on the structure of networks.

The network performance is greatly influenced by traffic aggregation. The power-law degree distribution of AS-level topology suggests that a few "hub" ASes aggregates traffic through their connecting links. However, the network performance is not characterized only by the degree. It is also characterized by the hierarchy of traffic aggregation. In this study, we investigate the evolution process of AS-level topology through a hierarchical analysis.

To understand how traffic is aggregated in the AS-level topology, we focus on a module defined by a set of ASes that are densely connected with many links. Two or more modules are connected with (relatively) few links at which traffic is aggregated. Additionally, each module contains a set of sub-modules and their connecting links. By focusing on a hierarchical structure of modules, *i.e.* the set of ASes where each AS densely connects to each other, we can extract hierarchy of traffic aggregation, and reveal how traffic is aggregated in AS-level topology.

Before we analyze the hierarchy of modules, we first investigate modular structure of AS-level topology, i.e., how the top-level modules are connected in the AS-level topology. Here, the top-level module corresponds to concentration of traffic on a few ASes. By analyzing the modular structure and its evolution, we reveal macroscopic view of traffic aggregation. After that, we reveal the hierarchy of traffic aggregation by analyzing the hierarchy of modules.

This paper is organized as follows. In Section 2, we describe how we obtain data of AS-level topology for analysis of network structure. We then explains classification method of class of AS. In Section 3, we show evolutional change of modular structure. Then, we present the longitudinal change in hierarchy of traffic aggregation in Section 4. Finally, we conclude this paper in Section 5.

II. Data Set

A. Adjacency matrix of AS-level topology

Analyzing the evolution of AS-level topology needs adjacency matrix of AS-level topology. However, the adjacency matrix has not been stored anywhere. Some studies infer adjacency matrix of AS-level topology by observing traffic traversing in the Internet. Inference methods of these studies can be classified two types. In the first type of methods, a lot of arbitrary PCs around the world send traceroute packets to specific servers, and the servers collect AS paths represented as a list of IP address of routers on which traceroute packets traverse. Adjacency matrix is derived from the lists of ASes which are converted from lists of IP. By this method, a lot of links can be found, however, the adjacency matrix is different depending on when the paths are collected because it is possible that PCs sending traceroute packets may change during the measurement. Because we cannot specify whether the difference of some adjacency matrix is due to difference of the structure in AS-level topology or difference of PCs sending traceroute packets. Therefore, this method is not suitable for analyzing evolutional change of AS-level topology. In the second type of methods, adjacency matrix is created from AS path in BGP routing table which is recorded at some famous ISP's gateway routers. Some servers collect BGP routing tables at some ISP's gateway routers. BGP routing table contains AS paths which are lists of ASes that describe routes between ASes. This method can capture most of ASes, however, 40% of peering links where two ASes exchange traffic for free are not detected [5, 9]. Even though this disadvantage is well known, it is more suitable than traceroute-base methods for analyzing evolution of AS-level topology because the gateway router recording AS paths remain unchanged while the AS paths is collected. Therefore, we use adjacency matrix obtained from AS paths in BGP routing table in this study.

BGP routing tables that we use in this paper are collected in both of servers of RouteViews Project [10] and RIPE NCC [11]. These servers have been collecting BGP tables from gateway routers of a lot of ISPs since 1997 and 1999, respectively. Table I shows the number of ASes and links of adjacency matrix obtained.

TABLE I. The number of ASes, links and AS paths in adjacency matrix of AS-level topology.

	2000/6/15	2004/6/15	2008/6/15	2012/6/15
# of ASes	8,162	18,015	29,320	42,009
# of links	17,533	40,205	64,305	93,470
# of AS paths	299,434	1,108,704	1,901,745	2,605,770

B. Classification of AS type

In AS-level topology, ASes are ranked based on two types of links. One of the link types is called "transit link" where one AS pays transit cost for forwarding traffic to the other AS. The amount of the fee is decided corresponding to the amount of traffic which traverses between two ASes. The other type of links is called "peering links" where transit cost is free. The peering link is constructed between ASes which traverse the same amount of traffic. AS that traverse the same amount of traffic constructs peering links to acquire high quality of communication with low transit cost, and constructs transit links to ensure connectivity. In AS-level topology, a few ASes called Tier-1 connect to each other with peering links, and huge amount of traffic is transferred on the links. Tier-2 ASes connect to Tier-1 ASes with transit links and pay transit fee to Tier-1 ASes. Similarly, Tier-3 ASes connect to Tier-1 or Tier-2 ASes with transit links, which forms hierarchical structure in AS-level topology.

To reveal what kind of ASes aggregate more traffic, we classify ASes into 6 types based on tier of hierarchical structure in AS-level topology. Types of ASes are Tier-1, sub Tier-1, Tier-2, Tier-3, Hyper Giants and Academic. Tier-1, sub Tier-1, Tier-2 and Tier-3 contain ISPs. Tier-1 ASes are large ISPs which traverse immense volume of traffic, and Tier-3 ASes are small ISPs. Sub Tier-1 contains ASes which are large ISPs and cannot be decided Tier-1 or Tier-2 because the AS is called Tier-1 and Tier-2 at a different time.

Classification of AS types is based on the hierarchy derived from the type of links, however, the information about type of link remain secret. Some studies propose the method to infer link type to analyze the structure of AS-level topology [12, 13, 1]. In most of studies to infer links, the authors verify their own method by comparing results of their own methods and a part of raw data about link type obtained from ISPs. The method in [1] can infer type of links with an accuracy rate of 99.1%. We use the result of Ref. [1] in this study.

We classify ASes based on following steps. First, we exploit peering links and ASes having peering links. We regard ASes connected component consisted of peering links as a tier because two ASes connected with peering link generally traverse much the same amount of traffic. Next, we check the commercial name of ASes in each connected component, and determine tier of each connected component from 6 types. Finally, tier of each AS is decided based on connected component that contains the AS.

III. Modular structure of AS-level topology

A. Internal structure in modules and structure among modules

To analyze containment hierarchy, we first investigate modular structure which is the structure in modules and the structure of connection among modules. By this investigation, we reveal structure of AS-level topology in a macro perspective.

We extract modular structure from AS-level topology to analyze modular structure. In extracting modular structure,

TABLE II. DEFINITION OF NOTATION FOR MODULARITY($\frac{1}{2m}\sum_{ij}[A_{ij} - \frac{k_i k_j}{2m}]\delta_{S_i S_j}$)

Notation	Definition
m	The 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.

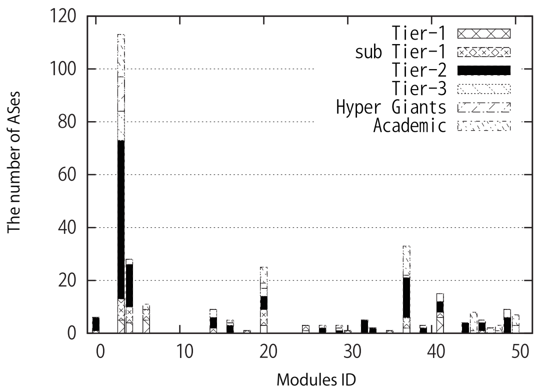


Fig. 1. AS types in each module. AS-level topology in 2012 contains 52 modules. In each module, various AS types is contained.

we split AS-level topology into modules based on Ref. [14]. In Ref. [14], topology is split such that modularity of the topology will be maximum. Modularity is the variable that represents how appropriate module division is when partition is given. Modularity is high when links between ASes in the same module is densely connected and links between ASes in different modules is sparsely connected. Formally, modularity is defined as Eq. (1) when partition P that splits AS-level topology is given. Descriptions of variables in the definition are shown in Table II.

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

The value of modularity $M(P)$ is closer 1 when links between ASes in the same module are densely connected, and is closer 0 when the graph is complete graph or star topology which cannot be split module.

In the investigation of modular structure, we first reveal AS types contained in each module to represent the internal structure in each module. Fig. 1 shows the number of ASes contained in each module according to AS types. In each module, there are ASes of various types, which means small AS connects to large AS in each module.

We next show type of ASes that have a lot of inter-module links to reveal how modules connect to each other. Table III shows the number of inter-module links by types of ASes. l_m is the number of inter-module links which ASes in each type have, and n_m is the number of nodes in each tier. l_m/n_m in Table III represents average of inter-module links of ASes in each tier. l_m/n_m decreases from top-level to bottom-level.

TABLE III. THE NUMBER OF INTER-MODULE LINKS THAT ASES HAVE IN EACH TIER

	l_m	l_m/n_m
Tier-1	12626	485.6154
sub Tier-1	3294	84.46154
Tier-2	3440	25.10949
Tier-3	158	6.583333

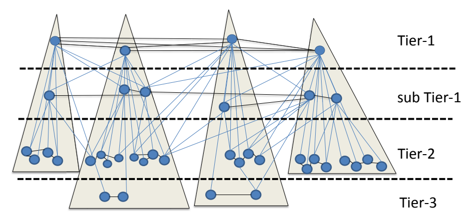


Fig. 2. Image of graph obtained by splitting AS-level topology into modules.

This suggests that ASes in higher tier tend to have more inter-module links compared to ASes in lower tier.

Each module contains ASes in different tiers, and ASes in higher tier have more inter-module links. Therefore, AS-level topology is depicted like Fig. 2. Fig. 2 shows image of graph obtained by splitting AS-level topology into modules. The number of ASes is 1/5 of the number of Tier-1 ASes, sub Tier-1 ASes, Tier-2 ASes and Tier-3 ASes of AS-level topology in 2012. The number of links is 1/5 of the number of links in Tier-1, sub Tier-1, Tier-2, and Tier-3 in 2012. Triangles in Fig. 2 represent modules. In AS-level topology, ASes in higher tiers, for example Tier-1 ASes, aggregate traffic which traverse in the module, and they transmit traffic to some ASes in the other modules.

Tier-1 ASes have heavy traffic load since they aggregate traffic in modules as shown in Fig. 2. To see this more clearly, we show correlation between the number of inter-module links that an AS and the traffic load on the AS. In this study, we define traffic load of an AS as a sum of AS paths through adjacent links of the AS. In other words, traffic load W_x of an AS x is defined as below.

$$W_x = \sum_{l \in L_x} w_l, \qquad (2)$$

where L_x is set of adjacent links of the AS x, and w_l is the number of AS paths through link l. The coefficient of correlation R^2 between traffic load W_x of an AS x and the number of inter-module links E_i are defined as following expression;

$$R^2 = \frac{\sum_{i=1}^{n}(E_i - \overline{E})(W_i - \overline{W})}{\sqrt{\sum_{i=1}^{n}(E_i - \overline{E})}\sqrt{\sum_{i=1}^{n}(W_i - \overline{W})}}, \qquad (3)$$

where n is the number of nodes in AS-level topology, $\overline{E}$ and $\overline{W}$ represent average of $E_i (i = 1, 2, \cdots, n)$ and $W_i (i = 1, 2, \cdots, n)$ respectively. In Fig. 3, the coefficient of correlation R^2 between traffic load of an AS and the number of inter-module links E_i of the AS are described. As shown in Fig. 3, the coefficient of correlation is around 0.9 from 2000 to 2012, and traffic load of an AS is positively correlated with the number of inter-module links.

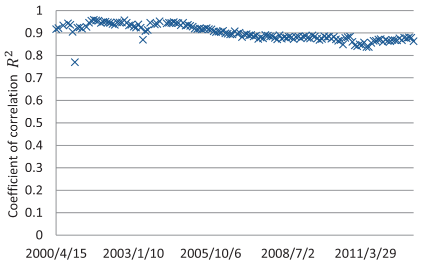
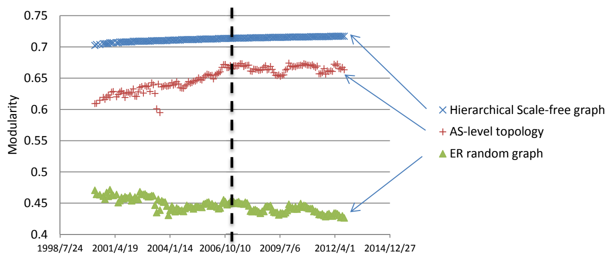
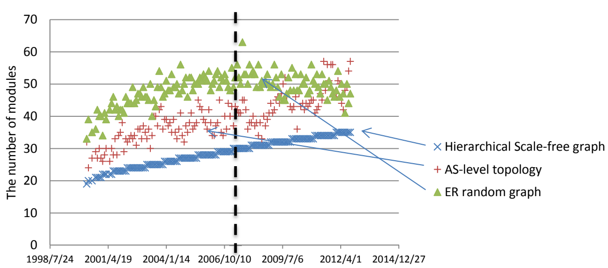


Fig. 3. The coefficient of correlation R^2 between traffic load of an AS and the number of inter-module links.



(a) Evolutional change of modularity.



(b) Evolutional change of the number of modules.

Fig. 4. Evolutional change of modularity and the number of modules on every month.

B. Evolutional change of modular structure

To reveal the trend about where and how traffic is aggregated, we investigate the longitudinal change of modular structure. Fig. 4(a) shows modularity and the number of modules on every month. We analyze the change of modularity and the number of modules of AS-level topology by comparing to those of other model graphs. Fig. 4(a) and Fig. 4(b) show modularity and the number of modules of ER random graph and hierarchical scale-free graph [15]. All of these graphs have the same number of nodes as AS-level topology. ER random graph is generated by adding links randomly between nodes deployed. Hierarchical scale-free graph is one of graph having characteristics that degree distribution exhibits power-law attribute, and generated by adding modules each of which has scale-free degree distribution to the graph incrementally.

As shown in Fig. 4(a), modularity of hierarchical scale-free graph is the highest of all, and that of ER random graph is the lowest. Fig. 4(b) shows that there are a lot of modules in ER random graph, and the number of modules in hierarchical scale-free graph is from 1/3 to 1/2 of the number of modules in ER random graph. In hierarchical scale-free graph, large volume of traffic tends to be aggregated at inter-module links due to high modularity. Because there are a few inter-modules links in hierarchical scale-free graph and modules connect to each other sparsely, large traffic is aggregated on inter-modules links and traffic load on inter-modules links became heavier.

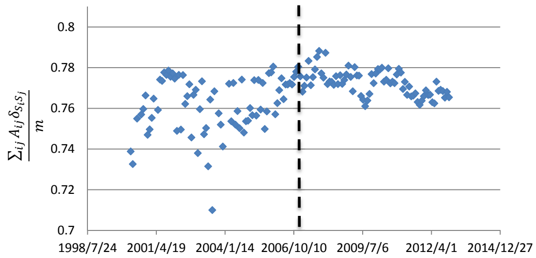
In Fig. 4(a), the increase of modularity in hierarchical scale-free graph and ER random graph is small. In AS-level topology, on the other hand, modularity has been increasing from 2000 to 2007, and remain steady since 2007. Dashed line in Fig. 4 means 1 January in 2007. This suggests that it is possible that structural change happened in around 2007. To clarify the factor affecting the change of increase of modularity in 2007, we investigate the change of value of terms in definition of modularity (Eq. (1)). Modularity depends on the ratio of inner-module links to all links and the node degree in each module. The key terms in Eq. (1) are $\sum_{ij} A_{ij}\delta_{S_iS_j}$ and $\sum_{ij} \frac{k_ik_j}{2m}\delta_{S_iS_j}$. $\sum_{ij} A_{ij}\delta_{S_iS_j}$ is the number of inner-module links in the topology, and $\sum_{ij} \frac{k_ik_j}{2m}\delta_{S_iS_j}$ is the probability of drawing a link between node i and node j when links are randomly deployed on the topology, and this relates to node degree in each module.

Fig. 5 shows the evolutional change of these terms normalized by the total number of links in AS-level topology. Fig. 5(b) shows the probability of drawing a link between node i and node j when links are randomly deployed on the topology. The probability comparatively remains constant from 2000 to 2012. On the other hand, the ratio of inner-module links has been increasing with a little fluctuation until 2007, and after this, the ratio of inner-module links gradually decrease. We suppose that the ratio of inner-module links affects modularity in AS-level topology. In Fig. 5(a), the factor of fluctuation of the ratio of inner-module links until 2007 is thought to be due to difference of the number of nodes in each modules every month. The increase of modularity is caused due to the increase of the scale of AS-level topology. Even though the scale of AS-level topology is becoming larger since 2007, the ratio of inner-module links decreases mainly because Hyper Giants, which are very large contents providers, have appeared, and they directly connect to a lot of ASes in different modules [5, 8]. Due to increase of the number of inter-module links between Hyper Giants and a lot of ISPs, modularity decreases since 2007. This means that the trend of traffic aggregation was continued until about 2006. In recently, however, the trend becomes weaker partly because appearance of Hyper Giants.

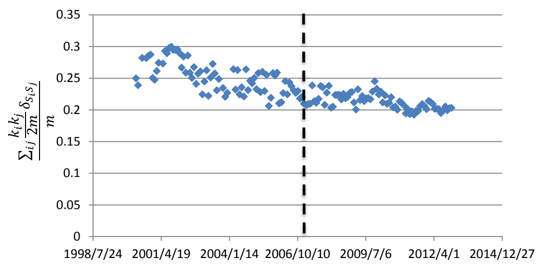
IV. Containment hierarchy

A. Extraction of containment hierarchy

By analyzing containment hierarchy, we investigate hierarchy of traffic aggregation and the longitudinal change of hierarchy of traffic aggregation which means the load of traffic on links from core to edge of AS-level topology. To analyzing containment hierarchy, we extract containment hierarchy from AS-level topology. Containment hierarchy is extracted by iteration of splitting topology into smaller modules. We first split AS-level topology into top-level modules. And, we split each of top-level modules into smaller sub modules. Furthermore, we split sub modules into even smaller sub-sub modules, and extract hierarchical structure. In this study, we



(a) Ratio of inner-module links.



(b) The probability of drawing a link between node i and node j when links are randomly deployed on the topology.

Fig. 5. Evolutional change of value of terms affecting modularity.

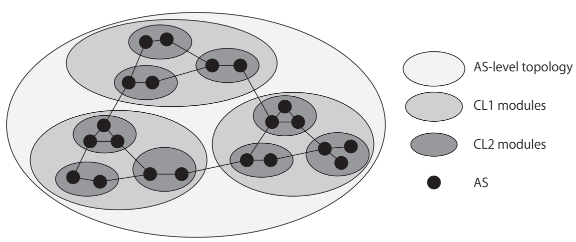


Fig. 6. Sample of sets of CL1 modules and CL2 modules.

call a set of modules which are generated by first splitting AS-level topology "Containment Level 1 (CL1)" modules. A set of smaller modules contained in CL1 modules is CL2 modules and so on over other level as shown in Fig. 6.

Containment hierarchy is extracted by following process.

1) Split AS-level topology into modules [14]. We call the modules generated by splitting AS-level topology CL1 modules.
2) If modularity of CL1 modules is not 0, split CL1 modules into smaller modules, which are CL2 modules.
3) Repeat above process over CL2

If modularity of a graph is 0, the graph cannot be split into modules because there is no mass of nodes in the graph, for example star and full mesh structure. Thus, AS-level topology is repeatedly split until modularity of modules are 0.

TABLE IV. The 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

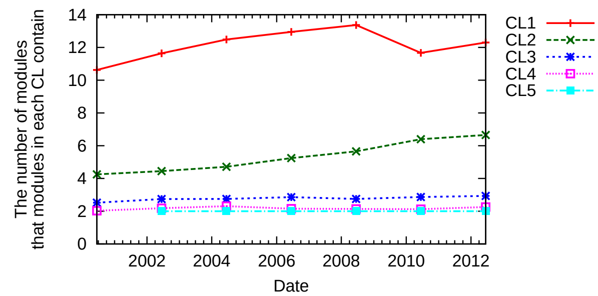


Fig. 7. The number of smaller modules that modules in each CL contain.

B. Evolutional change of containment hierarchy

To reveal the hierarchy of traffic aggregation, we investigate which CL tends to aggregate more traffic. For the purpose, we first show the number of modules in each CL in Table IV. Table IV shows 80% of all modules are contained in CL2 and CL3. The number of modules in CL1 is from 1/5 to 1/3 compared to CL2. The number of modules in CL1 is around 1/10 of the number of modules in CL2. Thus, inter-module links between ASes in CL1 and CL2 aggregate large volume of traffic. To see this more clearly, we investigate the number of sub modules contained in modules in each CL in Fig. 7. The number of sub modules in modules contain decreases from CL1 to CL5. The number of smaller modules contained in CL1 modules increase from 2008, however, it decrease after 2008. In CL3, CL4 and CL5, there is not change of the number of smaller modules. In CL2, the number of smaller modules contained in CL2 modules has been increasing. Thus, the amount of traffic aggregated on inter-module links between modules in CL2 is increasing. In other words, the count of aggregation of traffic sent by small ISP which is AS in Tier-3 or more tier is slightly increasing, and traffic is aggregated more hierarchically.

Finally, we analyze the change of the structure of containment hierarchy through investigating the depth of containment hierarchy. From the analysis, we can reveal what ASes take heavier load of traffic. In each CL, there are modules that cannot be split into smaller modules because structure of the module is complete graph or star. We call these modules "flat modules". Flat modules are corresponding to a lowest layer of containment hierarchy. Thus, the CL where flat modules are represents the depth of containment hierarchy. Table V indicates the number of flat modules in each CL. In AS-level topology in 2000, the number of flat modules in CL3 is the most of all CLs. The number of flat modules in CL4 and CL5 is increasing over the years. Even though the number of ASes and AS paths increase, the maximum number of CL keeps constant from 2002 to 2012, which is 6. Thus, the depth of containment hierarchy almost remains steady, and

TABLE V. THE NUMBER OF FLAT MODULES IN EACH CL.

Year	CL1	CL2	CL3	CL4	CL5	CL6
2000	2	64	602	494	71	0
2002	4	111	894	821	128	6
2004	6	138	1100	1083	205	6
2006	3	120	1337	1423	297	4
2008	2	77	1678	1906	386	6
2010	0	53	1874	2435	437	2
2012	4	104	2068	2898	632	12

the width of containment hierarchy becomes wider. When the width of containment hierarchy expands, the number of ASes in a module increases and more traffic traverses through inter-module links. This means that the amount of traffic aggregated on ASes that have a lot of inter-module links is becoming larger. Since Tier-1 ASes have a lot of inter-module links as shown in Table III, traffic load on Tier-1 ASes will become larger.

V. CONCLUSION

The understanding of the structural evolution in AS-level topology is important for expanding network and analyzing performance of new application and protocols. To understand how traffic is aggregated in the AS-level topology, we investigated the evolution process of AS-level topology through a hierarchical analysis. Before we analyze the hierarchy of modules, we first investigate modular structure of AS-level topology. In analyses of modular structure, we found a trend that modularity has been increasing until around 2007, and modularity remain steady after around 2007. This means that the amount of traffic aggregated in the module before forwarding to other modules had increased until about 2006. Thus, the trend of traffic aggregation was strong. In recently, however, the trend become weaker partly because appearance of Hyper Giants. By analyzing the change of containment hierarchy, it is confirmed that traffic is aggregated more hierarchically. Furthermore, it is found that the structure of containment hierarchy is evolving with expanding not depth but width of the structure. This means that the amount of traffic aggregated on ASes that have a lot of inter-module links is increasing.

In analyses of containment hierarchy in this study, the influence of Hyper Giants does not recognized. Therefore, we suppose that traffic aggregation does not directly relate to Hyper Giants. In the future work, we point out the influence of appearance of Hyper Giants, and analyze the evolution of AS-level topology.

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