Modularity Structure and Traffic Dynamics of ISP Router-level Topologies

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Abstract—Internet behavior becomes more complex due to ever-changing networking technologies and applications. Thus, understanding and controlling the complex behavior of the Internet are important for designing future networks. Previous studies revealed that flow control in the transport layer affects the traffic dynamics of the Internet. However, it is not clear how the topological structure impacts traffic dynamics. In this paper, we show the traffic fluctuation of the BA topologies generated by the Barabási-Albert (BA) model and the ISP router-level topologies. The number of links with highly fluctuating queue length increases dramatically compared to that in the stop-and-wait model. Even in this case, the high-modularity structures of the ISP topologies reduce the number of highly fluctuating links compared with the BA topologies.

1. Introduction

Dynamic interactions among various network-related protocols as a result of functional partitioning make the Internet a complicated system whose details are difficult to confirm because of its large-scale, heterogeneous structure. One of the complex behaviors of the Internet is traffic dynamics. For example, flow control and congestion control of TCP can cause short-range and long-range dependence of traffic [1]. Ever-changing networking technologies and applications make behavior of the Internet more complex; thus, understanding and controlling the complex behavior of the Internet are important for designing future networks.

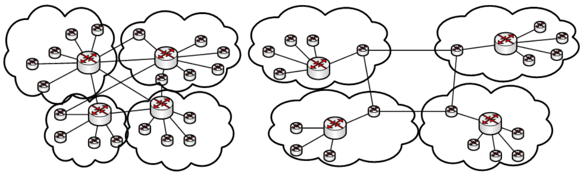
Measurement studies have revealed that the degree distribution of the Internet topology follows a power law. That is, the probability that nodes having k links of exist is proportional to $k^{-\gamma}$ (γ is constant). Li et al. showed several topologies that have different structures but have the same degree distribution [2]. They pointed out differences in structures lead to differences in the amount of traffic that the network accommodates. This study indicates that the power-law degree distribution alone does not determine network-level performance. That is, topological structure properties other than the degree distribution are essential to discuss the performance of networks [2].

In previous studies, the relationship between the statistical properties of Internet traffic and end-to-end flow control has been discussed. In Refs. [3], it is revealed that Internet traffic exhibits long-range dependence (LRD), where traffic fluctuation appears to be independent of measurement time scale. Various studies have investigated the reasons for LRD. One of the reasons is flow control in the transport layer, such as TCP [4]. However, these studies deal with small, simple topologies. We therefore need to investigate the traffic dynamics in large-scale topologies where the topological structure greatly affects the network performance. More specifically, we investigate traffic dynamics on ISP router-level topologies (ISP topologies) where the degree distributions exhibit a power-law nature, and the nodes interact via end-to-end feedback flow control functionality. We discuss how the structures of topologies and the flow controls affect the appearance of LRD in the queue length for each link. The results show that the TCP flow control make the queue length of links in the network fluctuate because TCP tries to use available bandwidth. However, we show that the queue length of many links does not fluctuate in the ISP topologies. This phenomenon is due to the high-modularity structure of the ISP topologies. We investigate the relationship between the modularity of topologies and queue fluctuation. We find that topologies with high-modularity structures reduce the number of highly fluctuating links.

This paper is organized as follows. We explain structural properties of ISP topologies in Section 2. In Section 3, we show the network model that we used for the simulations. In Section 4, we evaluate the influence of the power-law topologies and TCP flow control. Finally, in Section 5, we conclude this paper and mention future work.

2. Modularity Structure of ISP Topologies

Recently, there have been a considerable number of studies investigating power-law networks whose degree distribution follows a power law. Barabási et al. introduced the BA model as a method for generating a power-law topology in Ref. [5]. Many studies have investigated topological properties appearing in the BA model or its variants. However, when router-level topologies are concerned, the BA model does not emulate the structure of ISP topologies. We have compared the structural differences of the AT&T topology measured using the Rocketfuel tool [6] and the topology generated by the BA model [7]. The results in-



(a) The BA topology (b) The AT&T topology

Figure 1: Ilustrations of structural properties of each topology

dicate that the design principles of networks greatly affect the modularity structure of the ISP topologies: Design principles determine the node functionality, which in turn determines the connectivity of nodes. To confirm this, we divide a network into multiple modules and investigate the node's connectivity. We observe that the BA topology has many connector hub nodes that connect between modules with many inter-module links like Fig. 1(a). On the contrary, the AT&T topology has many provincial hub nodes that connect the nodes within modules like Fig. 1(b). The AT&T topology has high-modularity structure which has dence connections between the nodes within modules and sparse connections between nodes in different modules.

3. Simulation Model

3.1. Network Topologies

For the simulation, we use several ISP topologies measured by the Rocketfuel tool [6] and BA topologies generated by the BA model. BA topologies are generated such that the numbers of nodes and links are the same as the corresponding ISP topologies. In Ref. [2], it is shown that the BA model is insufficient to model ISP topologies. However, we use the BA topology in this paper, because one of our purposes in the current paper is to clarify how the high-modularity structures characterize traffic dynamics in ISP topologies.

3.2. Packet Processing Model at Node

Each node has limited buffers at each outgoing link. When a packet arrives at a given node and when the node is the packet's destination, the node removes the packet from the network. Otherwise, the node selects the next node based on a minimum hop routing algorithm and forwards the packet to a buffer of an outgoing link connecting to the next node. For simplification, each outgoing link sends packets to the next node based on FIFO and a drop-tail queuing discipline, and delivers C packets per unit time. Here, we do not use dynamic routing; i.e., each packet traverses the shortest path calculated beforehand. When multiple shortest paths to the destination are found, the next node is randomly determined by a packet's source node.

Table 1: The simulation parameters used in the TCP model

Buffer size	1,000 packets
Session arrival rate (λ)	1 session / unit of time
Maximum *cwnd*	10 packets
Link capacity (C)	3 packets / unit of time
Simulation time	300,000 units of time
Initial RTO	10,000 units of time

3.3. Flow Control between End Hosts

In the simulation, pre-specified numbers of sessions are created between nodes. Source and destination nodes are randomly selected and each session arrives at a node pair according to the Poisson process with mean rate λ. Each session always has data to send during the simulations, i.e., once a session is generated, it continues to send data to destination node until the simulation ends. In this model, source nodes control the amount of DATA packets based on the slow start and congestion avoidance algorithms. These two algorithms are basic flow-control functions of TCP. In our model, the congestion window (*cwnd*) size does not exceed a pre-decided maximum window size. If the source node does not receive any acknowledgement (ACK) packet within the retransmission time out (RTO) period, the source node recognizes that serious congestion has occurred. The source node resends the lost DATA packet and reduces the congestion window by one packet size. The time-out period is defined based on the estimated RTT and is doubled for every time out. In addition, we use the fast retransmit and fast recovery algorithms defined by RFC 2581.

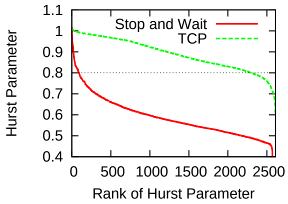
4. Dynamics of TCP in ISP Topologies

4.1. Queue Length Fluctuation

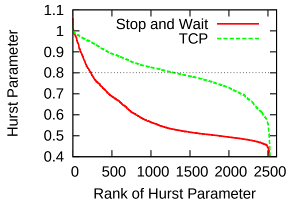
In this section, we show the results of simulation for TCP and discuss the end-to-end delay and queue-length fluctuation in detail. In the simulation, each link can transfer three packets per unit time. The other parameters are summarized in Table 1.

We evaluate the fluctuation of queue length. If queue length of a link fluctuates drastically, a session encounters a temporal congestion on the link, which leads to a packet drop and a longer delay. We evaluate the fluctuation using the Hurst parameter ($H, 0.5 < H < 1$) by applying the rescaled range (R/S) plot method [8]. The Hurst parameter represents the degree of LRD. High Hurst parameter means that queue length of the link highly fluctuates. We use the time series of queue lengths extract from the last 100,000 time units of simulation.

Figure 2 shows Hurst parameters for each link. The y-axis represents the Hurst parameter and the x-axis represents its rank in a descending order. In this figure, the results for the stop-and-wait model are also added. In the stop-and-wait model, when a source node sends a DATA



(a) The BA topology



(b) The AT&T topology

Figure 2: Correlations between Hurst parameter and rank of Hurst parameter

Table 2: The ratio of highly fluctuating links in each topology

Topology	10,000 sessions			100,000 sessions		
	Total	Inter	Intra	Total	Inter	Intra
BA topology	0.54	0.19	0.35	0.88	0.30	0.58
AT&T topology	0.39	0.080	0.31	0.50	0.066	0.44

packet to its destination node, the source node stops sending a new packet until the source node receives the ACK packet from the destination node. Looking at this figure, we observe that the number of links that take high Hurst parameters increases in the TCP model. Besides, we observe that the AT&T topology reduces the number of fluctuating links compared with the results of the BA topology.

To see the relation between the Hurst parameter and topological structure in the AT&T topology clearly, we show the ratio of links that take high H values ($H \geq 0.8$) in Table 2. When the number of sessions is small, the queue length of the links that connect two regions fluctuates drastically. That is, inter-module links tend to have highly fluctuating queue lengths. This is because many packets concentrate at inter-module links. As the number of sessions gets higher, the queue length of the links that connect inside a region fluctuates, whereas the Hurst parameter of inter-module links decreases. That is, the fluctuation spreads to tributary links of the bottleneck.

4.2. Fluctuation Reduction Effect of High-Modularity Structure

In the previous section, we showed that the structure of the AT&T topology reduces the number of fluctuating links. In this section, we examine the relationship between the modularity of topologies and the fluctuation reduction effects of those topologies.

Newman et al. [9] defined a modularity value (Q) as

$$Q = \sum_i (e_{ii} - a_i^2), \quad (1)$$

where e_{ii} is defined as the number of links connecting nodes of module i divided by the number of all links. While, a_i is defined as the number of random links that have one or both vertices inside of module i divided by the number of all links. The module is calculated using the method in [10]. According to this definition of Q, high Q value means that the topology has high modularity structure, that is, some modules are connecting with each other by a few inter-module links. The modularity value of the BA topology is nearly 0.32, and that of the AT&T topology is about 0.68. This result indicates that a high-modularity structure reduces the number of highly fluctuating links.

Table 3: Simulation results of ISP topologies

Topology	Nodes	Links	Modularity	Ratio of highly fluctuating links
AT&T	523	1,304	0.68	0.50
BA (AT&T)			0.32	0.88
Sprint	467	1,280	0.66	0.53
BA Sprint			0.30	0.81
Verio	817	1,874	0.70	0.46
BA Verio			0.25	0.77
Telstra	296	594	0.74	0.46
BA Telstra			0.29	0.78

To confirm that ISP topologies reduce the number of fluctuating links, we conduct simulations with other ISP topologies and compare them with BA topologies. Three ISP topologies, Sprint, Verio, and Telstra, are used for the simulations because the topologies have the similar numbers of nodes and links to the AT&T topology. The topological properties of ISP topologies and its corresponding BA topologies are summarized in Table 3. The simulation parameters are the same as the evaluation of AT&T topology and are summarized in Table 1. Note that the number of sessions is 87,320 in the Telstra topology and the BA Telstra topology due to limit of the number of node pairs. In the Table 3, the ratio of highly fluctuating links for each topology is also presented. We observe that each ISP topology reduces the number of fluctuating links compared with the results of the corresponding BA topologies. We also observe that each ISP topology has higher modularity value than the corresponding BA topology. These results indicate that topologies having high-modularity structure reduce the number of highly fluctuating links, as we observed in the AT&T topology.

To see the impact of modularity structure more clearly, we investigate queue fluctuation on three topologies that have the same number of nodes and links to the AT&T topology, but have different modularity values. We generated three topologies having N (= 523) nodes and E (= 1,304) links. And then, we control the modularity value by changing the number of inter-module links. More precisely, we generated the three topologies through following steps. the number of inter-module links in Step 3.

1. Generates 10 sub-networks each of which consists of $\dfrac{N}{10}$ nodes and $\dfrac{E-m}{10}$ links and is connected based on the BA model.

Table 4: Simulation results of generated topologies

Modularity	Ratio of highly fluctuating link
0.86	0.62
0.81	0.78
0.76	0.84

2. Considers each sub-network as a module.

3. Adds *m* inter-module links by randomly selecting two nodes belonging to different modules and connecting the nodes.

As the number of inter-module links increases, the modularity value decreases. The modularity values of the generated topologies were 0.86, 0.81, and 0.76, and we confirmed that these topologies had power-law degree distributions.

In the simulations, we again used the parameters in Table 1 and again randomly select the source and destination nodes for each session. This result is confirmed by the ratio of highly fluctuating links that have a Hurst parameter larger than 0.8 shown in Table 4. Thus, topological structures that have high modularity values prevent the appearance of highly fluctuating links.

A question is why the high-modularity structure reduces the number of highly fluctuating links. This is because the relationships between link load and queue fluctuation. Here, the link load is the number of end-to-end sessions that pass through the link. When a link load is low, the queue length does not fluctuate. However, if the link load exceeds a certain level, the queue length is mostly constant due to a limit of buffer size in queue. Although the queue length keeps nearly-constant, each of TCP sessions dynamically changes its sending rate. Thus, the queue length of the tributary links to the inter-module links is governed by the dynamics of each TCP session and thus fluctuates. This situation occurs when the links are close to the inter-module links because the large number of TCP sessions is aggregated. More precisely, connector hub nodes or non-hub connector nodes perform the aggregation of TCP sessions. However, connector hub nodes rarely exist in topologies with the high-modularity structure: most of hub nodes are provincial hub nodes. Thus, the situation occurs only around the connector non-hub nodes, and therefore the number of fluctuating links is small.

5. Conclusion

In this paper, we investigated the interaction between the structures of topologies and flow control between end hosts. Comparing the simulation results of the stop-and-wait model and the TCP model, the functionality of TCP makes the queue length to fluctuate. Even in this case, the high-modularity structure of the AT&T topology reduces the number of highly fluctuating links compared with the BA topology. We also evaluated the queue length on the other topologies and confirmed that the modularity structure is the essential structure to reduce the number of highly fluctuating links.

Our results suggest that reproducing the modularity structure is important when performance evaluation on transport protocols is concerned. Our future work is to developing a topology generation method that reproduces the modularity structure and apply it to performance evaluations.

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