Master's Thesis

Title

On Feedback-induced Packet Delay Dynamics in Power-law Networks

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Abstract

As the Internet becomes a social infrastructure of information exchange and global communication, many network devices are connected to the Internet and many users communicate via the Internet. Although, OSI's functional partition for network-related protocols makes various Internet to be distributed, large-scaled communication systems, dynamic interactions of the network-related protocols, induced by the functional partition also make the Internet to be an complicated systems. One of complex behaviors of the Internet is traffic dynamics. For example, flow control and congestion control performed by end host can show short-range and long-range dependence of traffic. The Internet is facing with ever-changing networking technologies and applications, so understanding and controlling the complex behaviors of the Internet are important in designing the network.

Although the statistical property of network traffic is hard to capture, measurement studies of the Internet topology revealed that the degree distributions of the Internet topologies follow a power law. That is, existing probability of nodes having k links is proportional to $k^{-\gamma}$. A power-law relation often appears in many complex systems, e.g., biological systems, brain systems, and some engineering systems. Thus, complex networks where their topology is formed based on the interaction between individuals of the network have been interested in recent years. The BA model and its variants are widely used in many studies concerned about power-law networks. However, only the power-law degree distribution does not determine network-level performance of networking methods. That is, the structural characteristics of topologies other than the degree distribution are essential to discuss the behavior of networking methods.

In this thesis, we investigate traffic dynamics on ISP's router-level topology where the degree distribution exhibits power-law attribute and each of the nodes interacts via end-to-end flow control functionality. In previous studies, the relationship between statistical properties of the Internet traffic and end-to-end flow control has been discussed. However, these researches deal with simple small topologies. We therefore investigate how structure of topologies impacts on traffic dynamics. We first show packet delay dynamics on the BA topology generated by the BA model and the ISP's router-level topology. We then discuss how structure of topologies and flow controls affect the end-to-end packet delay distribution and the queue length fluctuation of links. Extensive simulation results show that the end-to-end packet delay distributions exhibit a heavy tail by the TCP model. Moreover, the number of links that are highly fluctuated is more than twice comparing to the results of the stop-and-wait model. In the TCP model, 10% of total links are highly fluctuated when the number of session is large. When the number of session is small, 0.8% of total links are highly fluctuated. The results also indicate the queue length fluctuation disappears at bottleneck links and appears their tributary links due to the modularity structure of ISP's router-level topology. Even in this case, the modularity structure of the AT&T topology reduces the number of highly fluctuated link up to 40% comparing to the results of the BA topology.

Keywords

Power-law Networks

ISP's Router-level Topology

Traffic Dynamics

Stop-and-Wait

TCP

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1 Introduction

As the Internet becomes a social infrastructure of information exchange and global communication, many network devices are connected to the Internet and many users communicate via the Internet. Although, OSI's functional partition for network-related protocols makes the Internet to be distributed, large-scaled communication systems, dynamic interactions of various network-related protocols, induced by the functional partition also make the Internet to be an complicated systems; details are hardly captured because of large-scale, ever-changing, and heterogeneous structure.

One of complex behaviors of the Internet is traffic dynamics. For example, flow control and congestion control performed by end host can show short-range and long-range dependence of traffic [1]. Another example is the traffic fluctuation caused by the dynamic interaction between overlay routing by end users and traffic engineering by ISPs. Due to the dynamic interaction, traffic demand fluctuates depending on time and traffic is hard to control for network operators [2]. The Internet is facing with ever-changing networking technologies and applications, thus understanding and controlling the complex behaviors of the Internet are important for the network designing future networks

Although the statistical property of network traffic is hard to capture, measurement studies of the Internet topology revealed that the degree distributions of the Internet topologies follow a power law. That is, existing probability of nodes having k links is proportional to $k^{-\gamma}$. A power-law relation often appears in many complex systems, e.g., biological systems, brain systems, and some engineering systems [3]. Thus, complex networks where their topology is formed based on the interaction between individuals of the network have been interested in recent years [4]. Barabási et al. propose the BA model to generate topologies having power-law degree distribution [5]. The BA model and its variants are widely used in many studies concerned about power-law networks. However, structures of topologies are not determined only by degree distribution, but also by other factors. Li et al. shows several topologies that have different structures but having the same degree distribution [6]. They pointed out that difference in structures leads to difference in the amount of traffic that the network accommodates. Moreover, structures of power-law topologies also affect the performance of some networking mechanisms such as the routing mechanisms [7]. These work indicate that only the power-law degree distribution does not determine network-level performance. That is, the structures of topologies other than the degree distribution are essential to discuss the behavior of some networking methods.

In this thesis, we investigate traffic dynamics on ISP's router-level topology where the degree distribution exhibits power-law attribute and each of the nodes interacts via end-to-end flow control functionality. In previous studies, it has discussed about the relationship between statistical properties of the Internet traffic and end-to-end flow control. In Ref. [8], since the Internet traffic exhibits long-range dependence (LRD), Poisson process is failed to model the real traffic. In LRD traffic, traffic fluctuation is independent from time scale of measuring. Recently, it has revealed that the traffic generated by P2P application exhibits LRD, too [9]. Some researchers pointed out that LRD traffic in the Internet is caused by feedback flow control on the transport layer, such as TCP [10–12]. However, these researches deal with simple small topologies, we therefore investigate how structure of topologies impacts on traffic dynamics.

We first show packet delay dynamics and compare it with the BA topology generated by the BA model and the ISP's router-level topology. We then discuss how structure of topologies and flow controls affect the end-to-end packet delay distribution and the appearance of long-range dependence in queue length for each link. The results show that increased traffic caused by TCP makes queue length of links in the network fluctuate. However, we show that network throughput does not decline and queue length does not fluctuate against traffic caused by TCP in ISP topology.

This thesis is organized as follows. We introduce related work of this thesis in Section 2. Section 3 shows the network model that we use for the simulations. In Section 4, we evaluate the influence of the interaction of the power-law topologies and stop-and-wait flow control. Next, we evaluate the influence of the power-law topologies and TCP flow control. Finally, Section 6 concludes our thesis and mentions the future work.

2 Related Work

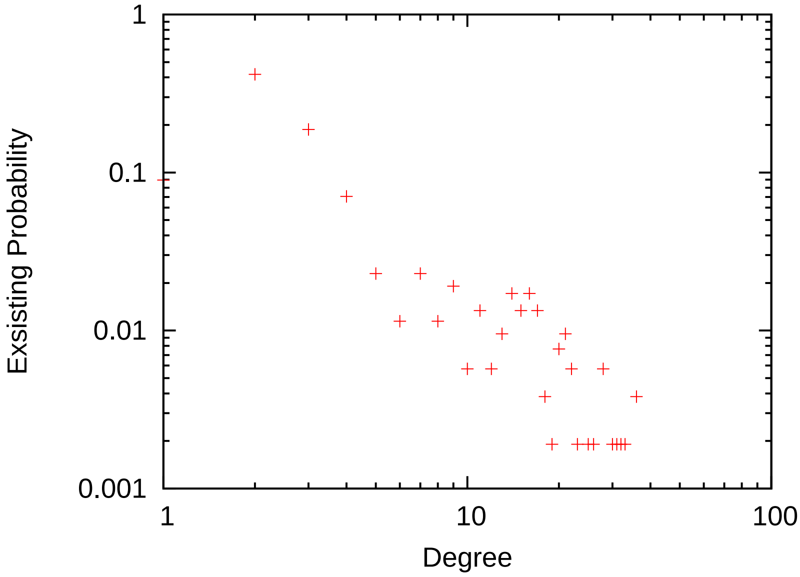
2.1 Power-law Degree Distribution in ISP's Router-level Topology

Recent measurement studies on topologies of the Internet show that the connectivity of nodes exhibits a power-law attribute [13]. That is, the existing probability of the nodes that have k links is proportional to $k^{-\gamma}$. We evaluate the degree distributions of two topologies. The topologies are AT&T topology and Sprint topology measured in Ref. [14]. AT&T and Sprint are major ISP in United States. We call these topologies the AT&T topology and the Sprint topology respectively. The AT&T topology has 523 nodes and 1304 links. The Sprint topology has 467 nodes and 1280 links. Figure 1 show the degree distributions of two topologies. X-axis represents degree of the nodes and Y-axis represents existing probability of nodes which have x links. We observe from these figures that the degree distributions follow a power-law.

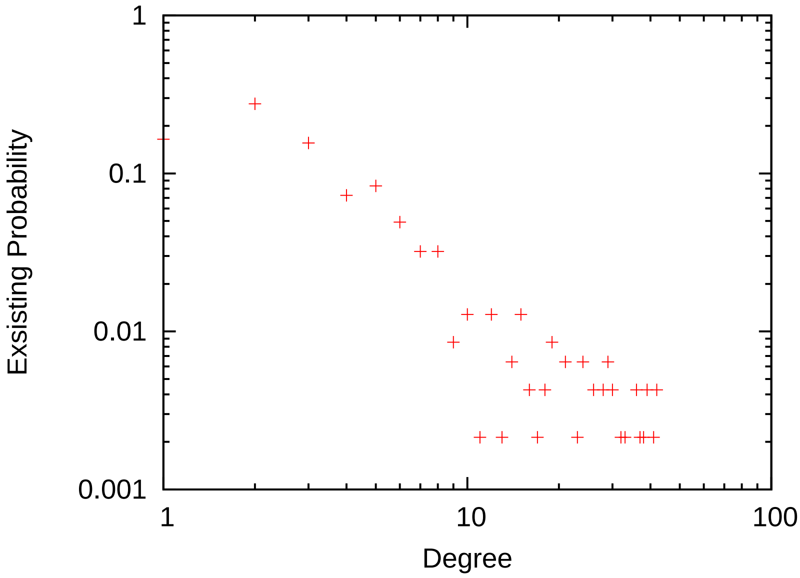
2.2 Structural Properties of Power-law Networks

Recent years, considerable numbers of studies have investigated power-law networks whose degree distribution follows a power law. Barabàsi et al. introduced the BA model as a power-law topology generating method in Ref. [5]. The BA model generates power-law topology based on two rules, one is incremental growth –nodes increase incrementally, and the other is preferential attachment –links tend to connect to the nodes which have many links. The resulting power-law networks have two main characteristics. First, many nodes have a few links and a few nodes so-called hub nodes have many links. Second, the average length of the shortest paths between nodes is small.

Many researches investigate topological properties appeared by the BA model or its variant models. However, when router-level topologies are concerned, the BA model where links are attached based on a preferential probability does not emulate the structure of the ISP's router-level topologies [15], since each ISP constructs its own router-level topology based on strategies such as minimizing the mileage of links and/or maximizing reliability [6, 16]. We have compared the structural differences of the AT&T topology and the topology generated by BA model in Ref. [6]. The results indicate that design principles of networks greatly affect the structure of the ISP topologies. Design principles determine a node functionality, which in turn determines the connectivity of nodes.



(a) The AT&T Topology



(b) The Sprint Topology

Figure 1: Degree distribution in ISP's router-level topologies

In [17], Guimeara et al. have proposed the classification method of node functions. The method divides a network to multiple modules and defines the within-module degree Z_i, and the participation-coefficient, P_i, for each node i. Assuming that the node i belongs to a module s_i, the within-module degree Z_i of node i is defined as,

$$Z_i = \frac{k_i - < k_{s_i} >}{\sigma_{s_i}}, \tag{1}$$

where k_i is the degree of nodes, $< k_{s_i} >$ represents the average degree in module s_i, and σ_i is the variance of the degree distribution of nodes in module s_i. The participation coefficient P_i of node i is also defined as,

$$P_i = 1 - \sum_{s=1}^{N_m} \left(\frac{k_{is}}{k_i} \right)^2, \tag{2}$$

where k_{is} represents the fraction of links connecting with nodes in module s_i. That is, when all the links of node i connect with nodes belonging to the same module of s_i, P_i becomes 0. Figure 2 shows that the roles of nodes are categorized by the value of Z_i and P_i.

Figure 3(a) and Figure 3(b) show the result of the Guimeara's method to the BA topology and the AT&T topology. The module is calculated from the method in [18]. In Figure 3, the horizontal axis indicates within-module degree Z and the vertical axis the participation coefficient P. Depending on the values of P and Z, the role of node is categorized into several classes. For example, when Z_i is large and P_i is relatively large, the node i has many links connecting to other modules. Thus, the node i is categorized into the "Connector hub(s)". "Provincial hub(s)" also takes the larger Z_i but smaller P_i; the node i has many links connecting with nodes in the same module.

Looking at Figure 3(a), we observe that the BA topology has many "Connector hub" nodes that connect between modules. However, Figure 3(b) shows that there is no "Connector hub" in the AT&T topology. This means that the AT&T topology has a few inter-module links that connect different modules.

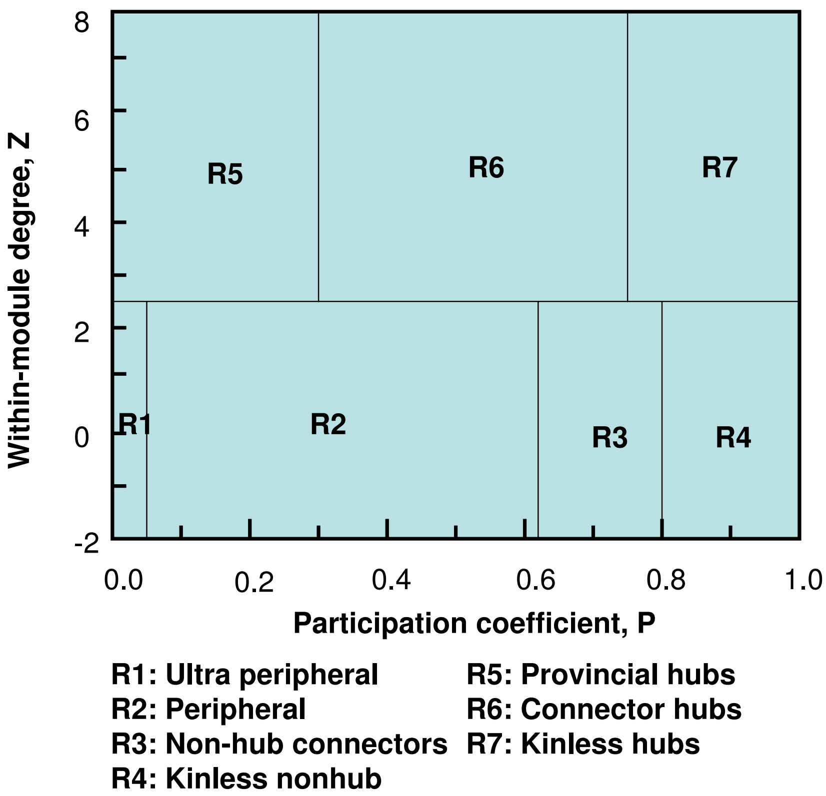
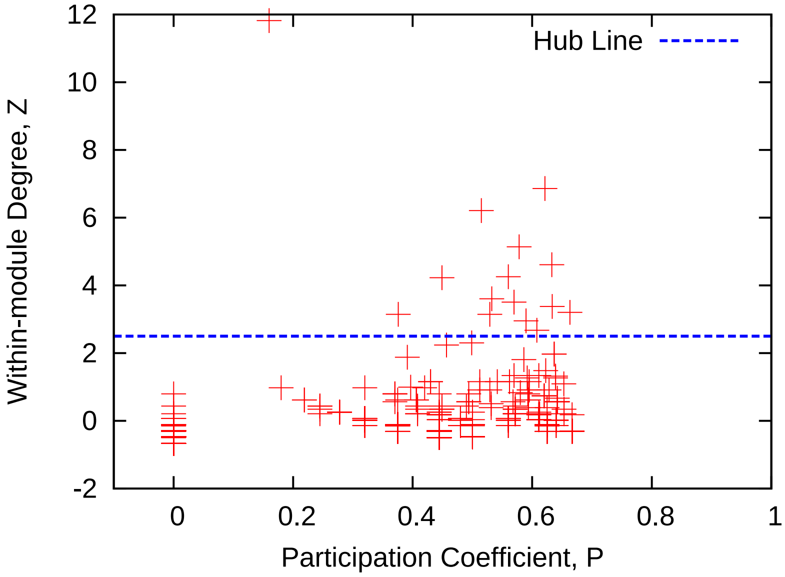
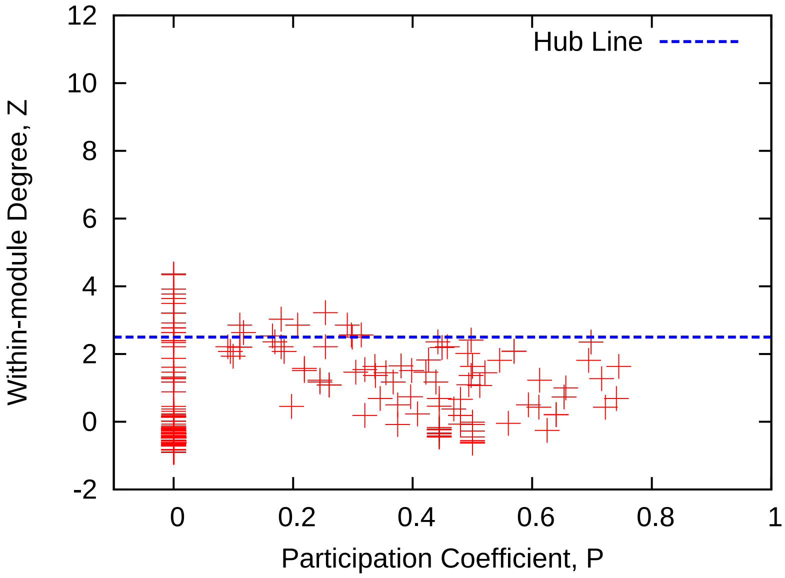


Figure 2: Classification of node function by participation coefficient and within-module degree



(a) The BA topology



(b) The AT&T topology

Figure 3: Classification of node function in each topology

2.3 Traffic Dynamics in Power-law Networks

Some papers investigate traffic-level behaviors in topologies having power-law degree distributions [19–21]. In Ref. [19], the authors investigate the distribution of numbers of node-pairs that pass through a node with a BA-based generation model. They show that, with the minimum-hop packet routing, the load distribution of nodes also exhibits a power-law attribute. Refference [20] investigates how congestion of traffic propagates over topologies. In the paper, each router has a finite size buffer and has a flow control mechanism between routers. When the buffer of a router is fully occupied by packets, the upstream router stops sending packets to the congested router and waits for a congestion elimination. Reference [20] demonstrates that the congestion spreads easily over the topologies in the BA topologies because of the low-diameter of topologies. The low-diameter effects also appear in the queuing delay distribution of topologies. They show that the queuing delay distribution of the BA topology follows a power-law when packet generating rate is low, while it follows a Pareto distribution as the packet generating rate gets higher. The effect of end-to-end flow control is also investigated on the topology obtained by the BA model [21]. The authors examined TCP control with long range dependence (LRD) input traffic and Poisson input traffic, and revealed that average of end-to-end packet delay sharply increases for both input traffic since packets more concentrate on the hub nodes in the BA topology.

The previous works have used topologies generated by the BA model or its variant models. However, even if the degree distributions of some topologies are the same, more detailed characteristics are often quite different. In Ref. [6], Li et al. has enumerated various topologies having the same degree distributions, and has shown the relation between characteristics and performances of these topologies. They have pointed out that difference of the structures leads to difference in performance. As discussed in Section 2.2, the BA model does not adequately model the structure of the ISP router-level topologies. This fact clearly indicates that the power-law degree distribution alone does not determine traffic-level behaviors in router-level topologies.

The traffic dynamics has receiven great interest from the networking research commnunity. In the Internet, it has revealed that the Internet wide-area and local-area traffic can have the long-range dependence or self-similarity [8]. That is, network traffic exhibits a large variability even at a wide range of time scales. Recently, these statistical properties has again observed in Peer-to-Peer traffic [9]. In Ref. [10, 11], TCP flow control is considered to be cause of long-range dependence in the Internet traffic. Simulation results of Ref. [12] show that long-range dependence is caused by feedback flow control functionality only, because when stop-and-wait protocol is used instead of TCP, long-range dependence is still observed in traffic. However, these studies deal with simple small topologies, we therefore investigate how structure of topologies impacts on traffic dynamics.

3 Simulation Model

In this section, we explain about the network model used in this thesis.

3.1 Network Topologies

We use the AT&T topology measured by Rocketfuel tool [14] as ISP's router-level topology. For comparison purpose, we use the BA topology generated by the BA model. The BA topology is generated such that the numbers of nodes and links of it are the same as that of the AT&T topology.

3.2 Packet Processing Model at Node

Each node has limited buffers at each out-going links. 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 out-going link connecting to the next node. Each out-going link sends packets to the next node based on FIFO and a drop-tail queuing discipline, and delivers n packets per unit of time. Here, we do not use the dynamic routing, i.e., each packet traverses the shortest path calculated beforehand. When multiple shortest paths to reach the destination are found, the next node is determined based on a packet's source node.

3.3 Flow Control between End Hosts

3.3.1 Stop-and-Wait Model

In this model, when a source node sends a DATA packet to its destination node, the source node stops sending a new packet until the source node receives the acknowledgement (ACK) packet from the destination node. If a source node does not receive the ACK packet longer than retransmission time out (RTO), the source node think the packet loss has occurred and resends a packet. Time-out period is defined based on round trip time (RTT) and doubled every time out.

3.3.2 TCP Model

In this model, source nodes control the amount of DATA packets based on the slow start and congestion avoidance algorithms. The slow start and congestion avoidance algorithms are basic flow-control functions of TCP. If the slow stat threshold is lower than slow start threshold, the source node uses the slow start algorithm. When the source node receives an ACK packet, it extends the congestion window ($cwnd$) by one packet size (= segment size, $smss$) and sends two new DATA packets to the destination node. If window size exceeds the slow start threshold ($ssthresh$), the source node uses the congestion avoidance algorithm. When the source node receives an ACK packet, it extends the congestion window by $1/cwnd$, and it sends the adequate number of DATA packets to the destination node. In our model, congestion window size does not exceed the pre-decided maximum window size. If the source node does not receive any ACK packet longer than RTO, the source node detects serious congestion and recognizes serious congestion has occurred. The source node resends the lost DATA packet, and reduces the congestion window to one packet size. Time-out period is defined in the same way as the stop-and-wait model.

In addition, we use the fast retransmit and fast recovery algorithms defined by RFC 2581 [22]. The source node uses the fast retransmit algorithm when it detects packet loss and light congestion by arrival of three duplicate ACKs. When the source node receives the third duplicate ACK, it reduces the congestion window to half and resends the lost DATA packet. After the retransmission, the source node extends the congestion window based on the fast recovery algorithm. The source node extends the congestion window by one packet size as long as it receives the same duplicate ACKs.

4 Stop-and-Wait Flow Control in Power-law Networks

In this section, we show the results of simulation by the stop-and-wait protocol and discuss the end-to-end delay and its fluctuation in detail. We first show the case when buffer size of each link is unlimited to see the effects of flow control more clearly. In the simulation, each link can transfer one packet for each unit of time. Each source node never retransmit packets until receiving ACK packet from its destination since there is no packet loss in the network. The other parameters are summarized in Table 1.

Table 1: The simulation parameters used in the stop-and-wait model

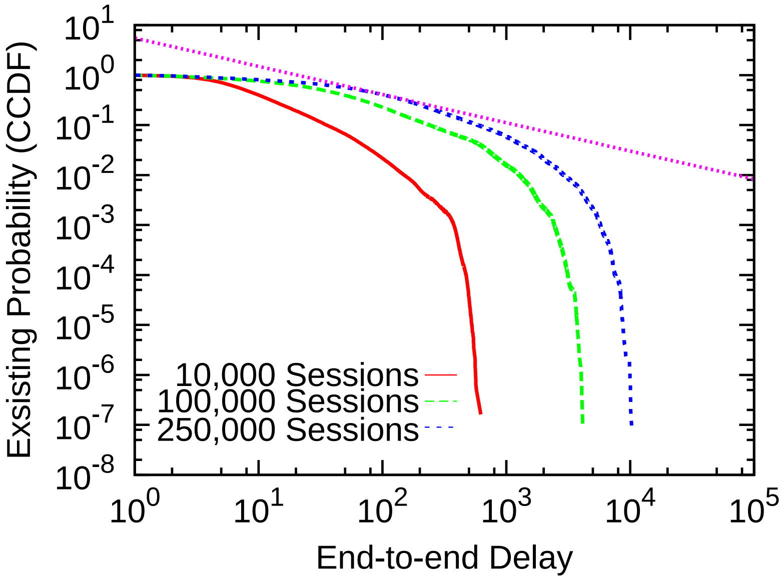
Buffer size	Unlimited
Session arrival rate	one session / unit of time
Link capacity	one packet / unit of time
Simulation time	100,000 units of time

4.1 End-to-End Packet Delay Distribution

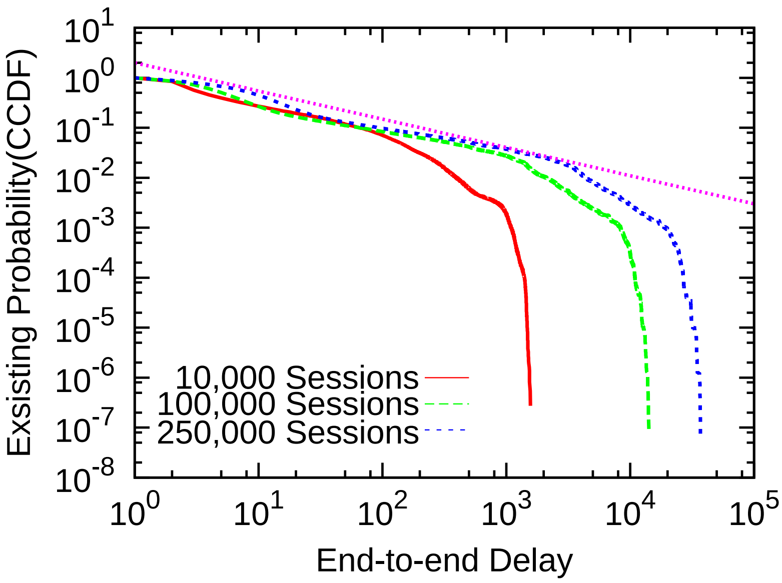
Figure 4 shows end-to-end packet delay distribution of the AT&T topology and the BA topology. X-axis represents the packet delay and Y-axis represents the complementary cumulative distribution of the packet delay. Here, the end-to-end packet delay is the time from when a packet is generated at source nodes to when the packet arrives at its destination nodes. In the figure, we also show a straight line with slope -0.56.

In either topology, as the number of sessions gets higher, packets spend more time in the network due to the heavier load of the network. The important point is that the shape of packet delay distribution of the AT&T topology is much different from the shape of packet delay distribution of the BA topology, especially when the number of sessions is 250,000 sessions. The packet delay distribution of the AT&T topology is characterized by the long-tail distribution, i.e., the slow decay of the end-to-end packet delay (Figure 4(b)). However, the packet delay distribution of the BA topology does not show the long-tail distribution (Figure 4(a)). These results indicate that the distribution of end-to-end packet delay differs dependent on the topology. The reason for this is the structural differences of topologies, more precisely a modularity structure of AT&T topology.

As discussed in Section 2.2, the BA topology has many “Connector hubs” and the AT&T topology has many “Provincial hub” nodes. In the BA topology, Connector hub nodes transfer large amount of packets between modules. However, in the AT&T topology, packets traveling between two modules, a.k.a. two region, are first aggregated at Provincial hub nodes and then forwarded via inter-module links. To see the impact of the modularity structure of the AT&T topology, we separate the packet delay distribution into the delay distribution for inter-module sessions that pass through the inter-module links and the delay distribution for intra-module sessions that uses only the intra-module links. Figure 5 shows the complementary cumulative distribution of packet delay for intra-module sessions and inter-module sessions. Looking at the packet delay distribution of intra-module sessions, we observe that most of packets arrive at destination nodes within a short time and the probability taking larger packet delay decays drastically. In contrast, the packet delay distribution of inter-module packets exhibits a long-tail characteristic; the probability taking larger packet delay does not decrease so fast when we compare it with the delay distribution of intra-module sessions. The modularity structure of the AT&T topology makes the inter-module links to be congested, which leads to the long-tailed packet delay distributions.



(a) The BA topology



(b) The AT&T topology

Figure 4: End-to-end packet delay distribution: the stop-and-wait model

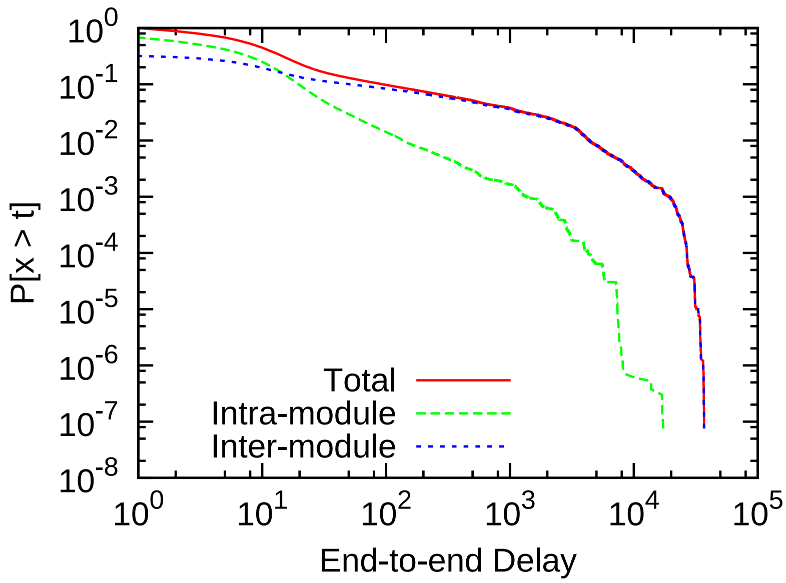


Figure 5: Comparison of packet delay distribution of intra-module and inter-module sessions

4.2 Queue Length Fluctuation

We next evaluate the fluctuation of queue length. If queue length of a link fluctuates drastically, packets that traverse the link experience non-constant queuing delay, which leads to the performance degradation. We evaluate the fluctuation using the measurement Hurst parameter (H, 0.5$< H <$1) by applying the R/S plot method [23]. The measurement Hurst parameter represents the degree of strength of long-range dependence. The detail of R/S plot method is as follows. First, we define R_n/S_n value as,

$$R_n/S_n \quad = \quad 1/S_n[\max(0, W_1, W_2, \cdots, W_n) - \min(0, W_1, W_2, \cdots, W_n)], \tag{3}$$

where

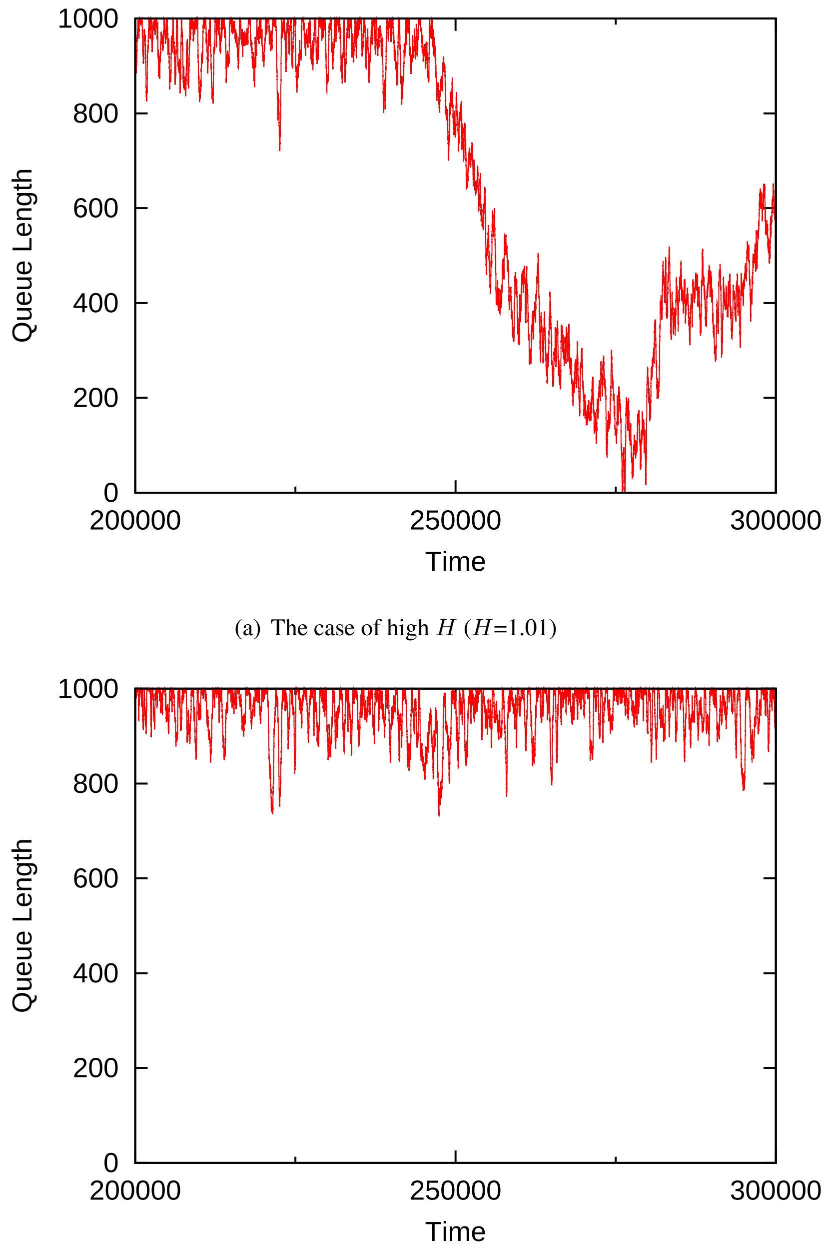
$$W_k \quad = \quad (X_1 + X_2 + \cdots + X_k) - kX(n),$$

where $(X_k : k = 1, 2, \cdots, n)$ is a data set of observation. $X(n)$ represents the mean value and $S(n)$ means standard deviation of the data set X. By estimating R_n/S_n value for a observation scale of n and plotting the correlation between n and R_n/S_n value, we can observe the statistical dependence over time. The slope of fitted curve of correlation function, αn^H, represents the Hurst parameter of a set of X. Figure 6 show examples of queue fluctuation in the AT&T topology when the number of sessions is 100,000. In this figure, R/S plot method estimate the Hurst parameter H = 1.01 for the Figure 6(a) and H = 0.5 for Figure 6(b). Looking at these figures, queue length fluctuates drastically from 0 to 1,000 when H is high.

When the number of sessions is small, high H values are observed at the links that takes higher betweenness centrality in both the BA topology (Figure 7(a)) and the AT&T topology (8(a)). However, when the number of sessions gets higher, the number of links which have high H value does not increase in the AT&T topology (Figure 8(b)), while high H values are observed at many links in the BA topology (Figure 7(b)). This result shows that the AT&T topology has a structure to reduce the queue length fluctuation. As we have discussed in previous subsection, packets are aggregated at hub nodes, and then forwarded via a few inter-module links in the AT&T topology. Figure 9 shows the histograms of Hurst parameters with separating inter-module and intra-module links. X-axis represents Hurst parameter and Y-axis represents the percentage composition of inter-module and intra-module links. When the number of sessions is small (10,000 sessions), most of high H values are observed at inter-module links. As the number of sessions increases, the number of intra-module links having high H value also increases. However, most of links keeps H values low although tne number of sessions increases. Since heavy traffic is aggregated on inter-module links, queue length of inter module links fluctuate drastically. In contrast, traffic that goes through intra-module links is not so heavy. As a result, queue length of intra-module links does not fluctuate drastically.

4.3 Effects of Feedback Control in Power-law Networks

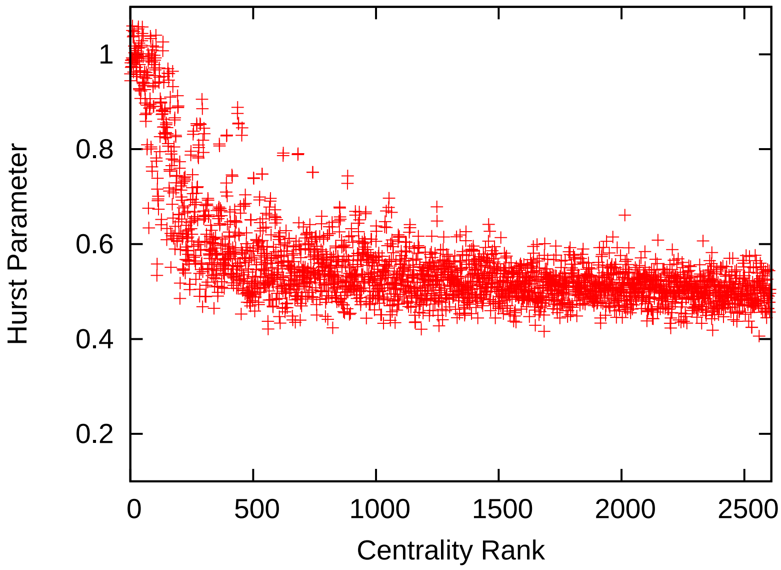
We investigated packet-level dynamics on each topology with stop-and-wait model in Section 4.1 and Section 4.2. According to the simulation results, feedback control like stop-and-wait protocol influences packet delay and queue fluctuation. If end hosts do not use feedback flow control and assume a Poisson process for packet injection, the Hurst parameter of each link will be 0.5. With the flow-control by stop-and-wait protocol, queue length of bottleneck links that take high betweenness centrality tend to fluctuate regardless of the number of sessions. As the number of sessions increases, the number of high fluctuated links increases because many sessions send packets to a various node in the network.



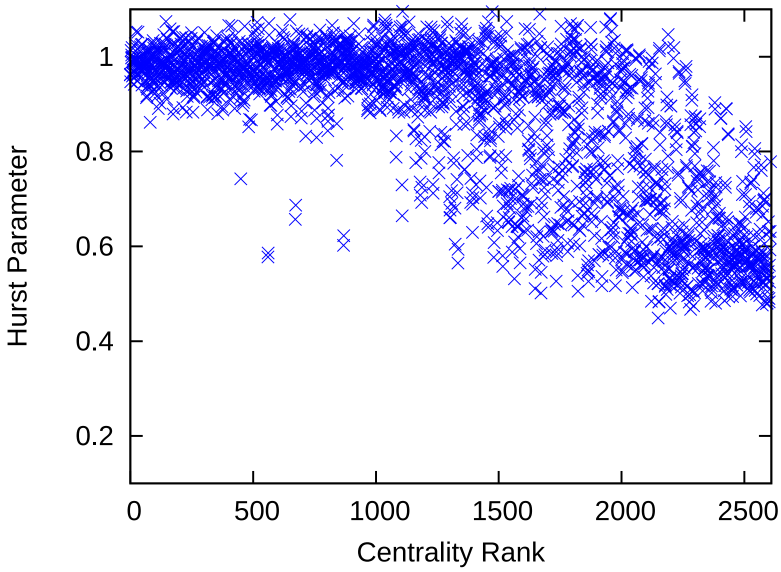
(a) The case of high H (H=1.01)

(b) The case of low H (H=0.5)

Figure 6: Typical examples of queue length fluctuation for Hurst parameter H

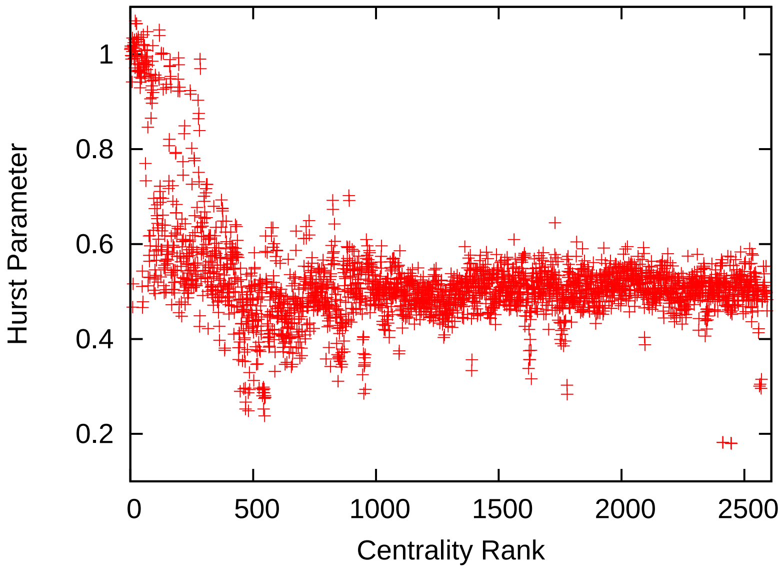


(a) 10,000 Sessions

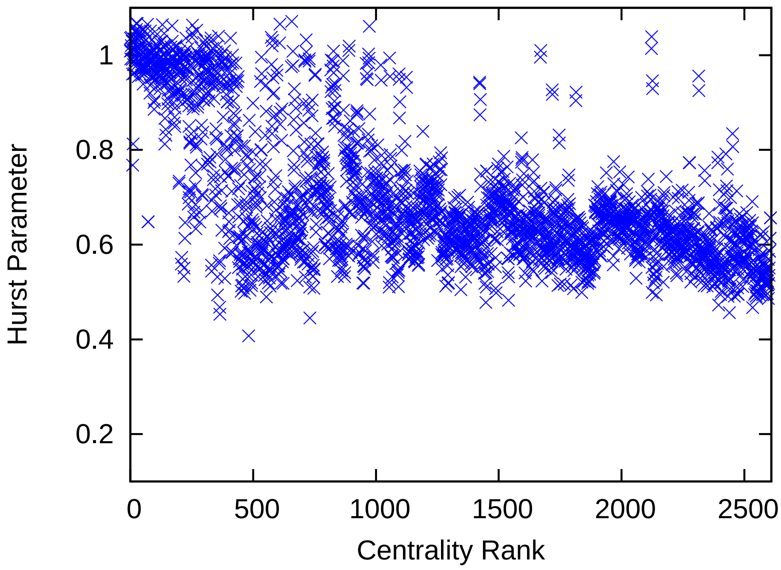


(b) 250,000 Sessions

Figure 7: Correlations between Hurst parameter and the rank of betweenness centrality: Stop-and-wait model, the BA topology

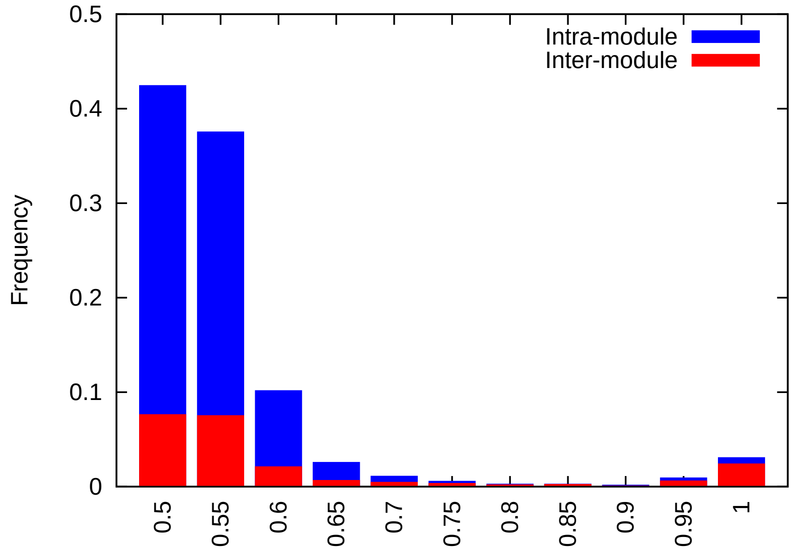


(a) 10,000 Sessions

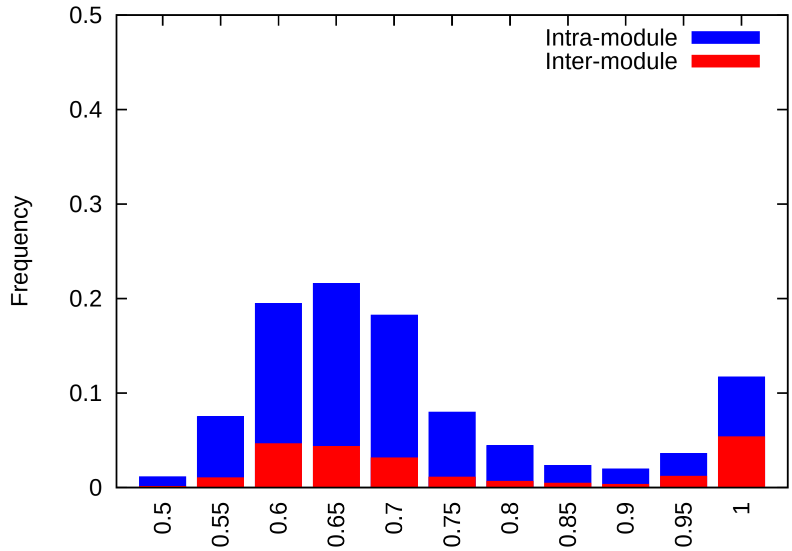


(b) 250,000 Sessions

Figure 8: Correlations between Hurst parameter and the rank of betweenness centrality rank: Stop-and-wait model, the AT&T topology



(a) 10,000 Sessions



(b) 250,000 Sessions

Figure 9: Histograms for Hurst parameter in the AT&T topology

5 Dynamics of TCP in Power-law Networks

In this section, we show the results of simulation by the TCP and discuss the end-to-end delay and its fluctuaion in detail. We show the case when each buffer size of each link is limited to see the effects of flow control in more realistic situation than Section 4. In the simulation, each link can transfer three packtes for each unit of time. Each source node retransmit packets when timeout has occured since there is some packet loss in the network. The other parameters are summarized in Table 2

Table 2: The simulation parameters used in the TCP model

Buffer size	1,000 packets
Session arrival Rate	1 session / unit of time
Maximum window size	10 packets
Link capacity	3 packets / unit of time
Simulation time	300,000 units of time

5.1 End-to-End Packet Delay Distribution

Figure 10 shows the end-to-end packet delay distribution of the BA topology and the AT&T topology. In this figure, the end-to-end packet delay distribution by the stop-and-wait model is also plotted. In the AT&T topology, when the number of sessions is 10,000, in the AT&T topology, packets spend longer time to reach their destination than the time in the BA topology. In contrast, when the number of sessions is 100,000, end-to-end packet delay distribution of the BA topology changes drastically. It has a long-tail distribution, i.e., many packets take a long time to go to their destination. End-to-end delay under 500 time units is hardly observed in the BA topology. However, end-to-end delay distribution of the AT&T topology does not change widely when the number of sessions increases.

The reason comes from that congestion tends to occur in the BA topology when TCP is applied. The term ”congestion” means that a buffer is occupied by packets and cannot receive more packets. Figure 11 shows changes in the number of congested links of each topology. In these figures, X-axis represents time step and Y-axis represents the number of congested links. In the BA topology, frequency of congestion is about 4 times larger than the frequency in the AT&T topology. Since packets concentrate in a variety of places and queuing delay gets longer, the end-to-end packet delay distribution of the BA topology exhibits a long tail.

To clarify the reason why congestion tends to occur in the BA topology, we focus on the difference in the structures between the BA topology and the AT&T topology. As discussed in 4.1, packets first concentrate on "Connector hub" nodes and reach to their destination through the "Connector hub" nodes in the BA topology. It seems that congestion occurs at links near "Connector hub" nodes. To confirm this assumption, we investigate composition percentages of congested links in each topology. We classify the link function based on function of nodes attached to the link. Links are categorized as follows,

- ConHub-to-NonHub link
  Download links of "Connector Hub" nodes forwarding non-hub nodes. These links deliver the packets that come from other modules to the nodes in a module.

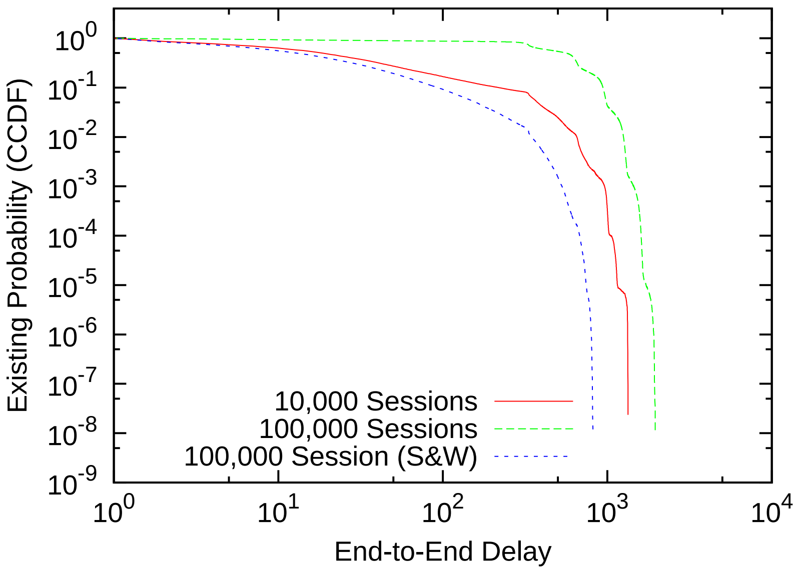
- NonHub-to-ConHub link
  Upload links between "Connector Hub" and non-hub nodes. These links transmit packets to "Connector Hub" nodes to deliver packets to their destination in different module.

- ProHub-to-NonHub link
  Download links of "Provincial Hub" nodes forwarding non-hub nodes. These links are used for delivering packets aggregated at "Provincial Hub" nodes to their destination in different module.

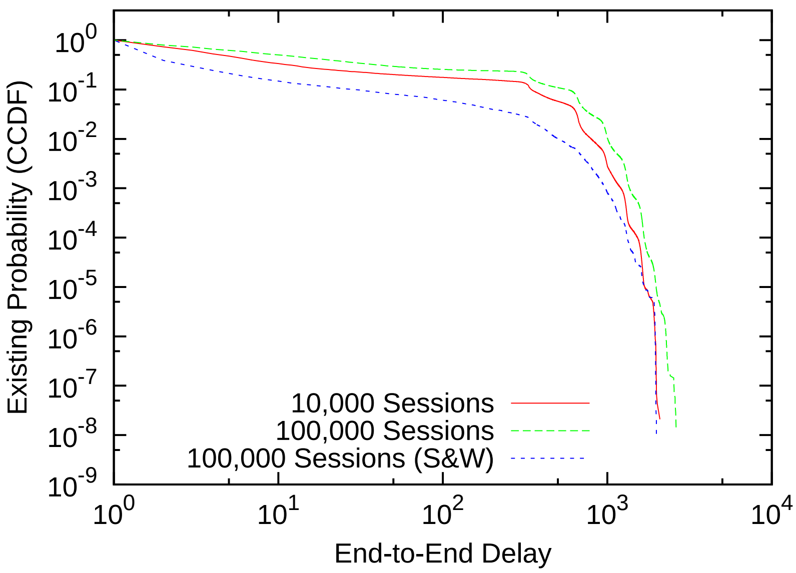
- NonHub-to-ProHub link
  Upload links of "Provincial Hub" nodes forward packets forwarding "Provincial Hub" nodes to aggregate packets for derivery to the distant module.

- ConHub-to-ConHub links
  Links connect between "Connector Hub" nodes.

- ConHub-to-ProHub links
  Links of "Connector Hub" nodes forwarding to "Provincial Hub" nodes.

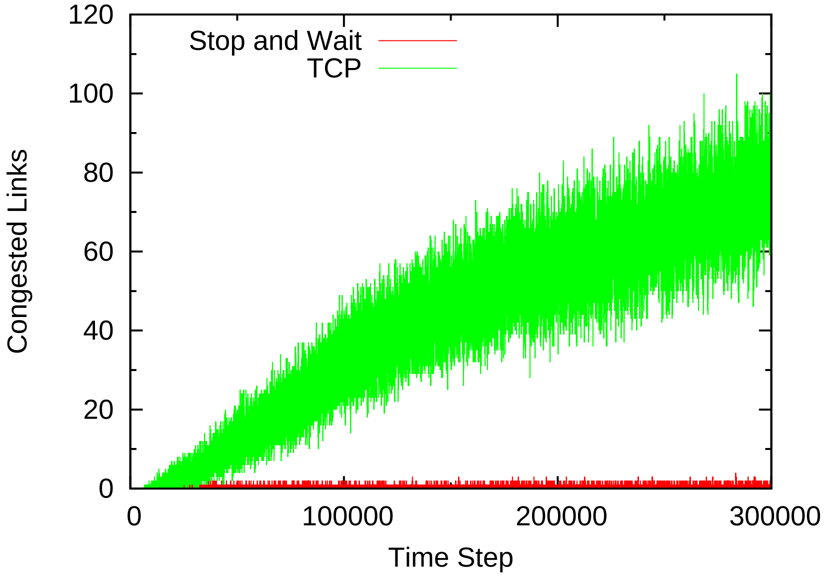


(a) The BA topology

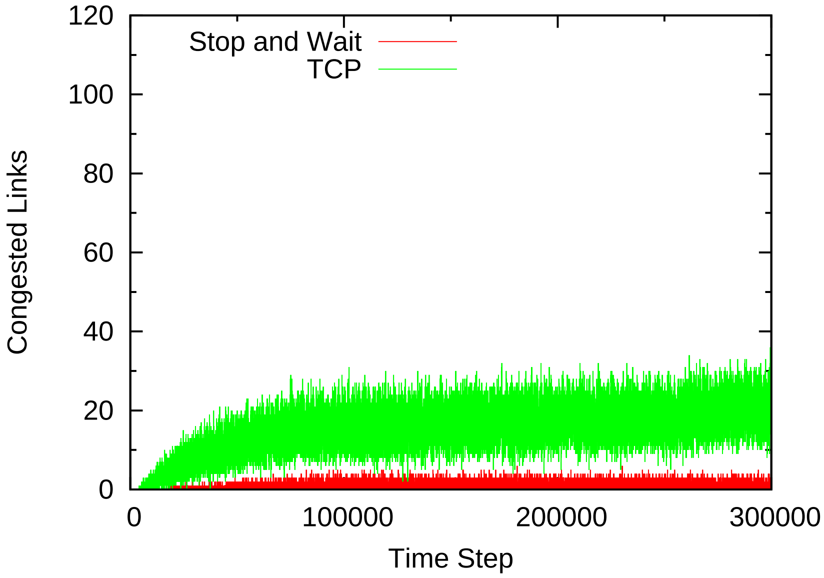


(b) The AT&T topology

Figure 10: End-to-end packet delay distribution: TCP model



(a) The BA topology



(b) The AT&T topology

Figure 11: Number of congested links

- ProHub-to-ProHub links

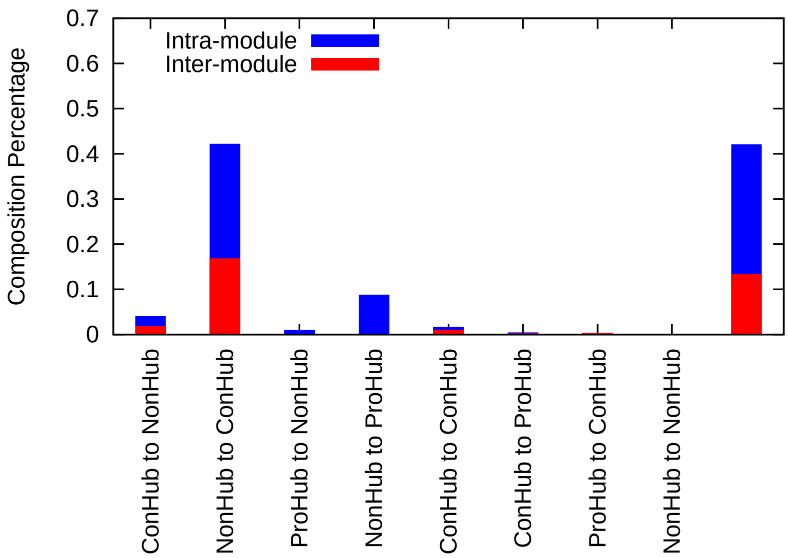
  Links connect between “Provincial Hub” nodes.

- NonHub-to-NonHub links

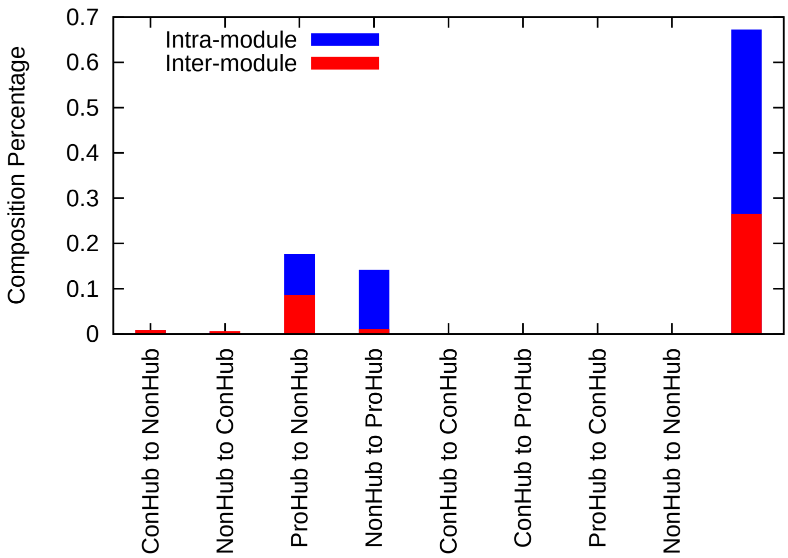
  Links does not belong to any links as identified above.

Figure 12 shows composition percentages of congested links of the BA topology and the AT&T topology. X-axis represents the kind of links and Y-axis represents content percentages of the links corresponding X-label in congested links observed in the simulation period between 290,000 and 300,000-time unit.

In Figure 12(a), it is found that the “NonHub-to-ConHub” links tend to be congested in the BA topology. As previously discussed, packets concentrate “Connector hub” nodes to reach to their destination in all over the network. So, the links forwarding packets to “Connector hub” nodes tend to be congested. Since congestion tends to occur near “Conndector hub” nodes, end-to-end delay distribution of the BA topology have a long tail.



(a) The BA topology



(b) The AT&T topology

Figure 12: Relation between node function and congested links: TCP model, 100,000 sessions

5.2 Queue Length Fluctuation

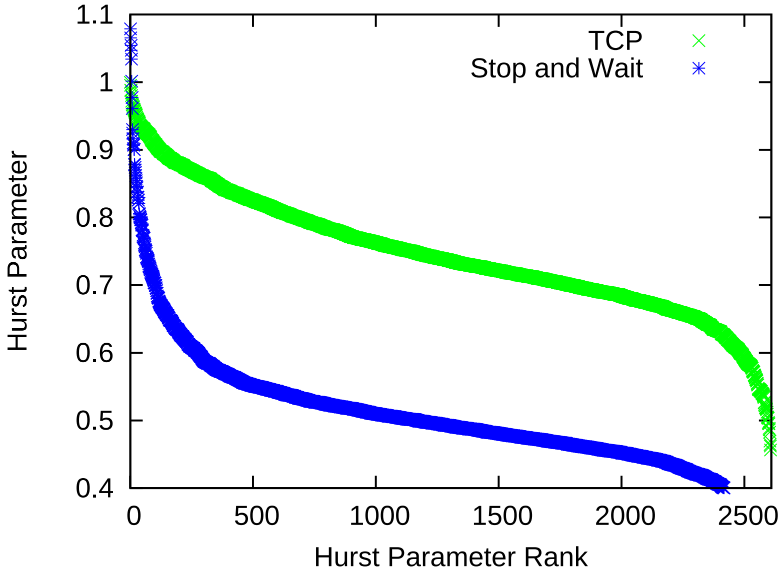
Figure 13 shows Hurst parameters for each link. Y-axis represents Hurst parameters and X-axis represents its rank. In this figure, the result of the stop-and-wait model is also added. Looking at this figure, we observe that the number of links that take high Hurst parameter increases by TCP model.

To see the relation between the Hurst parameter and topological structure in the AT&T topology clearly, we show the link that takes high H value ($H \geq 0.8$) in Figures 14 and 15.

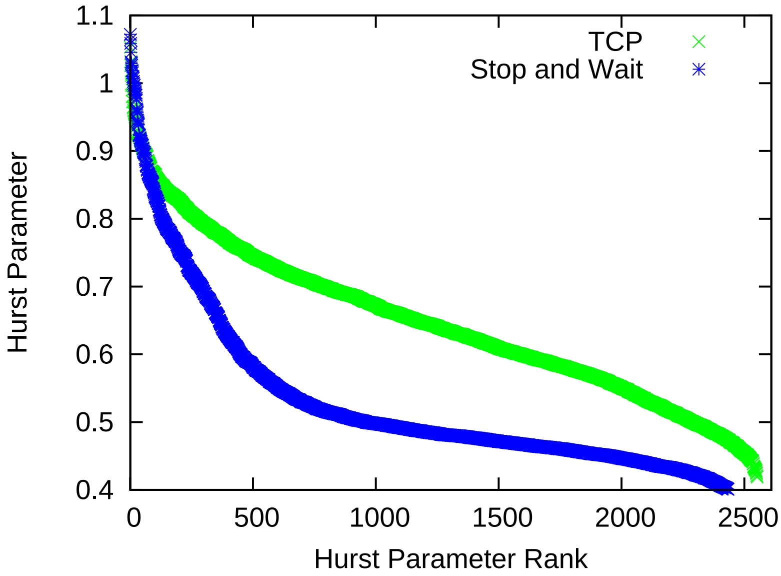
When the number of sessions is small (Figure 14), queue length of the links that connect two regions fluctuates drastically. That is, inter-module links tend to be highly fluctuated. This is because many packets concentrate on inter-module links. As the number of sessions gets higher (Figure 15), queue length of the links that connect inside a region fluctuates while the Hurst parameter of inter-module links decreased. That is, fluctuation spreads to tributary links of bottleneck. We can confirm this by looking at Table 3 where the the ratio of high fluctuated links in the TCP model and stop-and-wait model.

Table 3: The ratio of high fluctuated links in each topology

	10,000 sessions		100,000 sessions	
	Total	Inter-module	Total	Inter-module
The BA topology (TCP model)	0.257	0.21	0.26	0.21
The AT&T topology (TCP model)	0.08	0.025	0.11	0.017
The AT&T topology (Stop-and-wait model)	0.002	0.0007	0.05	0.016



(a) The BA topology



(b) The AT&T topology

Figure 13: Correlations between Hurst parameter and Hurst parameter rank: TCP model

5.3 Positive and Negative Effects of TCP

In Section 5.1 and 5.2, we discussed about packet delay dynamics in the TCP model. In this Section, we explain about the positive and negative effects of TCP. One of positive effects of TCP is improvement of throughput. Figure 16 shows the time series of throughput in each topology. X-axis represents the time and Y-axis represents network throughput that denotes the number of arrival packets to their destination. Comparing the results of stop-and-wait model with that of TCP model, network throughput is improved in the AT&T topology due to the functionality of TCP that adjusts packet sending rate to network condition.

In contrast, when the number of sessions gets larger, TCP become a factor of fluctuation of queue length as shown in Figure 13. If queue length of a given link fluctuate drastically, end-to-end delay of packets that pass through the link vary significantly. Since end hosts estimate network condition with Round Trip Time (RTT), when end-to-end packet delay fluctuate, end hosts cannot know network condition accurately and thus flow control becomes difficult.

Queue length of the inter-module links fluctuates drastically in the stop-and-wait model, while queue length of the intra-module links does not fluctuate in the AT&T topology. We confirm the number of links having high H value in the stop-and-wait model is smaller than the number of links in TCP model. This result indicates complex functionality of TCP, such as flow control, congestion control, and fast retransmit functionalities, causes fluctuation of queue length. This is one of negative effects of TCP.

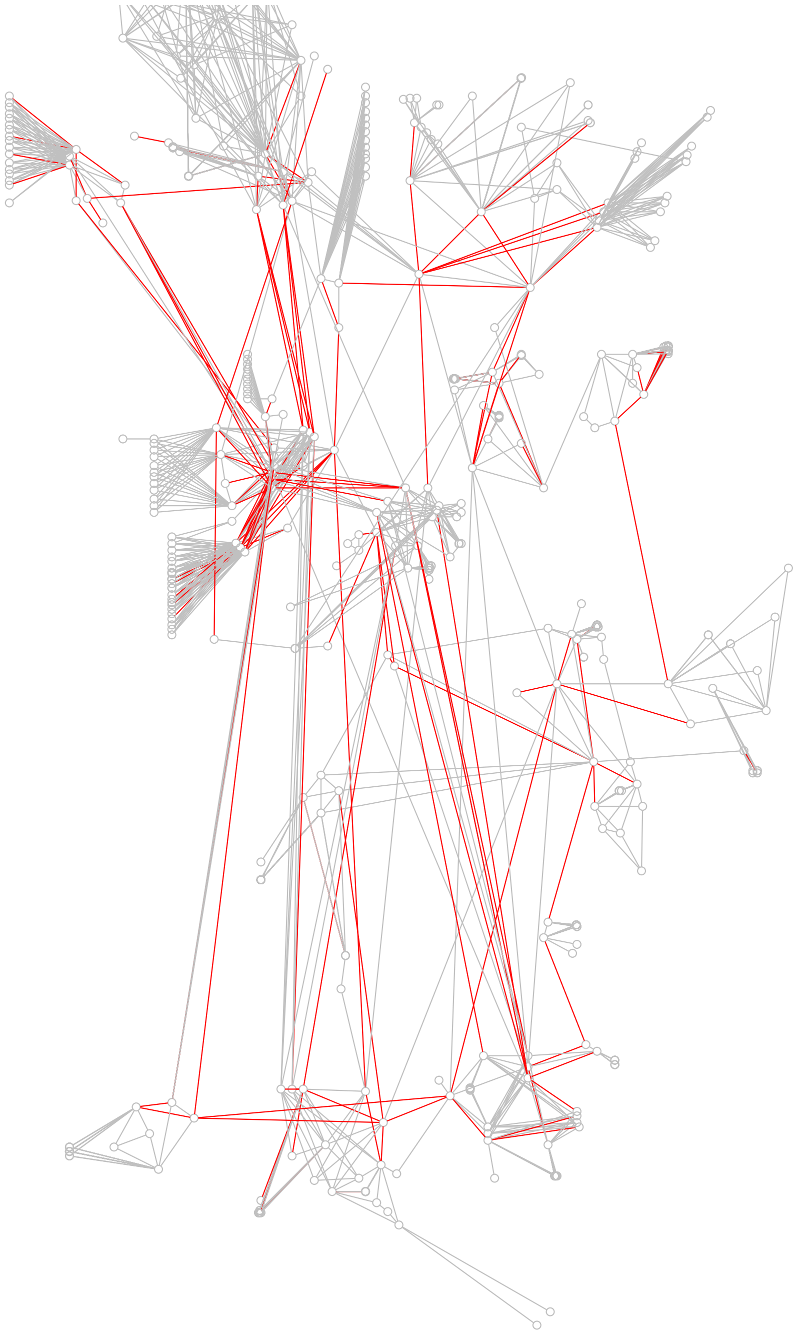


Figure 14: Links having high Hurst parameter in the AT&T topology: TCP model, 10,000 sessions

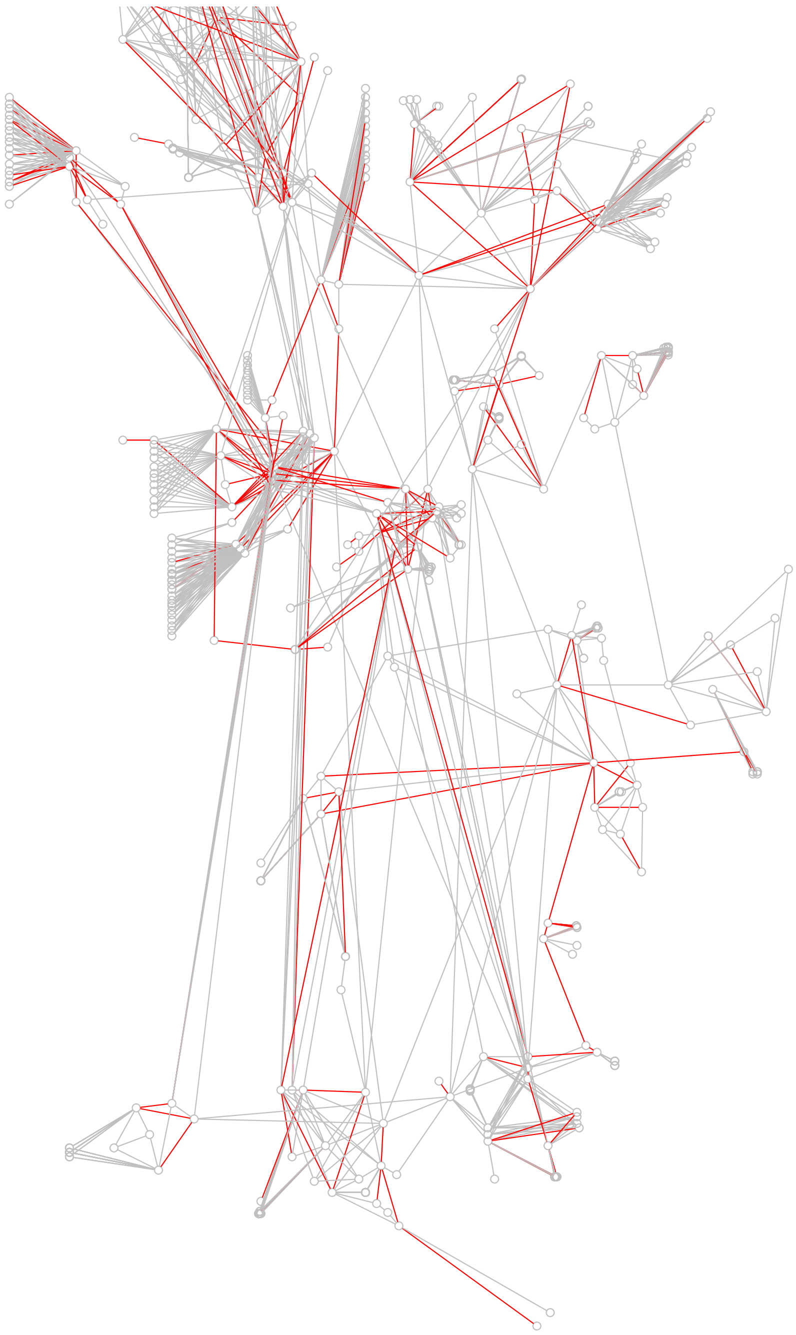
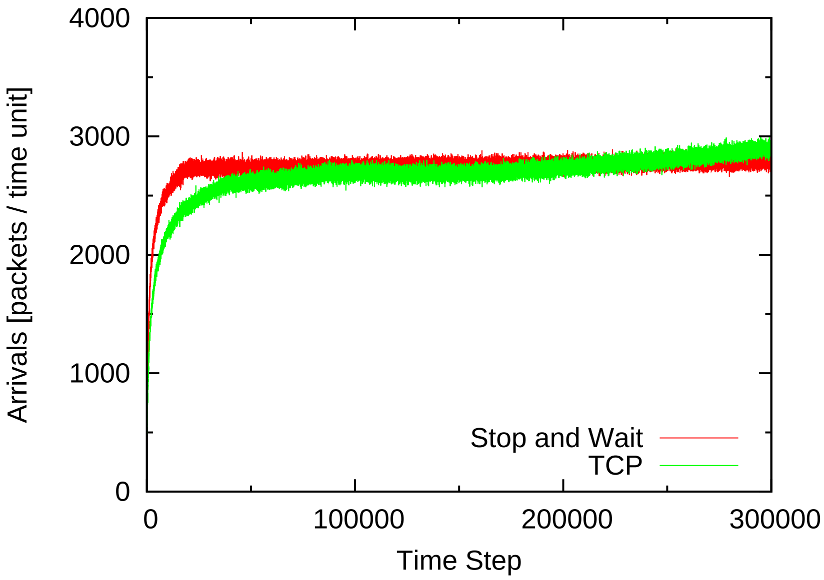
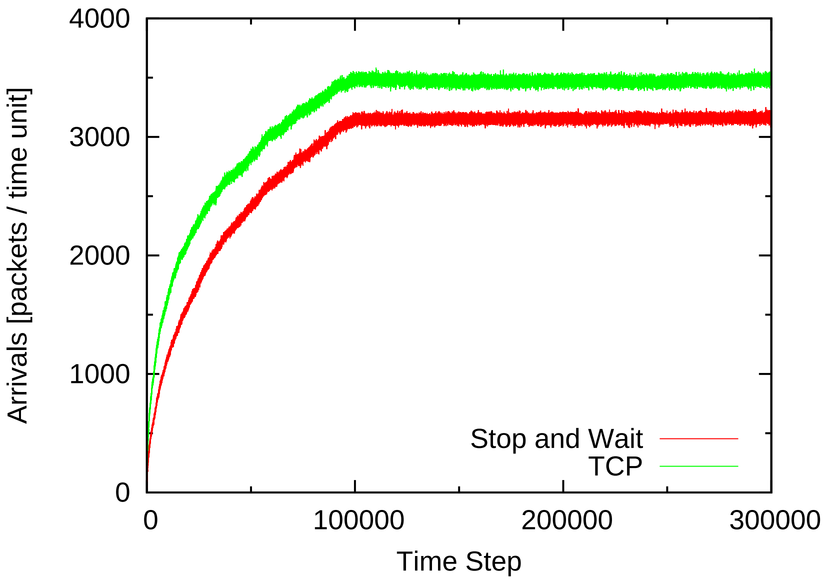


Figure 15: Links having high Hurst parameter value in the AT&T topology: TCP model, 100,000 sessions



(a) The BA topology



(b) The AT&Ttopology

Figure 16: Throughput of each topology: 100,000 sessions

6 Conclusions and Future Work

In this thesis, we investigated on the interaction between structures of topologies and flow control between end hosts. We showed traffic dynamics on ISP's router-level topology whose degree distribution exhibits power-law attribute and each of the nodes interacts via end-to-end flow control functionality. Comparing with the simulation results of stop-and-wait model and TCP model, functionality of TCP improves network throughput in the AT&T topology. On the other hand, functionality of TCP makes the queue length fluctuated. We then discuss how structure of topologies and flow controls affect the end-to-end packet delay distribution and the queue length fluctuation of links. Extensive simulation results show that the end-to-end packet delay distribution exhibit a heavy tail by the TCP model. Moreover, the number of links that are highly fluctuated is more than twice comparing to the results of the stop-and-wait model. In the TCP model, 10% of total links are highly fluctuated when the number of session is large. When the number of session is small, 0.8% of total links are highly fluctuated. The results also indicate the queue length fluctuation disappears at bottleneck links and appears their tributary links due to the modularity structure of ISP's router-level topology. Even in this case, the modularity structure of the AT&T topology reduces the number of highly fluctuated link up to 40% comparing to the results of the BA topology.

In the future work, we will conduct evaluations of packet delay dynamics on topologies that have heterogeneous link capacity, and evaluation of combination of end-host flow control and traffic engineering in more detail.

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