**Master's Thesis**

Title

# Analyzing network bandwidths of ISP topologies having power-law degree distributions

Supervisor

Professor Masayuki Murata

Author

Masahiro Shimizu

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Department of Information Networking

Graduate School of Information Science and Technology

Osaka University

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Masahiro Shimizu

## Abstract

Recent measurement studies on Internet topology show that the connectivities of nodes exhibit a power–law attribute. That is, the probability $p(k)$ that a node is connected to $k$ other nodes follows $p(k) \sim k^{-\gamma}$. However, even if the degree distributions of some topologies are the same, more detailed characteristics are often quite different. For example, ISP topologies had a much higher cluster coefficient than the other topologies attained with conventional modeling methods, and more importantly, these differences greatly affect methods of network control. Thus, for studies of higher–layer protocols such as routing and flow controls, more detailed information of ISP networks are required. One of our main motivations in this thesis is to investigate the link bandwidths of actual ISP topologies, and then gives some reasonings being that. For this purpose, in this thesis, we measure topologies and link bandwidths of two Japanese ISPs. The results of measurements show that the degree distribution of ISP networks shows power-law attribute. That is, the most of nodes have few out-going links, while few nodes have many out-going links. We next measure bandwidths of all the links on each Japanese ISP topology. The results show that the high bandwidth links are located at Tokyo. Furthermore, nodes that have a high bandwidth link also have a lot of out-going links, which is different from discussions given by other researcher's works where high bandwidth links are connected to lower-degree nodes. Following this observation, we present a geographical model to give a realistic bandwidth distribution of links, and we demonstrate that the geographical model certainly reproduces the link bandwidths of ISP networks.

**Keywords**

power-law, router-level topology, AS-level topology, scale-free, ISP network, link capacity, link bandwidth, measurement

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## 1 Introduction

Recent measurement studies on Internet topology show that the connectivities of nodes exhibit a power–law attribute [1, 2]. That is, the probability $p(k)$ that a node is connected to $k$ other nodes follows $p(k) \sim k^{-\gamma}$. In recent years, considerable numbers of studies have investigated power–law networks whose degree distributions follow the power–law [3–8]. Here, the degree is defined as the number of out–going links at a node. The theoretical foundation for the power–law network is introduced in Ref. [9] where they also presents the Barabashi–Albert (BA) model in which the topology increases incrementally and links are connected to nodes based on the degree distribution of topologies in order to form power–law networks. The resulting power–law networks have two main characteristics: (1) a small number of links are connected with numerous nodes, while a large number of links are connected with a few nodes, and (2) the number of hop–counts between nodes is small (*small–world* property).

However, even if the degree distributions of some topologies are the same, more detailed characteristics are often quite different. A work by Li et al. [10] has enumerated various topologies with the same degree distributions, and has shown the relation between the characteristics and performances of these topologies. With the technology constraints imposed by routers, the degree of nodes limits the capacity of links that are connected to. Li et al. point out that higher–degree nodes tend to be located at the edges of a network, and they then demonstrate in an Abilene–based topology where the power–law network can actually be constructed by maximizing the throughput of the network with the technology constraints imposed by routers. Their modeling method in [10] provides a new insight in that the location of higher–degree nodes are not always located at the core of networks. Actually, different to AS–level topology, each ISP constructs its own router–level topology based on strategies such as minimizing of the mileage of links, redundancies, and traffic demands. In this sense, their method is based on a strategy that maximizes the utilization of IP routers under current router technology constraints.

In Ref. [11], it is revealed that the ISP topologies had a much higher cluster coefficient than the AS topology [12], the topology examined by Li et al. [10], and the other topologies attained with conventional modeling methods. More importantly, these differences greatly affect methods of network control. One typical example is routing control: the link utilization in the router–level topology is much far from the one in the conventional modeling method [11]. The optimal routing method gives much smaller the maximum link utilization (about $1/3$) compared with minimum hop routing, while a topology by the BA model achieves about $1/10$ of the maximum link utilization. The same argument could also be applied to the higher–layer protocols. That is, for vital network researches, a modeling method for a realistic router–level topology is urgently needs to be developed. The above paper has concentrated on the routing control as one of network control mechanisms, and has proposed a modeling method for router–level topology that can be applied to the routing control. However, for the higher–layer protocols, it requires more detailed modeling, which may give much impact on studies of higher–layer protocols such as routing and flow controls.

There have been several measurement studies of Internet topologies [13, 14]. However, less studies measure the link bandwidths of an Internet topology. Ref. [15] introduces a diagnostic tool, `pchar` , to measure the link bandwidths of a path, but no work investigates bandwidths of all the link in the Internet topologies. One of our main motivations in this thesis is to investigate the link bandwidths of actual ISP topologies, and then gives some explanations. For this purpose, we measure topologies and link bandwidths of two Japanese ISPs via `traceroute` [16] and `pchar` [15] tools. The results of measurements show that the degree distribution shows power-law attribute. That is, the most of nodes have few out-going links, while few nodes have many out-going links. We also find that, by looking the name of routers via reverse DNS lookup carefuly, most of the nodes of the two Japanese ISP networks are at Tokyo, the capital city of Japan, and the other nodes are reachable within a few hops from the nodes in Tokyo.

We next measure bandwidths of all the links on each Japanese ISP topology. The results show that the high bandwidth links are located at Tokyo. Furthermore, nodes that have a high bandwidth link also have a lot of out-going links, which is different from the discussion in Ref. [10] where high bandwidth links are connected to lower-degree nodes. In the Japanese ISP topologies, processing capability of nodes, which is defined as the sum of bandwidths of links that connected to, becomes high. Following this observation, we present a geographical model to give a realistic bandwidth distribution of links, and we demonstrate that the geographical model reproduces the link bandwidth of ISP networks.

This thesis organized as follows. Section 2 presents related work for measurement and modeling the ISP topologies and explain the properties of power-law networks. Section 3 explain measurement method of ISP topologies and shows the results of two ISP topologies. Section 4 gives the result of measurement, and discuss the relation between ISP topologies and link capacities. Finally, Section 5 concludes this thesis.

## 2 Related works

In the Internet, the degree distribution has been shown to follow the power–law at the AS–level [1, 2, 13]. Barabasi and Albert [9] presents a BA model in which the topology grows incrementally and links are attached to nodes based on a preferential probability, $\Pi(i) = d_i / \sum_j d_j$ where $d_i$ is the degree of node $i$. The characteristic of topologies attained with the BA model is further investigated by other researchers [6].

Bu and Towsley [12] compares the structure of the BA model with AS–level topology. Their results show that degree distribution as well as the cluster coefficient with the BA model does not match those with the AS topology because new ASs have a stronger preference for hub nodes compared to the linear preference used with the BA model. They then propose a new preferential probability, $\Pi'(i) = (d_i - \beta)/\sum_j (d_j - \beta)$, to generate AS–like topologies. $\beta$ $(< 1)$ is a parameter that increase the preferential probability for high–degree nodes. Zhou and Mondragon [17] discusses the effect of positive and negative feed–back have on the degree $d_i$.

In addition to topological modeling for AS–level topologies, several researches focus on flow–level behavior. Goh et. al [6] pointed out that, under minimum hop routing, the distribution in the number of node–pairs that pass through node $i$, $l_i$, also follows the power–law, $P_L(l_i) \sim l^{-\sigma}$. Gkantsidis et. al [18] derives the lower bound of "congestion", which is defined as the maximum number of demands that pass through a link in a power–law network. They show that when an approximate multicommodity max–flow min–cut theorem is used, the congestion scales as $O(n \log^2 n)$ where $n$ is the number of nodes. Akella et. al [3] shows how the congestion scales as $n$ increases when single shortest path routing is used. The simulation and analytical results revealed that the congestion scales as $\Omega(n^{(1+\Omega(1))})$, which implies that the congestion increases linearly as the number of nodes $n$ increases. They also demonstrated that BGP's policy routing [19] marginally better than the minimum hop routing. However, all these works focus on the AS–level topology.

There are relatively few studies on modeling router–level Internet topology are relatively less. Heckman et al. [20] present parameter settings for topology generator tools, such as BRITE, TIERS, and GT–ITM, to construct ISP topologies. However, the topology they examined is a POP (point–of–presence) level topology. Li et al. [10] enumerated various topologies with the same degree distributions, and showed the relation between their structure and performances of those topologies. They pointed out that because of a technology constraint of commercial routers, high–degree nodes[1] accommodate low–bandwidth access lines while lower–degree nodes accommodate high-bandwidth core lines because of technology constraints with commercial routers. Due to technology constraints, the hub node is located at the edges of the network, while in the AS–level topology the hub node is located at the core of the network. With a three–level hierarchical structure based on the Abilene network and the previously mentioned link capacity constraints, Li et al. show that there exists a topology such that the throughput of the topology is maximized while the degree distribution follows a power–law. In the Abilene–based topology presented in Fig. 6 (e) of Ref. [10], there are no redundant links between nodes (except in network cores), and a single node/ link failure will easily split the network, while the ISP topologies presented in Ref. [14] clearly include redundant links. Therefore, we cannot apply their modeling method to traffic flow level researches like routing control.

[1] We call several nodes with a much larger number of outgoing links than other node as “hub nodes” without clear definition.

# 3 Measurement of IP network topologies

For vital network researches, a modeling method for a realistic router–level topology and a realistic network bandwidths is urgently needs to be developed. In this section, we explain measurement methodology and the results of ISP topologies that we obtained, and the measurement results of network bandwidths are presented in Sec. 4.

## 3.1 A measurement method

We use the `traceroute` [16] to measure the network topologies. The `traceroute` gives a information of IP addresses of intermediate nodes on a path to the pre-specified destination node. By changing the IP address of destination nodes, we obtain the IP's connectivity of nodes in ISP networks. On measuring ISP topologies, we need to know IP addresses that is allocated to ISPs. However, the list of IP addresses that ISPs have is not an open information for us. In this thesis, we try to obtain IP addresses used by ISP networks heuristically. The procedures are as follows.

(1) Executing `traceroute` to the IP address which is known already.

(2) If we newly find new IP addresses from the result of `traceroute` , we execute `traceroute` to the IP addresses.

During the above procedure, we have to check the new IP addresses whether they are in the target ISP network. By looking the domain name included in the hostname, we distinguish whether the IP address is in the target network or not.

If we find that the IP address is not included in the network, we don't execute `traceroute` for it. In order to obtain more IP address of target ISP network, we also explore the other IP addresses allocated within the consecutive range to ISPs (e.g., 192.168.0/24).

For this purpose, we check the hostname of IP addresses that match 24 high rank bits of IP addresses that are already found. We check the domain name whether the IP addresses include

Table 1: Measurement result: the number of nodes and links

| | Nodes | Links |
|---|---|---|
| ISP A | 1095 | 2448 |
| ISP B | 1232 | 2885 |

the domain name of target network or not. Against nodes that are newly found and belongs to the target ISP network, we again execute `traceroute` and try to get more connectivity information of the target ISP network.

We measured two Japanese ISP topologies.

We measured the ISP topologies at two location: one from Osaka university and another from Japanese ISP network. The measurement was performed from June 2006 to December 2006.

### 3.2 Results and discussion

We show the results of the topologies measurement. Table 1 summarises the number of nodes and links of ISP topologies via the measurement. To see the geographical location, we present each ISP topology in Figs. 1 and 2. In the figures, we locate the nodes according to the geographical information obtained from the hostname [21]. Note that the hostname includes prefecture-level information, such as "`tky001bb01`" or "`osaknt01`".

The node where its corresponding hostname does not include the geographical information, such as, "`jproxy01`" or "`route-server`". we assume that it is located at Tokyo. Table 2 lists the number of nodes located at Tokyo. From this, we observe that around 40% of nodes in Japanese ISP networks are located at Tokyo.

Table 2: The number of nodes at Tokyo and other areas

| | Tokyo | other areas |
|---|---|---|
| ISP A | 698 | 397 |
| ISP B | 760 | 472 |

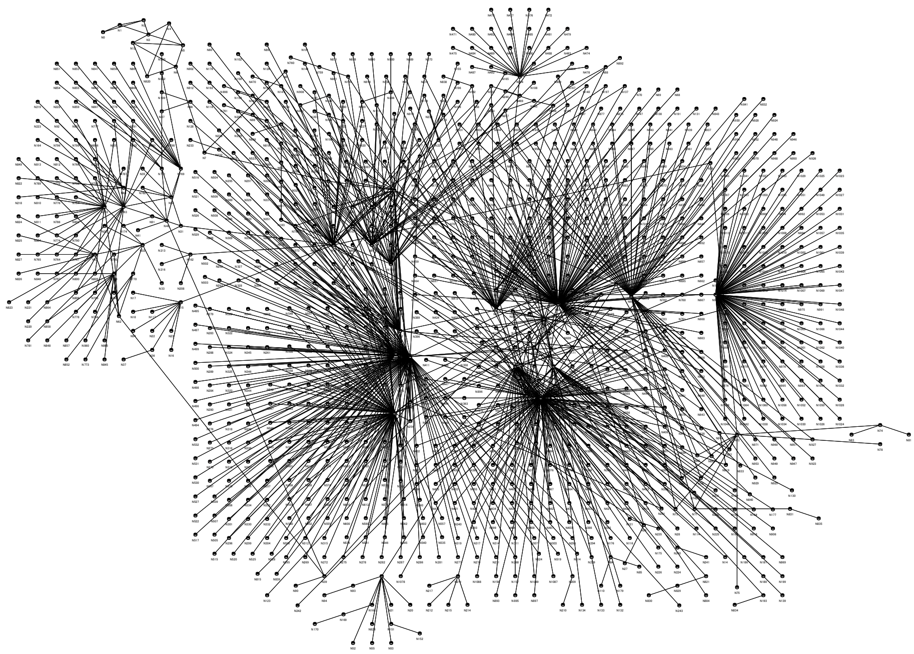


Figure 1: Topology map: ISP A

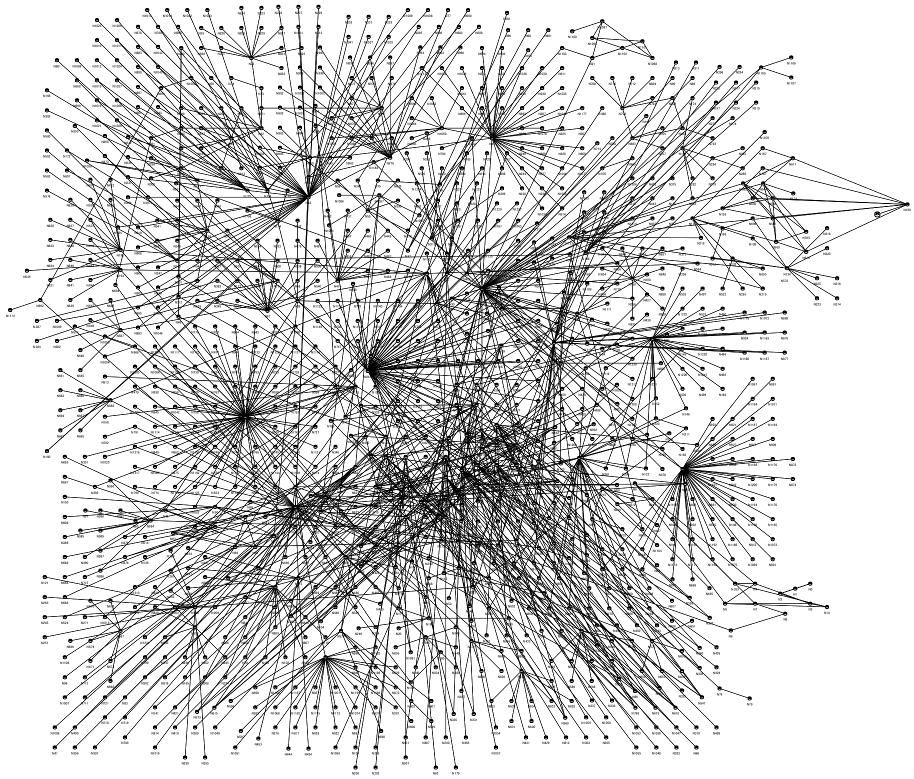


Figure 2: Topology map: ISP B

# 4 Measurement of link bandwidths of ISP networks

## 4.1 Measurement methods

Since the link bandwidths of ISP networks are not available in public, we need to measure them. In this section, we explain a methodology to measure the link bandwidths of ISP networks, and discuss the characteristics of a link badnwidth distribution. For this purpose, we use `pchar` [15] to obtain the link bandwidth of each link in the ISP network. `pchar` measure the link bandwidths on its way to the destination node by sending probe packets. The probe packets are injected into the target ISP networks. We configured that `pchar` sends 11 pieces of packets by changing packet sizes from 128Bytes to 1408Bytes increasing the size by 128Bytes. And it is repeated 10 times per node. In this result, a node receives 110 packets totally. `pchar` injects the probe packet into the ISP networks by changing the packet size and increasing time-to-live (TTL) by one. When a node on path to the destination node receives the packet whose TTL equal zero, it sends a ”Time Exceeded Message” packet to the probe packet sender node. The ”Time Eceeded Message” is a kind of ICMP message [22]. For timing the Round Trip Time (RTT) between the sending time of probe packet and receiving time of ICMP packet at the source node, we can obtain the link bandwidths by follwing calculations.

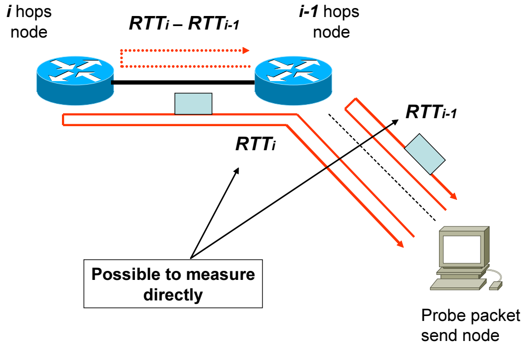
Assume that the probe packet send node and the destination node are connected by a link directly. In this situation, the link bandwidths is calculated by,

$$B = \frac{P}{2 * RTT}, \tag{1}$$

where $B$ is the link bandwidths, $P$ is the probe packet size. However, when we measure the link bandwidths in ISP networks, we can not connect each node directly. Therefore, the link bandwidths in ISP networks are calculated as follows.

$$B_i = \frac{P}{2 * (RTT_i - RTT_{i-1})}. \tag{2}$$

Figure 3: Measurement method: Link bandwidths




where $i$ is the node index, $B_i$ is the link bandwidths between the node $i$ and $i-1$, $RTT_i$ is the RTT of the node $i$. We can obtain the RTT between the node $i$ and $i-1$ by calculating the difference of $RTT_i$ and $RTT_{i-1}$. So, we can calculate the bandwidths of the link which is not connecting with the measuring machine directly.

`pchar` repeatedly sends probe packets by increasing its TTL by one until it receives the reply packets from the destination node. When receiving the reply packets, we can obtain the bandwidths of link between the destination node and the previous (in terms of the path) node.

## 4.2 Measurement environment

In 4.1, we explained the methods of link bandwidths. Here, we describe the environment of the measurement. First, we show the node's spec that we use for measurement.

- OPTIPLEX GX620 (DELL)
  - OS: Fedora Core 5
  - CPU: Pentium[R] 4 3.80GHz
  - Ethernet controlar: NetXtremeR Gigabit Ethernet Controller for Desktops

Using this machine, we measured two Japanese ISP networks (we call them ISP A and ISP B) by using the topology information obtained by the method described in Sec. 3.

Next, we show the place and the timing that we executed `pchar` for the measurement.

- The place
  - Osaka University
- The time
  - There is especially no timing.

We measured repeatedly about 4 to 5 times,because the result may include measurement error margin. So, we tried to remove it as many as possible by repeated measurement.

Last, we show the parameter settings of `pchar` .

- Probe packet size

  1500 Bytes is the maximum size of the Eathernet frame. Therefore, We limited the packet size till 1500 Bytes, and the size was changed every 128 Bytes. In the result, we use 11 kinds of packet size.

- Sending packet times per node

  `pchar` sent probe packets 10 times per measurement and node. So, the number of obtaind RTT are 110 per node.

- Probe packet type

  We used ”one shot”-type communication packet: UDP and ICMP.

## 4.3 Results and discussion

We show here the results of bandwidths measurement. Figure 4 is the result of ISP A, and Figure 5 is that of ISP B. They show the relashions of the nodes degrees and the nodes total bandwidths. The node total bandwidths mean the all amount of bandwidths which the links connecting to

Table 3: High performance nodes

| | Tokyo | Other areas |
|---|---|---|
| ISP A | 22 | 4 |
| ISP B | 36 | 23 |

the node have. The dots in figures denote the nodes in each ISP network. The lines represent the technology constraints of routers. When thinkig about the fabric of the routers, a router has a maximum number of packets which can be processed. This constraints the number of link connections, that is node degree. And it also constraints the connection speeds, that is bandwidth. This limitation creates possible bandwidth-degree combinations for each router. That is, a router is able to have a few high bandwidth connections or a lot of low bandwidth connections.

Cisco-CRS-1 and Cisco-12416 are the one of the most expensive and highest bandwidth routers now. From routers constraints, each node in ISP networks is recognized whether it is high performance router or not. We discriminate routers high perfomance or low perfomance by the region of the dots in figures. We can say, at least, that the dots between the lines of Cisco-7513 and Cisco-12416 represent high performance routers because they have high connection speeds or high degrees. We distinguish where the high performance routers are set by this way. The result is Table 3.

### 4.4 Modeling network bandwidths of ISP networks

The results of previous section show that nodes that have a high bandwidth link also have a lot of out-going links, which is different from the discussion in Ref. [10] where high bandwidth links are connected to lower-degree nodes. Based on this observation, we introduce a geographical model. The geographical model uses the information of population distribution in Japan. Based on the geographical information obtained from the reverse DNS lookup, we calculate traffic matrix of

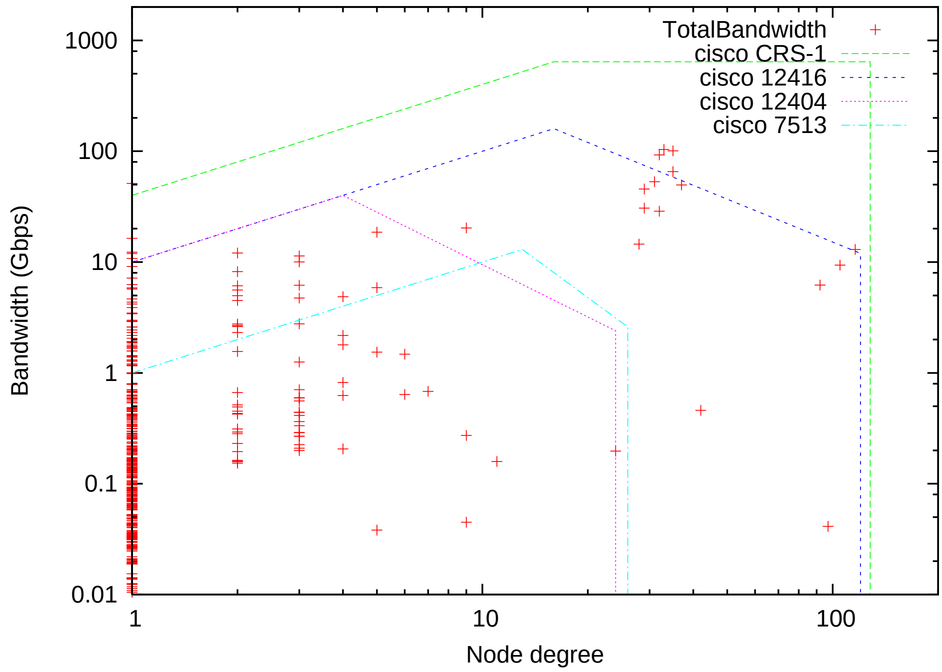



Figure 4: Distributions of totalbandwidths: ISP A

ISP networks by a gravity model [23]. The details of our geographical model are as follows.

**Geographical model** In the geographical model, we take into account node locations and its correspoinding population. That is, the weight of traffic through nodes is determined by the setting place of the node.

Our based idea is that the high performance node will be setting on populous prefecture. It is simply expected that the amount of traffic becomes large in populous place. So, this is merged the population distributions. By utilizing the result of the national population census, we determine the amount of traffic flowing between node–pair.

Table 4 is the result of the national population census [24].

We summarise the procedure that proposed model is applicated to the topologies.

**Step 1:** Set the weight to the nodes. The weight is determined by Table 4.

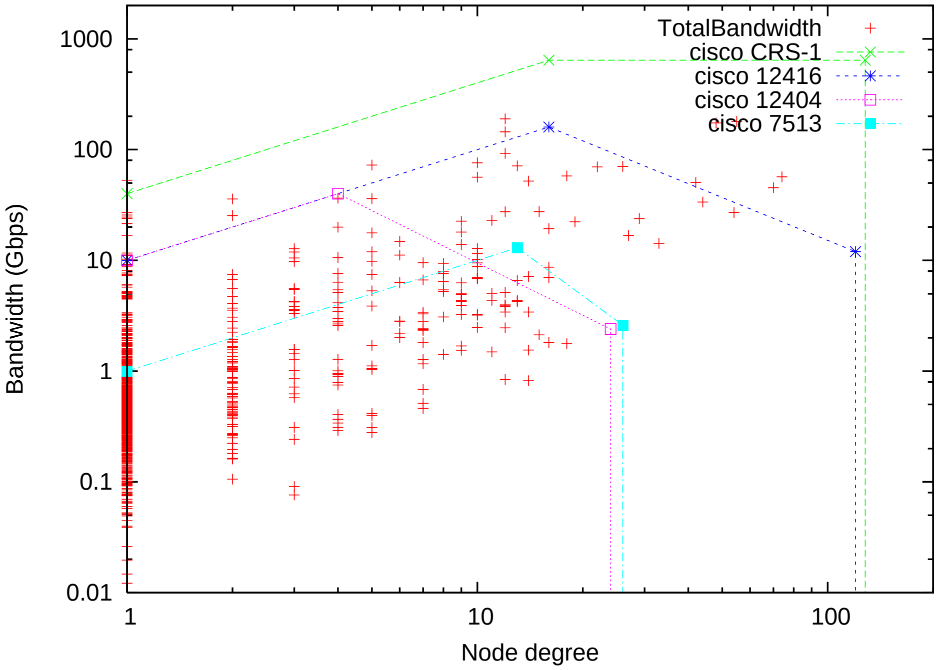



Figure 5: Distributions of totalbandwidth: ISP B

**Step 2:** For each node–pair $i$,$j$, the multiplication of each weight. Here, $w_i$,$w_j$ represent the weights of node $i$,$j$.

$$C \cdot w_i \cdot w_j \tag{3}$$

$C$ is a const number to scale the weights to the measured bandwidths.

**Step 3:** All multiplication of each weight are added to the links that is on path of minimum short path of each node–pair $i$,$j$.

$$L_k = \sum_{i,j} w_i \cdot w_j, \mathrm{if} l_k \mathrm{isontheshortestpathofnode} - -\mathrm{pair} i, j \tag{4}$$

where $l$ represent a link, $L_k$ is the total amount of traffic through $l_k$.

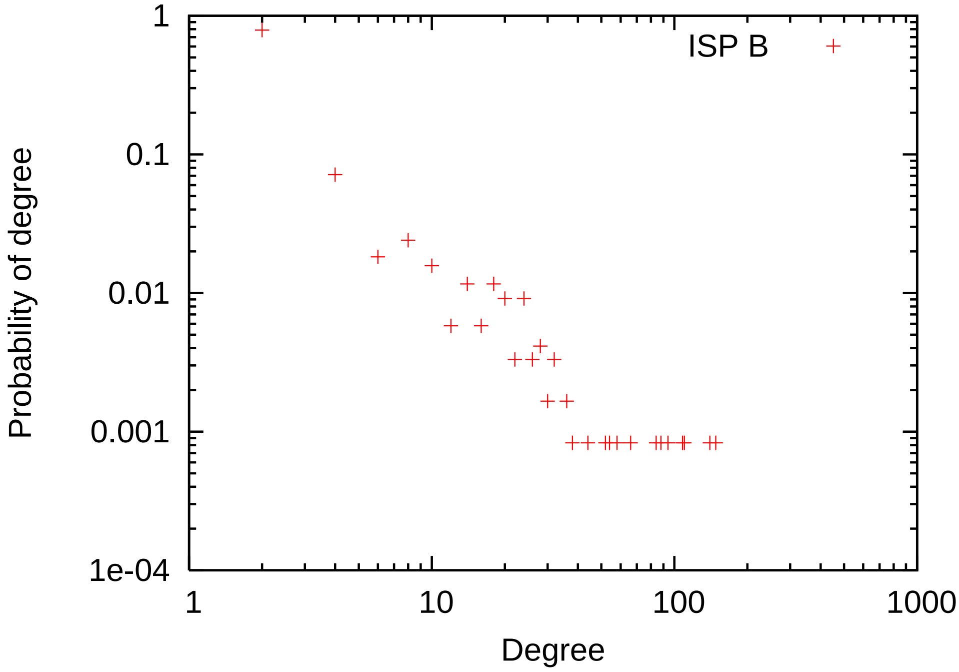



Figure 6: Digree distributions: ISP B

## 5 Conclusion

Recent measurement studies on Internet topology show that the connectivities of nodes exhibit a power–law attribute. That is, the probability $p(k)$ that a node is connected to $k$ other nodes follows $p(k) \sim k^{-\gamma}$. However, even if the degree distributions of some topologies are the same, more detailed characteristics are often quite different. For example, ISP topologies had a much higher cluster coefficient than the other topologies attained with conventional modeling methods, and more importantly, these differences greatly affect methods of network control. Furthermore, for studies of higher–layer protocols such as routing and flow controls, more detailed information of ISP networks are required. In this thesis, we measure topologies and link bandwidths of two Japanese ISPs. The results of measurements show that the degree distribution of ISP networks shows power-law attribute. That is, the most of nodes have few out-going links, while few nodes have many out-going links. We next measure bandwidths of all the links on each Japanese ISP

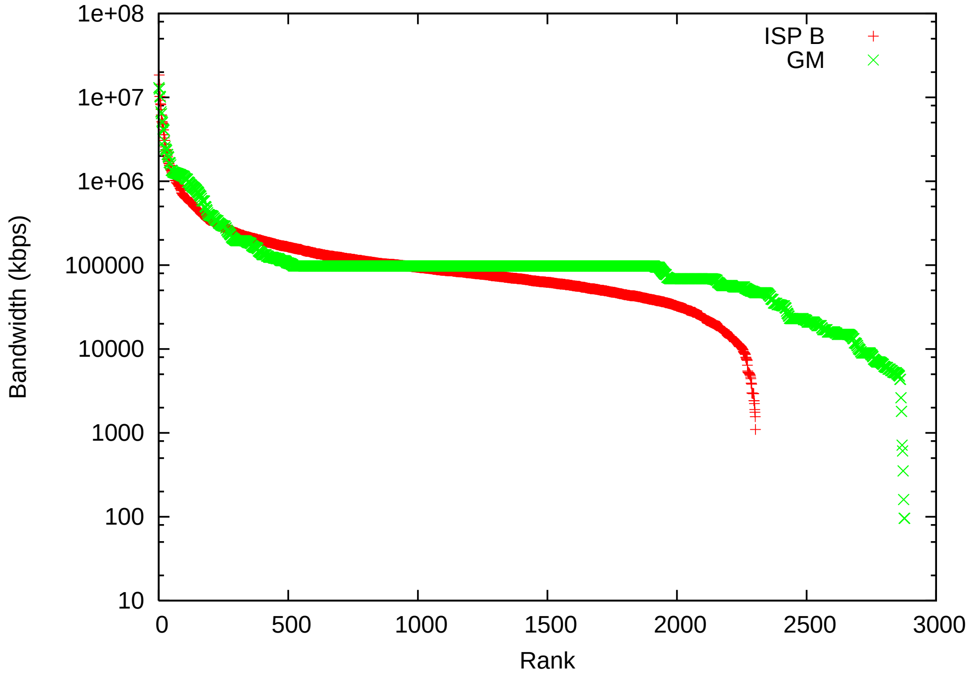



Figure 7: measurment bandwidth and models

topology. The results show that the high bandwidth links are located at Tokyo, the capital city of Japan. Furthermore, nodes that have a high bandwidth link also have a lot of out-going links, which is different from discussions given by other researcher's works where high bandwidth links are connected to lower-degree nodes. Following this observation, we present a geographical model to give a realistic bandwidth distribution of links, and we demonstrate that the geographical model certaily reproduces the link bandwidths of ISP networks.

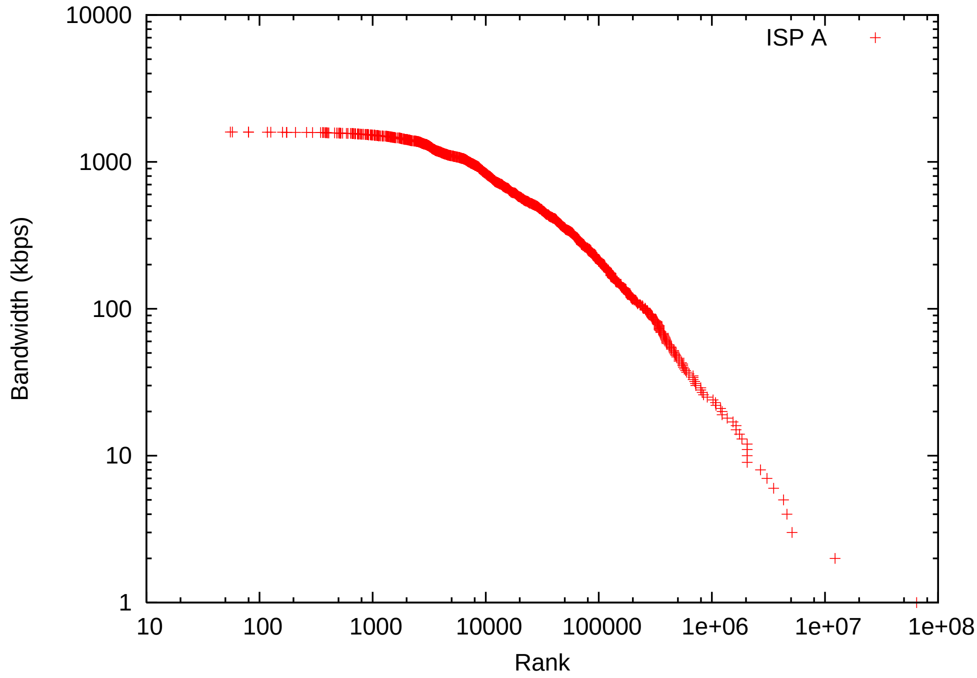



Figure 8: Distribution of bandwidth: ISP A

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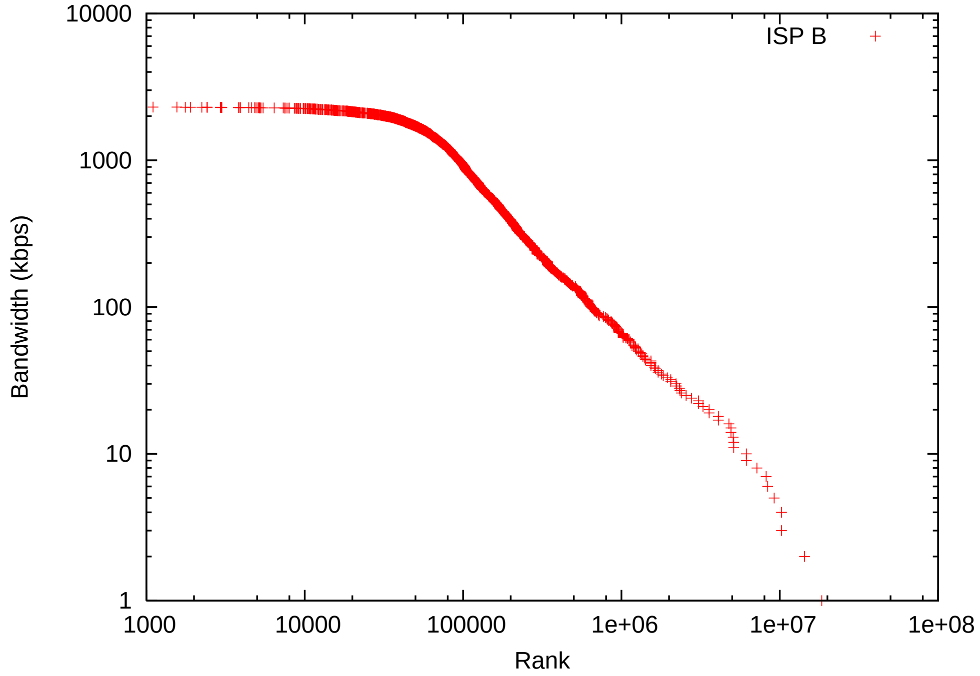


Figure 9: Distribution of bandwidth: ISP B

nology of Osaka University for their support.

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Table 4: Population Distribution

| Place | Percentage | Place | Percentage |
|---|---|---|---|
| Hokkaido | 4.4 | Shiga | 1.1 |
| Aomori | 1.1 | Kyoto | 2.1 |
| Iwate | 1.1 | Osaka | 6.9 |
| Miyagi | 1.8 | Hyogo | 4.4 |
| Akita | 0.9 | Nara | 1.1 |
| Yamagata | 1.0 | Wakayama | 0.8 |
| Fukushima | 1.6 | Tottori | 0.5 |
| Ibaraki | 2.3 | Shimane | 0.6 |
| Tochigi | 1.6 | Okayama | 1.5 |
| Gunma | 1.6 | Hiroshima | 2.3 |
| Saitama | 5.5 | Yamaguchi | 1.2 |
| Chiba | 4.7 | Tokushima | 0.6 |
| Tokyo | 9.8 | Kagawa | 0.8 |
| Kanagawa | 6.9 | Ehime | 1.1 |
| Niigata | 1.9 | Kochi | 0.6 |
| Toyama | 0.9 | Fukuoka | 4.0 |
| Ishikawa | 0.9 | Saga | 0.7 |
| Fukui | 0.6 | Nagasaki | 1.2 |
| Yamanashi | 0.7 | Kumamoto | 1.4 |
| Nagano | 1.7 | Oita | 0.9 |
| Gifu | 1.6 | Miyazaki | 0.9 |
| Shizuoka | 3.0 | Kagoshima | 1.4 |
| Aichi | 5.7 | Okinawa | 1.1 |
| Mie | 1.5 | | |
| | | total | 100 |