The Role of Switching Hub in Global Internet Traffic

by

CHANG-HO YOON*, YOUNG-WOONG SONG, AND BYOUNG HEON JUN**

In the recent decade, global backbone providers have emerged to link dispersed networks. Local networks obtain global connectivity through transit contracts with switching hubs. Using the Shapley value, the paper shows that the bargaining position of the local network depends upon the quality adjusted volume of net traffic, and that the rent to the hub depends on the volume of traffic between local networks. When there are two competing switching hubs, the larger hub can appropriate most of the rent. Anticipating this, the hubs tend to expand their capacity to preempt the market like in the prisoners' dilemma. (JEL-Code: L1, L86)

1 Introduction

The recent surge of Internet traffic is phenomenal. According to the OECD statistics, the IP traffic grows in the order of factor 2 per annum, and far outweighs the voice traffic in driving expansion of telecom capacity. The number of the Internet users was 160 million (2.7 percent of the world population) in 1998, and reached 675.7 million (11.1 percent) in 2003. The number of broadband subscribers in the world was a little more than 3 million (1.4 percent of Internet users) in 1999, and at the start of 2003, it was already increased to 63 million (9.3 percent of Internet users). The central force

* Chang-Ho Yoon's research is supported by the special faculty grant from Korea University
** Corresponding author. E-mail address: bhjun@korea.ac.kr

driving the development of Internet traffic is a newly created global market for digital content which has been growing rapidly from 93 billion US dollars in 2001 to 165 billion US dollars in 2003 with an expected annual growth rate being more than 30 percent.

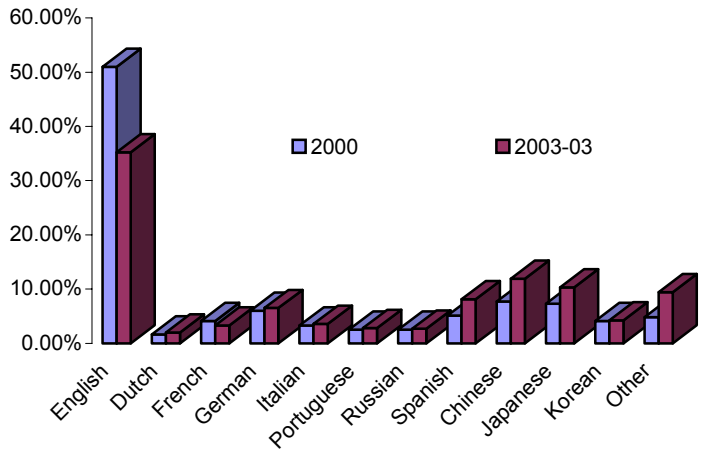
As the spectacular growth of Internet traffic continues, various bargaining mechanisms in the backbone market have emerged to link dispersed networks and facilitate exchange of traffic in a seamless manner. Internet networks are connected by peering, transit, or multi-homing connection. The peering contract is often observed between the networks of equal size that can be interconnected at a number of geographically diverse locations. Other than capacity costs of connecting two networks that are borne on an equal basis at the beginning stage of peering agreement, peering partners do not pay any further for extended connectivity. In the late 1990s, larger backbones such as UUNET, Sprint and Genuity, however, refused peering with smaller backbones believing that they would free ride on their infrastructure. Smaller backbones therefore had to purchase access to the global backbones only through transit contracts. The wholesale connectivity has been charged on a monthly basis for example and is settled through bargaining process.

The bargaining power of network operators differs substantially depending upon the network size and cross-border flow of information traffic. In particular, the ability to host popular content and provide connectivity to other entities providing such content seems an important determinant. Recent evolution of the international Internet connectivity has been influenced not only by advances in routing technologies, but by

the global market for digital contents as well and becomes more sophisticated.

Figure 1

Distribution of Internet Users by Language

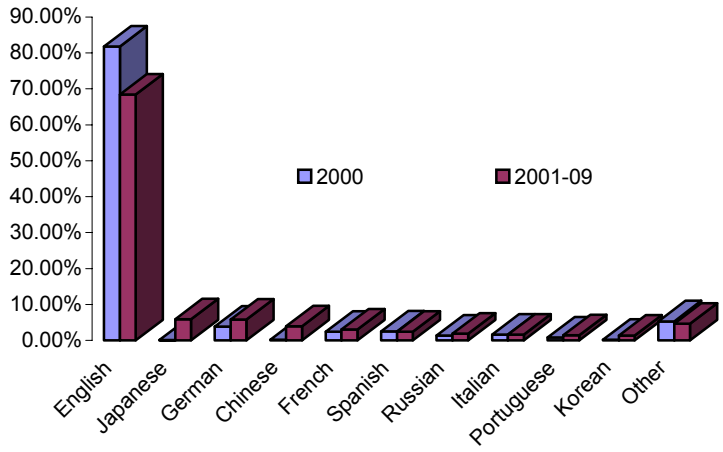


Sources: NANTHIKESAN [2000] and Global Reach

In the earlier stage of development, the global backbones from the USA were main switching hubs, and asymmetric bargaining situation began to develop. High quality content provided in the USA attracted many foreign subscribers, and for other countries the resulting inbound traffic flow surpassed outbound flow to a great extent. The distribution of users and Web Pages by language also shows that they were heavily concentrated on English in 2000. The concern over the possibility of persistent asymmetry in bargaining power among network operators in commercial negotiations was once a serious policy issue in the late 1990s. The US government was keen to monitor abuse of market power by the global backbones, and in fact prevented the merger between MCI WorldCom and Sprint in 1998.

Figure 2

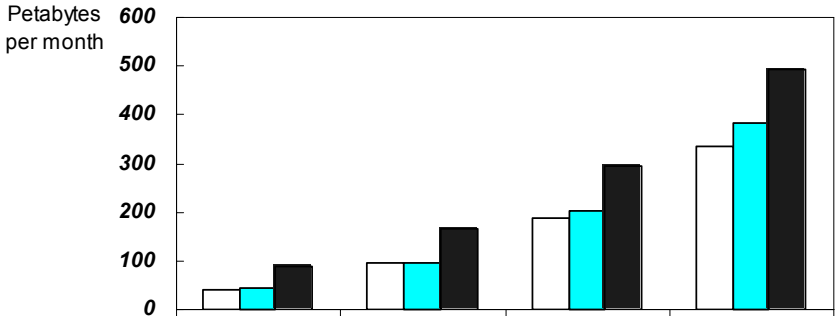
Distribution of Internet Host by Language



Sources: NANTHIKESAN [2000] and Global Reach

Figure 3

World's Internet traffic



	2001	2002	2003	2004
Asia-Pacific	42	94	187	335
Europe	44	95	201	384
North America	90	167	294	492

Source: RHK Inc., re-cited and rebuilt from CADE [2003].

The trend however has changed recently. Local application of contents reinforced regional trend of Internet traffic. Figure 1 and 2 show that the proportion of English users decreased to 35 percent, and in the case of Web Pages, to 68 percent in 2003. Late comers from the relatively less developed world who might have been faced with

the possible abuse of dominant market power of backbone providers and possibly encountered entry barriers in global markets for digital contents seem to have found growing outlets in regional markets. As Table 1 shows, more traffic now tends to stay within each region. Due to increasing teledensity and local application of contents, regionalization and localization of Internet traffic gains speed in Europe and Asia (see Figure 3 and Table 1). Regional hubs are growing rapidly in London, Paris, Frankfurt, Amsterdam, Tokyo and Singapore among others.[1]

Table 1

International Internet Traffic between Regions

Terminating / Originating	Yr	Europe	Asia	Oceania	North America	CCASA	Africa
Europe	’01	71%			28%		
	’07	85%			7%		4%
Asia	’01		12%		79%		
	’07		82%		8%		4%
Oceania	’01		32%	1%	65%		
	’07	18%	23%	41%	18%		
North America	’01	40%	21%		32%		
	’07	21%	18%		46%		
CCASA	’01				61%	30%	
	’07	17%			33%	49%	
Africa	’01				77%		8%
	’07	17%	13%		16%		53%

Source: Probe Research, Jan 2003, re-cited and rebuilt from CADE [2003].

In recent times global backbone players in the US faced intense competition among themselves and from outside, and as a result suffered from excess capacity. The mergers and acquisitions had followed severe financial distress in this industry.

This paper examines the role of switching hubs in a game theoretic framework that

[1] In the appendix, a regional pattern of traffic flow and contractual arrangements for Korea are presented for illustrational purposes.

models commercial bargaining agreement among network operators. Local networks obtain global connectivity through transit contracts with Internet backbone providers of switching hubs. As we explained earlier, the current location of global switching hubs has been historically determined throughout the past decade of evolutionary process of Internet traffic. We therefore do not attempt to model the assignment of roles such as hub and non-hub to the networks, and start from the monopoly model of the switching hub to explain the rent accruing to the hub and the terms of transit contract. Applying the value allocation rule of cooperative game theory, we show that the bargaining powers of the local networks depend upon the quality adjusted volume of net traffic (the difference between the outbound traffic and the inbound traffic weighted by the quality of content), and that the rents to the hub depend on the volume of traffic between the local networks that are connected to the switching hub. In the next part of the paper, various modes of competition among switching hubs are introduced, and the value allocations are reexamined. The rents to the switching hubs decrease when neither of the hubs is capacity constrained. If however traffic volume is increased and the smaller hub faces the capacity constraint, the larger hub can collect greater premium and there arises tendency between the hubs to expand their capacity to preempt the market. The market may then lead to excess capacity equilibrium. In the last section of the paper, we also examine the possibility of bypassing the switching hubs through peering among local networks.

The growing importance of network connectivity has been already observed in the literature. LAFFONT ET AL. [2001], [2003] introduced a model of off-net cost pricing of access charges that is based on pricing of unit traffic. However, in the case of digital

content, often the caller becomes the receiver of the content, which makes it difficult to apply either caller-pays-principle, or receiver-pays-principle. MILGROM, MITCHELL AND SRINAGESH [2000], and BESEN ET AL. [2001] deal with peering contracts between networks and introduce bargaining solutions to explain bill-and-keep practice and multi-homing. In this paper, we start from focusing on transit purchase to explain how a small network operator bargains with global backbone providers and then move to more interesting issues that result from competition among global backbone players and their investment incentives.

2 The Model

One of the basic ideas of bargaining models in Internet interconnection is that interconnection increases the network size and the profitability of the network operator and that this increase in profitability determines the *price* of interconnection. When two networks are interconnected, the customers in both networks benefit from the increased access to diverse contents. Since the network operator hosts different kinds of contents to varying numbers of subscribers, the corresponding benefits accruing to each connecting network would not be the same in principle. Non-homogeneity poses an important issue when the networks of two different countries are interconnected. We think there is important asymmetry that arises from language barriers across the border. We model this explicitly in the following.

We denote a network by $i \in I$. There can be one or several hub network(s). It has the essential facilities and technologies required to transmit the packets anywhere in the

world. Networks except hub(s) are customers of transit service that is provided by hub(s). We assume that network i hosts one contents provider, CP_i and serves n_i identical consumers.[2] We assume that a consumer of network *i* has the following separable quadratic utility function.

$$u_i(q, y) = \sum_j (\theta_j q_j - \frac{1}{2}\lambda_{ij} q_j^2) + y, \tag{1}$$

where θ_j and q_j denote the quality and the quantity consumed of CP_j's Internet contents, respectively. λ_{ij} measures how quickly consumer *i*'s marginal utility of q_j decreases. y denotes the amount of numeraire good. Given the utility function, consumer *i*'s demand for Internet contents *j* can be derived as follows.

$$q_{ij} = \alpha_{ij}(\theta_j - p_j) \tag{2}$$

where $\alpha_{ij} = 1/\lambda_{ij}$. Through rescaling of units, one can normalize α_{ii} to be 1. It is natural (but not necessary) to assume that $\alpha_{ij} < 1$ for $i \neq j$. For notational convenience, let us denote a coalition of networks by a non-empty set $S \in 2^I \setminus \phi$. The market demand for contents of CP_j in a coalition S would then be

$$Q_j(p_j; \theta_j) = \sum_{i \in S} n_i q_{ij} \ . \tag{3}$$

[2] Alternatively we can assume that there are many competitive contents providers in each network.

We assume that the marginal costs are constant and equal to 0 for simplicity. Then CP_j's profit is $\pi_j(p_j;\theta_j) = p_j Q_j(p_j,\theta_j)$, and the resulting profit maximizing price is $p_j(\theta_j) = \theta_j / 2$ regardless of how many networks are interconnected. Now we can calculate the net surplus of a consumer in network *i* obtained from the consumption of CP_j's contents (assuming sufficient income).

$$CS_{ij} = \theta_j q_j - \frac{1}{2}\lambda_{ij} q_j^2 - p_j(\theta_j) q_j = \alpha_{ij} \frac{\theta_j^{\,2}}{8}. \tag{4}$$

Each network operator can extract the entire consumer surplus by raising membership fee. Network i's total surplus that can be obtained by participating in a coalition S will be

$$TS_i^S = \sum_{j\in S} n_i CS_{ij} = \frac{1}{8}\sum_{j\in S} \alpha_{ij} n_i \theta_j^{\,2},\ \alpha_{ii} = 1.^{3} \tag{5}$$

We assume the surplus of networks from interconnection is divided according to the Shapley value, a cooperative bargaining solution.[4] Shapley value has many nice properties. It is one of the well studied concepts of game theory, both cooperative and non-cooperative. It is unique and reflects the (marginal) contributions of each member of the coalition. The non-cooperative analyses mentioned in footnote 4 provide us with

[3] In obtaining this result we assumed monopolistic pricing in contents markets. Qualitatively similar result obtains if we assume competitive pricing.

[4] See SHAPLEY [1953]. GUL [1989], HART AND MAS-COLELL [1996], and MASKIN [2003] provide non-cooperative game theoretic foundation of the Shapley value.

some idea of how the bargaining may proceed. For these reasons we use the Shapley value for our analysis.

Let us denote the total surplus of each coalition S by $v(S)$, and the potential total surplus, $\bar{v}(S)$. $\bar{v}(S)$ represents the total surplus when all the participants are interconnected. By definition, $\bar{v}(S)$ is expressed as follows.

$$\bar{v}(S) = \sum_{i \in S} TS_i^S \quad \text{for} \quad S \in 2^I \setminus \phi .$$

Now we consider the case of three networks denoted by $i \in \{1,2,3\} = I$. Network 3 is the hub. Networks 1 and 2 are customers of transit service. Under our assumption that networks can be connected only through the network 3, the hub, the total surplus can be expressed as follows.[5]

$$v(1) = \bar{v}(1) = TS_1^{\{1\}}, \quad v(2) = \bar{v}(2) = TS_2^{\{2\}}, \quad v(3) = \bar{v}(3) = TS_3^{\{3\}}$$

$$v(1,2) = v(1) + v(2) = TS_1^{\{1\}} + TS_2^{\{2\}} \neq \bar{v}(1,2),$$

$$v(1,3) = \bar{v}(1,3) = \sum_{i \in \{1,3\}} TS_i^{\{1,3\}}, \quad v(2,3) = \bar{v}(2,3) = \sum_{i \in \{2,3\}} TS_i^{\{2,3\}},$$

$$v(1,2,3) = \bar{v}(1,2,3) = \sum_{i \in \{1,2,3\}} TS_i^{\{1,2,3\}} .$$

The Shapley value is known as the average of the marginal contribution of possible orderings of the players. There are six possible orderings of the network operators: $(1,2,3)$, $(1,3,2)$, $(2,1,3)$, $(2,3,1)$, $(3,1,2)$, $(3,2,1)$. Table 2 shows the marginal

[5] To lighten the notation we omit the curly bracket to denote sets in the value function.

contributions of each network in these orderings. Except $v(1,2)$, all of $v(\cdots)$ are $\bar{v}(\cdots)$.

Table 2

Marginal contributions of each network

	Network 1	Network 2	Network 3
(1,2,3)	$v(1)$	$v(1,2)-v(1)$	$v(1,2,3)-v(1,2)$
(1,3,2)	$v(1)$	$v(1,2,3)-v(1,3)$	$v(1,3)-v(1)$
(2,1,3)	$v(1,2)-v(2)$	$v(2)$	$v(1,2,3)-v(1,2)$
(2,3,1)	$v(1,2,3)-v(2,3)$	$v(2)$	$v(2,3)-v(2)$
(3,1,2)	$v(1,3)-v(3)$	$v(1,2,3)-v(1,3)$	$v(3)$
(3,2,1)	$v(1,2,3)-v(2,3)$	$v(2,3)-v(3)$	$v(3)$

Therefore, the Shapley value of each network would be

$$Sh_1 = \frac{1}{48}[(6\theta_1^{\,2} + 2\alpha_{12}\theta_2^{\,2} + 3\alpha_{13}\theta_3^{\,2})n_1 + 2\alpha_{21}\theta_1^{\,2}n_2 + 3\alpha_{31}\theta_1^{\,2}n_3]$$

$$Sh_2 = \frac{1}{48}[2\alpha_{12}\theta_2^{\,2}n_1 + (2\alpha_{21}\theta_1^{\,2} + 6\theta_2^{\,2} + 3\alpha_{23}\theta_3^{\,2})n_2 + 3\alpha_{32}\theta_2^{\,2}n_3]$$

$$Sh_3 = \frac{1}{48}[(2\alpha_{12}\theta_2^{\,2} + 3\alpha_{13}\theta_3^{\,2})n_1 + (2\alpha_{21}\theta_1^{\,2} + 3\alpha_{23}\theta_3^{\,2})n_2 + (3\alpha_{31}\theta_1^{\,2} + 3\alpha_{32}\theta_2^{\,2} + 6\theta_3^{\,2})n_3]$$

Here one can easily check the well known property that no utility is wasted, i.e.,

$$\sum_{i\in\{1,2,3\}} Sh_i = \sum_{i\in\{1,2,3\}} TS_i^{\{1,2,3\}} \equiv \bar{v}(1,2,3). \tag{6}$$

We define *net payment* from network i to other networks as

$$NP_i \equiv TS_i^{\{1,2,3\}} - Sh_i \,. \tag{7}$$

By summing up (7) with respect to all $i \in \{1,2,3\}$ and applying (6), we obtain

$$\sum_{i\in\{1,2,3\}} NP_i = 0 \,.$$

Net payments are calculated as follows:

$$NP_1 = \frac{1}{48}[3\alpha_{13} n_1 \theta_3{}^2 - 3\alpha_{31} n_3 \theta_1{}^2 + 4\alpha_{12} n_1 \theta_2{}^2 - 2\alpha_{21} n_2 \theta_1{}^2],$$
$$NP_2 = \frac{1}{48}[3\alpha_{23} n_2 \theta_3{}^2 - 3\alpha_{32} n_3 \theta_2{}^2 + 4\alpha_{21} n_2 \theta_1{}^2 - 2\alpha_{12} n_1 \theta_2{}^2],$$
$$NP_3 = -(NP_1 + NP_2).$$

Since the equilibrium demand of each consumer in Network j for content i is $\theta_i / 2$, the total traffic from network i to network j, denoted by $\tau^{i\to j}$, is

$$\tau^{i\to j} \equiv \alpha_{ji} n_j \theta_i / 2 \text{, for } i \neq j \,.$$

Now we can rewrite net payment in terms of traffics defined above.

$$
\begin{aligned}
NP_1 &= \frac{1}{8}[(\theta_2\tau^{2\to 1} - \theta_1\tau^{1\to 2}) + (\theta_3\tau^{3\to 1} - \theta_1\tau^{1\to 3})] \\
&\quad + \frac{1}{24}(\theta_1\tau^{1\to 2} + \theta_2\tau^{2\to 1}) \\
NP_2 &= \frac{1}{8}[(\theta_1\tau^{1\to 2} - \theta_2\tau^{2\to 1}) + (\theta_3\tau^{3\to 2} - \theta_2\tau^{2\to 3})] \\
&\quad + \frac{1}{24}(\theta_1\tau^{1\to 2} + \theta_2\tau^{2\to 1}) \\
NP_3 &= \frac{1}{8}[(\theta_1\tau^{1\to 3} - \theta_3\tau^{3\to 1}) + (\theta_2\tau^{2\to 3} - \theta_3\tau^{3\to 2})] \\
&\quad - \frac{1}{12}(\theta_1\tau^{1\to 2} + \theta_2\tau^{2\to 1})] \\
&= -(NP_1 + NP_2).
\end{aligned}
\qquad (8)
$$

We can interpret the term $\theta_j\tau^{j\to i} - \theta_i\tau^{i\to j}$ as quality-adjusted net inbound traffic of network i against network j, which is the same as the net outbound traffic of network j against network *i*.

Net payments consist of two parts. The first part in each expression is proportional to the sum of quality-adjusted net inbound traffic. Focusing only on this part one can see that the net payment of network *i* increases as the (quality adjusted) net inbound traffic increases. However, there is another factor which affects the net payment. The second part of the net payment reflects the asymmetry of bargaining power between the hub and non-hub networks. Non-hub networks pay some premium, and the hub network collects it. The premium is proportional to the total (quality adjusted) traffic between the two non-hub networks.

We summarize this result in the following proposition.

Proposition 1. According to the Shapley value, the payment of the transit purchaser consists of two parts. The first part is proportional to the quality adjusted net inbound traffic. The second part is proportional to the quality adjusted total traffic between the non-hub networks. Hence, the transit purchasers' payments increase as the net inbound traffic increases, and in addition the payments increase as the total traffic between the non-hub networks increases.

Remark. As a special case consider the case where $\alpha_{31} = \alpha_{32} = 0$, $\theta_1 = \theta_2 = \theta_3 = 1$. If $2\alpha_{21}n_2 > 3\alpha_{13}n_1 + 4\alpha_{12}n_1$, then $NP_1 < 0$ and $NP_2 > 0$. That is, if the volume of traffic from network 1 to network 2 ($\alpha_{21}n_2 = 2\tau^{1\to 2}$) is large enough, network 1 can request some payment from network 2 (maybe indirectly through negotiation with the hub network). In spite of this theoretical possibility, any phenomenon like that has not been witnessed in the real world.

3 Competition between Two Hubs

In this section we analyze a competition between two hubs which may or may not have capacity constraints. We use the results of this analysis and consider a two stage dynamic game of investment in capacity. We will show that the investment decision that the two hubs are facing is like a prisoners' dilemma game which results in over-investment in the capacity compared to the globally efficient level.

Let 1 and 2 denote the transit purchasers as before and let 3 and 4 denote the potential hubs. Therefore in this section we consider the case of $I = \{1,2,3,4\}$. We maintain the assumption that peering between the two hubs is always possible. Assume as before that network operators can extract the entire consumer surplus. The total value of coalition S is denoted by $v(S)$ as before. We also assume that $v(1,2) = v(1) + v(2) \neq \bar{v}(1,2)$. The Shapley value of network 1 is calculated as follows.

$$\begin{aligned} Sh_1 = \ & \frac{1}{4}v(1) \\ & + \frac{1}{12}[v(1,2) - v(2) + v(1,3) - v(3) + v(1,4) - v(4)] \\ & + \frac{1}{12}[v(1,2,3) - v(2,3) + v(1,2,4) - v(2,4) + v(1,3,4) - v(3,4)] \\ & + \frac{1}{4}[v(1,2,3,4) - v(2,3,4)] \end{aligned}$$

where $v(S) = \bar{v}(S)$ for all $S \neq \{1,2\}$.

In the same way we can calculate the Shapley values of the other networks.

Case I: No capacity constraints

First we consider the case where there is no capacity constraint so that either hub can provide interconnection to both customer networks. After somewhat complicated calculations we obtain the following:

$$\begin{aligned} Sh_1^I = \frac{1}{96}\Big[& (12n_1 + 5\alpha_{21}n_2 + 6\alpha_{31}n_3 + 6\alpha_{41}n_4)\theta_1^{\,2} \\ & + (5\alpha_{12}n_1\theta_2^{\,2} + 6\alpha_{13}n_1\theta_3^{\,2} + 6\alpha_{14}n_1\theta_4^{\,2})\Big] \end{aligned}$$

$$Sh_3^I = \frac{1}{96}\Big[(\alpha_{21}n_2 + 6\alpha_{31}n_3)\theta_1{}^2 + (\alpha_{12}n_1 + 6\alpha_{32}n_3)\theta_2{}^2 + (6\alpha_{13}n_1 + 6\alpha_{23}n_2 + 12n_3 + 6\alpha_{43}n_4)\theta_3{}^2 + 6\alpha_{34}n_3\theta_4{}^2\Big]$$

and symmetric expressions for 2 and 4.

Net payments are

$$NP_1^I = \frac{1}{8}\Big[(\theta_2\tau^{2\to1} - \theta_1\tau^{1\to2}) + (\theta_3\tau^{3\to1} - \theta_1\tau^{1\to3}) + (\theta_4\tau^{4\to1} - \theta_1\tau^{1\to4})\Big] + \frac{1}{48}(\theta_2\tau^{2\to1} + \theta_1\tau^{1\to2}),$$

$$NP_3^I = \frac{1}{8}\Big[(\theta_1\tau^{1\to3} - \theta_3\tau^{3\to1}) + (\theta_2\tau^{2\to3} - \theta_3\tau^{3\to2}) + (\theta_4\tau^{4\to3} - \theta_3\tau^{3\to4})\Big] - \frac{1}{48}(\theta_1\tau^{1\to2} + \theta_2\tau^{2\to1})$$

Hence, compared to the one hub case each transit purchaser pays one half of the premium, and each hub receives one quarter. Hence, the competition between the hubs increases the bargaining power of the transit purchaser and weakens the bargaining position of the hubs.

Proposition 2. When there are two hubs, the premium payments are reduced to half the level when there is only one hub, and each hub receives one quarter of the premium received when there is only one hub.

Case II: Capacity constraints

Here we assume that each hub can host only one transit purchaser. Hence the two transit purchasers can be interconnected only when the grand coalition is formed. Since $v(1,2,3)$ and $v(1,2,4)$ are different from $\bar{v}(1,2,3)$ and $\bar{v}(1,2,4)$ due to capacity constraint, we need to recalculate the Shapley value taking into account the following changes.

$$v(1,2,3) = \max\{\bar{v}(1) + \bar{v}(2,3),\ \bar{v}(2) + \bar{v}(1,3)\} \neq \bar{v}(1,2,3)$$
$$v(1,2,4) = \max\{\bar{v}(1) + \bar{v}(2,4),\ \bar{v}(2) + \bar{v}(1,4)\} \neq \bar{v}(1,2,4)$$

After substituting the values we obtain

$$\begin{aligned} Sh_1^{II} = \frac{1}{96}\Big[&(12n_1 + 3\alpha_{21}n_2 + 5\alpha_{31}n_3 + 5\alpha_{41}n_4)\theta_1^{\,2} \\ &+ (3\alpha_{12}n_1 - \alpha_{32}n_3 - \alpha_{42}n_4)\theta_2^{\,2} \\ &+ (5\alpha_{13}n_1 - \alpha_{23}n_2)\theta_3^{\,2} + (5\alpha_{14}n_1 - \alpha_{24}n_2)\theta_4^{\,2} \\ &+ \max\{\alpha_{31}n_3\theta_1^{\,2} + \alpha_{13}n_1\theta_3^{\,2},\ \alpha_{32}n_3\theta_2^{\,2} + \alpha_{23}n_2\theta_3^{\,2}\} \\ &+ \max\{\alpha_{41}n_4\theta_1^{\,2} + \alpha_{14}n_1\theta_4^{\,2},\ \alpha_{42}n_4\theta_2^{\,2} + \alpha_{24}n_2\theta_4^{\,2}\}\Big] \end{aligned}$$

$$\begin{aligned} Sh_3^{II} = \frac{1}{96}\Big[&(3\alpha_{21}n_2 + 5\alpha_{31}n_3 + 3\alpha_{41}n_4)\theta_1^{\,2} + (3\alpha_{12}n_1 + 5\alpha_{32}n_3 + 3\alpha_{42}n_4)\theta_2^{\,2} \\ &+ (5\alpha_{13}n_1 + 5\alpha_{23}n_2 + 12n_3 + 6\alpha_{43}n_4)\theta_3^{\,2} \\ &+ (3\alpha_{14}n_1 + 3\alpha_{24}n_2 + 3\alpha_{34}n_3)\theta_4^{\,2} \\ &+ \max\{\alpha_{31}n_3\theta_1^{\,2} + \alpha_{13}n_1\theta_3^{\,2},\ \alpha_{32}n_3\theta_2^{\,2} + \alpha_{23}n_2\theta_3^{\,2}\} \\ &- 3\max\{\alpha_{41}n_4\theta_1^{\,2} + \alpha_{14}n_1\theta_4^{\,2},\ \alpha_{42}n_4\theta_2^{\,2} + \alpha_{24}n_2\theta_4^{\,2}\}\Big] \end{aligned}$$

Net payments for networks 1 and 3 are

$$NP_1^{II} = \frac{1}{8}\left[(\theta_2\tau^{2\to1} - \theta_1\tau^{1\to2}) + (\theta_3\tau^{3\to1} - \theta_1\tau^{1\to3}) + (\theta_4\tau^{4\to1} - \theta_1\tau^{1\to4})\right]$$
$$+ \frac{1}{16}(\theta_2\tau^{2\to1} + \theta_1\tau^{1\to2}) + \frac{1}{48}(\phi_3 + \phi_4)$$

$$NP_3^{II} = \frac{1}{8}\left[(\theta_1\tau^{1\to3} - \theta_3\tau^{3\to1}) + (\theta_2\tau^{2\to3} - \theta_3\tau^{3\to2}) + (\theta_4\tau^{4\to3} - \theta_3\tau^{3\to4})\right]$$
$$- \frac{1}{16}(\theta_1\tau^{1\to2} + \theta_2\tau^{2\to1}) - \frac{1}{24}\phi_4 + \frac{1}{48}(\phi_3 - \phi_4)$$

where, $\phi_3 \equiv \min\{\theta_1\tau^{1\to3} + \theta_3\tau^{3\to1},\ \theta_2\tau^{2\to3} + \theta_3\tau^{3\to2}\}$

$\phi_4 \equiv \min\{\theta_1\tau^{1\to4} + \theta_4\tau^{4\to1},\ \theta_2\tau^{2\to4} + \theta_4\tau^{4\to2}\}$

Net payments for networks 2 and 4 are symmetric. The payment of transit purchaser (NP_1^{II}) consists of three parts. The first part is common to all the participating networks and the same as in the previous cases. The last two parts can be interpreted as a premium paid to the hubs. Since interconnection to the hub is a scarce resource, it has higher premium. It is more sensitive to the increase in the traffic between the two purchasing networks, 1/16 compared to 1/48. This increase (1/24 = 1/16 – 1/48) is due to the increased scarcity. And the additional charge applies to the traffic with the hubs as well (the third part), since the traffic with the hub also uses up the scarce resources. Suppose that $\theta_1\tau^{1\to h} + \theta_h\tau^{h\to1} < \theta_2\tau^{2\to h} + \theta_h\tau^{h\to2}$ so that ϕ_h = the quality adjusted total traffic between 1 and hub *h*. Then network 1 pays this premium, but network 2 is exempt from paying the premium for $(\theta_2\tau^{2\to h} + \theta_h\tau^{h\to2}) - (\theta_1\tau^{1\to h} + \theta_h\tau^{h\to1})$, the amount of total traffic between 2 and *h* that exceeds the total traffic between 1 and *h*. It is because this additional traffic can be accommodated with no extra cost under our assumption. The traffic between the two hubs does not affect the premium, since there is no scarcity of resources required for interconnecting them.

The part of the premium priced for the traffic between 1 and 2 are equally divided between 3 and 4. However, the part of the premium priced for the traffic between the purchaser and the provider of the interconnection is divided according to the source of the traffic. If the source of the traffic is 3 then the premium goes to 4 and vice versa. The last part of the net payment of a hub (NP_3^{II}) represents the adjustment payments between the two hubs. Network 3 pays more to network 4 as more traffic occurs between 3 and the purchasers, and it pays less to network 4 as more traffic occurs between 4 and the purchasers.

Case III: Partial capacity constraint

Here we assume that only network 4 has capacity constraint. That is, network 3 can provide the interconnection service to both networks 1 and 2, but network 4 can provide the service to only one network. In this case we should bear in mind the following.

$$v(1,2,3) = \bar{v}(1,2,3)\text{, but}$$
$$v(1,2,4) = \max\{\bar{v}(1) + \bar{v}(2,4),\ \bar{v}(2) + \bar{v}(1,4)\} \neq \bar{v}(1,2,4)\ .$$

The Shapley values are what follow.

$$Sh_1^{III} = \frac{1}{96}\Big[(12n_1 + 4\alpha_{21}n_2 + 6\alpha_{31}n_3 + 5\alpha_{41}n_4)\theta_1^{\,2} + (4\alpha_{12}n_1 - \alpha_{42}n_4)\theta_2^{\,2} + 6\alpha_{13}n_1\theta_3^{\,2} + (5\alpha_{14}n_1 - \alpha_{24}n_2)\theta_4^{\,2} + \max\{\alpha_{41}n_4\theta_1^{\,2} + \alpha_{14}n_1\theta_4^{\,2},\ \alpha_{42}n_4\theta_2^{\,2} + \alpha_{24}n_2\theta_4^{\,2}\}\Big]$$

$$Sh_3^{III} = \frac{1}{96}\Big[(4\alpha_{21}n_2 + 6\alpha_{31}n_3 + 3\alpha_{41}n_4)\theta_1^{\,2} + (4\alpha_{12}n_1 + 6\alpha_{32}n_3 + 3\alpha_{42}n_4)\theta_2^{\,2} + (6\alpha_{13}n_1 + 6\alpha_{23}n_2 + 12n_3 + 6\alpha_{43}n_4)\theta_3^{\,2} + (3\alpha_{14}n_1 + 3\alpha_{24}n_2 + 6\alpha_{34}n_3)\theta_4^{\,2} - 3\max\{\alpha_{41}n_4\theta_1^{\,2} + \alpha_{14}n_1\theta_4^{\,2},\ \alpha_{42}n_4\theta_2^{\,2} + \alpha_{24}n_2\theta_4^{\,2}\}\Big]$$

$$Sh_4^{III} = \frac{1}{96}\Big[5\alpha_{41}n_4\theta_1^{\,2} + 5\alpha_{42}n_4\theta_2^{\,2} + 6\alpha_{43}n_4\theta_3^{\,2} + (5\alpha_{14}n_1 + 5\alpha_{24}n_2 + 6\alpha_{34}n_3 + 12n_4)\theta_4^{\,2} + \max\{\alpha_{41}n_4\theta_1^{\,2} + \alpha_{14}n_1\theta_4^{\,2},\ \alpha_{42}n_4\theta_2^{\,2} + \alpha_{24}n_2\theta_4^{\,2}\}\Big]$$

Net payments for networks 1, 3, 4 are

$$NP_1^{III} = \frac{1}{8}\Big[(\theta_2\tau^{2\to1} - \theta_1\tau^{1\to2}) + (\theta_3\tau^{3\to1} - \theta_1\tau^{1\to3}) + (\theta_4\tau^{4\to1} - \theta_1\tau^{1\to4})\Big] + \frac{1}{24}(\theta_2\tau^{2\to1} + \theta_1\tau^{1\to2}) + \frac{1}{48}\phi_4$$

$$NP_3^{III} = \frac{1}{8}\Big[(\theta_1\tau^{1\to3} - \theta_3\tau^{3\to1}) + (\theta_2\tau^{2\to3} - \theta_3\tau^{3\to2}) + (\theta_4\tau^{4\to3} - \theta_3\tau^{3\to4})\Big] - \frac{1}{12}(\theta_1\tau^{1\to2} + \theta_2\tau^{2\to1}) - \frac{1}{16}\phi_4$$

$$NP_4^{III} = \frac{1}{8}\Big[(\theta_1\tau^{1\to4} - \theta_4\tau^{4\to1}) + (\theta_2\tau^{2\to4} - \theta_4\tau^{4\to2}) + (\theta_3\tau^{3\to4} - \theta_4\tau^{4\to3})\Big] + \frac{1}{96}\Big[(\theta_1\tau^{1\to4} + \theta_4\tau^{4\to1}) + (\theta_2\tau^{2\to4} + \theta_4\tau^{4\to2}) - (\psi_4 - \phi_4)\Big].$$

where $\phi_4 \equiv \min\{\theta_1\tau^{1\to4} + \theta_4\tau^{4\to1},\ \theta_2\tau^{2\to4} + \theta_4\tau^{4\to2}\}$

and $\psi_4 \equiv \max\{\theta_1\tau^{1\to4} + \theta_4\tau^{4\to1},\ \theta_2\tau^{2\to4} + \theta_4\tau^{4\to2}\}$

Network 2's net payment is symmetric to network 1's. At first glance this result may

look somewhat against the intuition; the supply of transit service becomes more competitive compared to the monopoly case, and yet the purchasers pay more premium than in the monopoly case. In order to understand this seemingly unintuitive result, let us think of network 4 as another purchaser of transit service, for the moment, just like 1 and 2. From network 1's point of view interconnection to the hub is more valuable than before network 4 joins the market. The premium would have been $(1/24)(\theta_2\tau^{2\to 1} + \theta_1\tau^{1\to 2} + \theta_4\tau^{4\to 1} + \theta_1\tau^{1\to 4})$ instead and similarly for 2 and 4. But, luckily enough network 4 comes with its own interconnecting facilities. At least one of the customers could go to 4 instead of 3. So the premium gets discounted, especially for the traffic between 4 and the other purchasers, from 1/24 to 1/48 (compared to equation (8)). Suppose again that $\theta_1\tau^{1\to 4} + \theta_4\tau^{4\to 1} < \theta_2\tau^{2\to 4} + \theta_4\tau^{4\to 2}$ so that ϕ_4 = the quality adjusted total traffic between 1 and 4. Then network 1' premium will be

$$\frac{1}{24}(\theta_2\tau^{2\to 1} + \theta_1\tau^{1\to 2}) + \frac{1}{48}(\theta_4\tau^{4\to 1} + \theta_1\tau^{1\to 4}).$$

As for network 2 the premium will be

$$\frac{1}{24}(\theta_2\tau^{2\to 1} + \theta_1\tau^{1\to 2}) + \frac{1}{48}(\theta_4\tau^{4\to 2} + \theta_2\tau^{2\to 4}) - \frac{1}{48}(\theta_4\tau^{4\to 2} + \theta_2\tau^{2\to 4} - \phi_4).$$

The last term represents the exemption explained in case II.

Naturally network 4 gets the highest discount (from 1/24 to 1/96). Network 4 pays some premium rather than collects some, hence in a sense it is not a hub. It is natural

because 4's hub facility is redundant from the grand coalition's view point. Although it is redundant from the grand coalition's point of view, it is still quite useful from 4's view point because it provides a stronger bargaining position.

Comparing Cases I, II, and III, we can think of a two stage dynamic model of investment in interconnecting facilities. At the initial stage, the global backbone providers would have expected shortage; if no one makes investment the situation would be like in Case II in say 10 years. With no one investing all firms could have make a lot of profit (Case II). But if no other firms are investing, any single firm can make money by investing (like network 3 in Case III). Or maybe more realistically, if others are investing, I want to invest as well to avoid being network 4 in Case III, paying premium rather than collecting it. As a result everyone invests, and we have Case I, low premium or excessive capacity.[6] Figure 4 describes the overall game matrix. (Actual payoffs are replaced by symbols for simplicity.)

Figure 4

Investment game matrix.

		Hub 4	
		Not invest	Invest
Hub 3	Not invest	++, ++	–, +++
	Invest	+++, –	+, +

4 The Occurrence of Peering

[6] Here we mean excess capacity in comparison with the globally efficient level.

In the previous subsection we excluded the possibility of interconnection between networks 1 and 2 bypassing the hub. In some sense this assumption reflects the fact that the costs are practically prohibiting to connect all the networks bilaterally. In this section we introduce the possibility of peering arrangement with some (construction) cost, F. First, for simplicity we consider one hub, two transit purchaser case as in section 3. (Hub network is denoted as 0.) We replace the equation $v(1,2) = v(1) + v(2)$ by the following.

$$v(1,2) = \bar{v}(1,2) - F = \sum_{i \in \{1,2\}} TS_i^{\{1,2\}} - F \tag{9}$$

One can easily check that

$$v(1,2) > v(1) + v(2) \quad \text{if and only if} \quad \frac{1}{8}(\alpha_{12} n_1 \theta_2^2 + \alpha_{21} n_2 \theta_1^2) > F \ .^{7}$$

We assume that this condition holds. Otherwise we are back to the no peering case. Each network's Shapley value can now be recalculated using (9). We can then recalculate the net payments using the new Shapley values;

$$NP_1 = \frac{1}{8}[(\theta_0 \tau^{0 \to 1} - \theta_1 \tau^{1 \to 0}) + (\theta_2 \tau^{2 \to 1} - \theta_1 \tau^{1 \to 2})] + \frac{F}{6},$$
$$NP_2 = \frac{1}{8}[(\theta_0 \tau^{0 \to 2} - \theta_2 \tau^{2 \to 0}) + (\theta_1 \tau^{1 \to 2} - \theta_2 \tau^{2 \to 1})] + \frac{F}{6}.$$

[7] This is equivalent to $(1/24)(\theta_1 \tau^{1 \to 2} + \theta_2 \tau^{2 \to 1}) > (F/6)$.

Notice that the premium is smaller compared to the case where $v(1,2) = v(1) + v(2)$ (no peering) and it is proportional to the peering cost. In the extreme case, there will be no premium if peering is costless ($F = 0$). Hence, we obtain the following.

Proposition 3. If peering generates more benefit to the interconnecting networks than the construction cost, the premium to the hub network is reduced. The smaller is the peering cost, the smaller the premium becomes. There will be no premium if peering is costless.

The premium becomes smaller as the construction cost becomes smaller, even if peering actually does not take place. The mere presence of (low cost) peering possibility can actually lower the premium through changes in bargaining power.

In view of this result we can explain the occurrence of peering as a result of rigidity in transit pricing. In order to introduce more reality we consider one hub, three transit purchaser case now. Hub is denoted as 0 and the transit purchasers as 1, 2, and 3. In the beginning suppose that the construction costs are too high compared to the traffic. That is, we assume that $(1/8)(\alpha_{ij} n_i \theta_j^2 + \alpha_{ji} n_j \theta_i^2) < F$, for $i, j = 1,2,3$, $i \neq j$. In this case the net payments are

$$NP_1^{IV} = \frac{1}{8}\left[(\theta_0 \tau^{0\to 1} - \theta_1 \tau^{1\to 0}) + (\theta_2 \tau^{2\to 1} - \theta_1 \tau^{1\to 2}) + (\theta_3 \tau^{3\to 1} - \theta_1 \tau^{1\to 3})\right]$$
$$+ \frac{1}{24}\left[(\theta_1 \tau^{1\to 2} + \theta_2 \tau^{2\to 1}) + (\theta_1 \tau^{1\to 3} + \theta_3 \tau^{3\to 1})\right].$$

$$NP_2^{IV} = \frac{1}{8}\left[(\theta_0\tau^{0\to 2} - \theta_2\tau^{2\to 0}) + (\theta_1\tau^{1\to 2} - \theta_2\tau^{2\to 1}) + (\theta_3\tau^{3\to 2} - \theta_2\tau^{2\to 3})\right]$$
$$+ \frac{1}{24}\left[(\theta_1\tau^{1\to 2} + \theta_2\tau^{2\to 1}) + (\theta_2\tau^{2\to 3} + \theta_3\tau^{3\to 2})\right].$$

$$NP_3^{IV} = \frac{1}{8}\left[(\theta_0\tau^{0\to 3} - \theta_3\tau^{3\to 0}) + (\theta_1\tau^{1\to 3} - \theta_3\tau^{3\to 1}) + (\theta_2\tau^{2\to 3} - \theta_3\tau^{3\to 2})\right]$$
$$+ \frac{1}{24}\left[(\theta_1\tau^{1\to 3} + \theta_3\tau^{3\to 1}) + (\theta_2\tau^{2\to 3} + \theta_3\tau^{3\to 2})\right].$$

Suppose that the net traffic between any two networks are close to 0 and qualities are similar ($\theta_i = \theta$, $i = 0,1,2,3$) so that the hub charges transit price proportional to total traffic among the transit purchasers. For example the hub charges network 1 the price

$$NP_1 = \frac{\theta}{24}\left[(\tau^{1\to 2} + \tau^{2\to 1}) + (\tau^{1\to 3} + \tau^{3\to 1})\right].$$

Suppose the situation has been changed so that now $(\theta/24)(\tau^{1\to 2} + \tau^{2\to 1}) > (F/2)$. This can happen because the traffic between 1 and 2 increases or because the technological progress reduces the construction cost in addition to some geographical reasons or both. But suppose the way transits are priced does not change for some reason.[8] Then it would be better for networks 1 and 2 to bypass the hub by peering their networks.

5 Concluding Comments

The paper examines how the Internet networks are interconnected through switching

[8] There are many transit purchasers. Reducing the rate for some country may cause problems with other countries. It would also be difficult to price discriminate based on the source of traffic.

hubs. Assuming that the location of global switching hubs is historically determined through the evolution of Internet traffic over time in the past decade, the paper focuses more on the contractual arrangements among the networks that are likely to shape the global backbone industry.

The main theoretical tool for the analysis of bargaining arrangements among networks is the Shapley value which is regarded as an outcome of the fundamental forces underlying the bargaining procedure among various players. The paper starts from the monopoly model of the hub and examines various modes of competition such as between the sufficiently large hubs, and between large backbone and smaller hub that may be regarded as a late comer, either on a global or local scale. The paper shows that the backbone industry is likely to stay in excess capacity equilibrium and offers some explanation for industry-wide financial turmoil.

It is now well recognized that contrary to initial optimism that prevailed in the late 1990s when the global hubs emerged, the industry had suffered from excess capacity and underwent severe structural change. The phenomenal growth of Internet traffic around the world in the recent times failed to justify aggressive move toward heavy investment in Internet infrastructure. The trend certainly stimulated down-stream industries for digital content, and ushered new telecom services such as VoIP that will eventually threaten traditional services. In the short-run, the telecom industry as a whole is likely to suffer from severe price competition and resulting lack of investment incentives for infrastructure. In the long-run, the industry needs a new wave of technological progress that will boost global demand for digital content.

One shortcoming of the main model of the paper is that efficiency is always taken for granted. In reality various sorts of rigidity and inefficiency are often encountered. Hence, it has to be used with much precaution. The paper examined one case where some sort of rigidity leads to failure of efficient bargaining and tries to explain bypassing possibility that arise from increasing local traffic and progress in network technology. Complete analysis of more specific situations however would require a non-cooperative multi-lateral bargaining theory, which is yet to be fully developed in the future.

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Appendix: A Brief Overview of Korean Experience

Korean experience provides insights into the entry barrier and the role of the switching

hubs of backbone providers in the United States. Although Korea has the largest number of Internet subscribers per 100 inhabitants among OECD countries in 2000, the number of Internet hosts and Websites fell much below OECD average.

Table A1

Comparison between OECD and Korea

	Korea	OECD Average
Internet subscribers per 100 inhabitants (2001/06)	23.2	10.9
Websites per 1000 inhabitants (2000/06)	6.7	17.5
Hosts per 1000 inhabitants (2001/06)	11.07	100.6

Sources: www.oecd.org

Until recently the inbound traffic for Korea from the United States had exceeded outbound traffic, and given the small size of the Internet network relative to the US backbone, bargaining asymmetry between the two countries persisted for a while. The question is whether the initial disadvantage of bargaining power caused by the negative traffic balance will continue even after Korea has managed to send more traffic abroad than inbound traffic.

In the year 2003, KT (formerly Korea Telecom) has secured traffic capacity of 6 Gbps through transit contract with Tier-1 US backbone providers, and 2.6 Gbps through peering contract with Tier-2 US providers and 3.4 Gbps through peering with Asian providers. KT has also taken advantage of multi-homing strategy adopted by the popular US content providers and established direct connectivity to the portal site such as “Yahoo!”. Despite recent improvement of net traffic balance, Korea Telecom pays substantial fee to the switching hubs in the US.

Table A2

Peak-time Internet traffic of KT

		2003/05	2003/08	2003/11	2004/02	2004/04
Transit (USA)	Capacity	6	8	8	9	9
	Outbound traffic	4.5	5.2	5.2	6.8	6.3
	Inbound traffic	3	2.6	2.7	2.8	2.9
Peering (USA)	Capacity	2.6	3.7	5.7	5.7	5.7
	Outbound traffic	0.6	1.2	1.1	1.5	1.5
	Inbound traffic	1.5	0.5	1.5	1.7	1.1
Peering (Asia)	Capacity	3.4	3.2	3.5	4.2	4.2
	Outbound traffic	2.6	2.1	2.4	3	3.2
	Inbound traffic	1.6	1.2	1.5	1.5	1.5

Source: unpublished data of KT

According to Table A2, the outbound traffic from Korea to the United States is greater than the inbound traffic in transit contracts. The traffic balance is also positive against the neighboring Asian countries that are connected through peering contracts. However KT has paid to global backbones in the United States despite positive traffic balance between two countries. The paper shows that what matters most must not be the simple physical volume of traffic but quality adjusted volume of traffic. Also the traffic between Korea and European countries that are also connected to the US global backbones is not accounted here. KT may have to pay rent to switching hub in the United States.

The cause for the reversal of the traffic balance in the year 2003 is not clear. As one can see in Table A3, P2P traffic is growing rapidly in outbound traffic. One may interpret this as traffic caused by the increasing foreign demand for games and other

entertainment contents.

Table A3

Traffic share (as of January, 2003)

Type	P2P	www	Win media	Others*
Outbound traffic	34 %	9.4 %	2.1 %	54.5 %
Inbound traffic	25.8 %	25.4 %	5.7 %	43.1 %

Source: unpublished data of KT, *: mail, FTP etc.

Chang-Ho Yoon
Department of Economics, Korea University,
Anam-Dong 5-1, Sungbuk-Ku, Seoul, 136-701, Korea
E-mail: chyoon@korea.ac.kr

Young-Woong Song
Information Communication Technology Research Office,
SK Research Institute for SUPEX Management,
Seorin-Dong 99, jongro-Ku, Seoul, 110-110, Korea
E-mail: ywsong@sktelecom.com

Byoung Heon Jun
Korea University,
Anam-Dong 5-1, Sungbuk-Ku, Seoul, 136-701, Korea
and
Institute of Economic Research, Hitotsubashi University
2-1 Naka Kunitachi Tokyo, Japan
E-mail: bhjun@korea.ac.kr