The Implication of Overlay Routing on ISPs' Connecting Strategies

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***Abstract*—The Internet is composed of many distinct networks, operated by independent Internet Service Providers (ISPs). There are primarily two kinds of relationships between ISPs: transit and peering. ISPs' traffic and economic relationships are mainly decided by ISPs' routing policy. However, in today's Internet, overlay routing, which changes traffic routing at the application layer to better satisfy the applications' demands, is rapidly increasing, and brings challenge to the ISPs' settlement interconnection researches. The goal of this paper is to study the economic implications of overlay routing on ISPs' peering incentive, costs and strategy choice. For this purpose, we introduce an ISP interconnection business model based on a simple ISPs' network. We then study the overlay traffic patterns in the network in various conditions. Combining the business model with traffic patterns, we study the ISPs' economic issues such as incentive to upgrade peering link and cost reduction conditions with various overlay traffic patterns and settlement methods. AT last, we analyze the bilateral Nash equilibrium (BNE) strategy of ISPs in the network. We also give some numerical examples to explain our results.**

I. Introduction

The Internet is composed of many distinct networks, operated by independent Internet Service Providers (ISPs). There are primarily two kinds of relationships between ISPs: transit and peering [1]. In transit relationship, a traffic-originating provider pays a transit provider for the traffic destined to outside the originator's local network. On the other hand, in a peering relationship, only traffic between the two peering ISPs and their respective customer ISPs can be exchanged on the peering link. Such traffic exchange on a peering link helps both peering ISPs to reduce the dependence on their transit providers for transit service, and thus save monetary cost. In today's Internet, peering relationships are mostly "Bill-and-Keep (BK)" [2] due to ease of implementation. In this arrangement, the peering providers do not charge each other for the traffic on the peering links. There are also kinds of paid peering relationships depending on ISPs' agreement [3] [4].

Various aspects of ISPs peering settlement have been analyzed in the literature of [3], [5]–[7]. The authors in [5] are the first to analyze ISP peering in depth from an economic perspective. It analyzes the impact of symmetric access charge on strategies of the providers and shows that operators set prices for their customers as if their customers' traffic were entirely off-net. The authors in [6] extend the model in [5] to include the fact that ISPs are geographically located. It thus analyzes the local ISP interactions separately from the local and transit ISP interactions. The authors in [7] use a different model of symmetric ISP peering. It focuses on the equilibrium of early exit routing and late exit routing, and gives the characteristics of the Nash equilibrium [8] and corresponding conditions. The authors in [3] use a more general asymmetric peering network, and look at how ISPs could charge each other in response to the externalities caused by their traffic strategies.

All the above researches are based on the policy routing with focuses on business considerations and do not consider the performance of the networks and services for subscribers and their applications. However, in today's Internet, overlay application, which changes traffic routing at the application layer to better satisfy the applications' demands, is rapidly increasing, and brings challenge to the ISPs' settlement interconnection research. [9] is the first paper to study the impact of the application layer routing of P2P applications on ISPs' peering and provisioning strategies. It proposes simple models to represent P2P traffic demands, peering and routing in a market place of two competing ISPs, and investigates alternative peering and provisioning strategies available to ISPs and analyzes their effectiveness. The authors in [10] extend [9] to include more general P2P traffic models and the subscribers' choice process. It builds a multi-leader-follower game-theory model of subscribers choosing ISPs, and the ISPs' making provisioning and peering decisions. [9] and [10] both focus on P2P applications. Today's ISPs can take various kinds of P2P localized technologies such as P2P caching [11] and P4P [12] to reduce the inter-ISP P2P traffic, so that the impact of P2P applications on ISPs' economic can be significantly reduced. However, ISPs have not got effective methods to manage another important kind of overlay application: overlay routing traffic. [13] first studies the tussle between overlay routing applications and ISPs' monetary profits, and discusses the guidelines for overlay routing applications to select paths that are more effective while with less negative effects on ISPs' profits.

In this paper we also focus on the interaction of ISPs' profit

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and overlay routing applications, while it is from the viewpoint of ISPs interconnection strategies and economic issues. In the present paper, we assume a typical ISPs interconnection scenario with two ISPs and an abstracted transit service provider. As we focus on ISPs' economic issues, we introduce an ISP cost model composed of the monetary cost and link latency cost. For monetary cost, linear pricing scheme is assumed in both transit service and paid peering agreement. For latency cost, a general convex, increasing and continuous link latency function is assumed to be used. As the ISPs' costs are closely relative to the inter-ISP traffic pattern, we then study the inter-ISP traffic patterns in Nash equilibrium with various peering link capacities. The traffic in our network is composed of non-overlay routing traffic and overlay routing traffic. Non-overlay routing traffic is transmitted in accordance with policy routing, while all the overlay routing flows play a selfish routing game. We assume the overlay routing applications are latency sensitive, and are willing to take the paths with the least link latency. We find three traffic patterns in Nash equilibrium exist. Corresponding to each traffic pattern, we identify the peering link capacity as low level, medium level and high level, and show that different ISPs with different peering agreements have different preferences to each level. With BK peering, the ISP which free-rides the other prefers medium and high level peering, while the ISP being free-ridden prefers only peering of medium level. With paid peering, both ISPs show similar preference to low level and medium level peering. Based on the results above, we also analyze bilateral Nash equilibrium (BNE) [14] strategies for the two ISPs. The strategy space includes no peering, BK peering and paid peering by Nash bargaining [15], and we give the conditions in which certain strategy is in BNE.

Our work is different from [3], [5]–[7], because they focus on ISPs economic problems based on policy routing, while we build different ISPs business model and introduce overlay routing traffic into it. It is different from [9] and [10], because their focuses are on P2P applications, while ours is on overlay routing traffic. This paper is also different from [13], because it is from the viewpoint of overlay routing applications, and give guidelines on overlay protocol design, while our work is a research from the viewpoint of ISPs' connecting strategy choices.

The paper is organized as follows. Section 2 builds ISP network and business models. Section 3 studies the traffic pattern under the network model. Section 4 analyzes the economic issues of ISPs peering connection influenced by overlay routing traffic. Section 5 makes conclusion and offers an outlook on the future work.

II. Network and business models

We consider a network as shown in Figure 1. ISP_A and ISP_B are two ISPs connecting with each other through a peering link of capacity c_{AB}. R represents the rest of the Internet, and both ISP_A and ISP_B have a connection with R of capacity c_{AR} and c_{BR}. Subscribers of both ISPs may have traffic demand between each other as well as the rest of the Internet. As we focus on inter-ISP traffic in the paper, the intra-ISP demand is not considered. The traffic is composed of non-overlay routing and overlay routing traffic. The overlay routing traffic takes ratio ρ to the total traffic amount. For example, given the traffic with source-destination pair in ISP_A and ISP_B as t_{AB}, then overlay routing traffic is ρt_{AB}. Non-overlay routing traffic is transmitted with policy routing, while overlay routing traffic is performance sensitive and user-directed, and chooses routes by itself. Overlay routing applications can get better performance by choosing multi-hop paths to avoid the bottleneck link. In this paper, the multi-hop overlay traffic is denoted as t^o_{ijk} ($i, j, k \in \{A, B, R\}$, $i \neq j \neq k$). We assume overlay routing traffic takes latency as performance criterion as in general cases, and overlay routing prefers the routes with the least latency. As the existence of overlay routing, the actual traffic on link l_{ij} may not equal t_{ij}, we denote it as $\tilde{t}_{ij}$. A general link latency function $D_{ij}(c_{ij}, \tilde{t}_{ij})$ is used to denote the latency of link l_{ij}, c_{ij} is link capacity and $\tilde{t}_{ij}$ is actual traffic on the link. We assume $D_{ij}(c_{ij}, \tilde{t}_{ij})$ is continuous and twice differentiable, and also with the following properties: $\frac{\partial D_{ij}(c_{ij},\tilde{t}_{ij})}{\partial \tilde{t}_{ij}} > 0$, $\frac{\partial D_{ij}(c_{ij},\tilde{t}_{ij})}{\partial c_{ij}} < 0$, and $\frac{\partial^2 D_{ij}(c_{ij},\tilde{t}_{ij})}{\partial^2 \tilde{t}_{ij}} > 0$. The latency is assumed the same of both directions of traffic. Without loss of generality, we assume that

$$D_{AR}(c_{AR}, t_{AR}) > D_{BR}(c_{BR}, t_{BR}). \quad (1)$$

The results for the case $D_{AR}(c_{AR}, t_{AR}) < D_{BR}(c_{BR}, t_{BR})$ is similar, with the ISPs swapping roles. We note that the case $D_{AR}(c_{AR}, t_{AR}) = D_{BR}(c_{BR}, t_{BR})$ is not interesting, since in this case it can be verified that no free-riding happens. In this paper, we assume t_{ij}, c_{AR} and c_{BR} are fixed, and study the effect of various c_{AB}.

An ISP's cost is composed of monetary cost and performance cost. In order to access the Internet, ISPs have to pay higher tier ISPs for transit service. We assume linear pricing scheme is used, then ISP_A is charged P_A for per unit of traffic transmitting, and ISP_B is charged P_B for per unit of traffic transmitting. If paid peering agreement is reached, a linear peering price p_{AB} is also assumed to be used. $p_{AB} > 0$ implies ISP_A pays ISP_B, while $p_{AB} < 0$ implies ISP_A charges ISP_B. Particularly, $p_{AB} = 0$ implies BK peering agreement

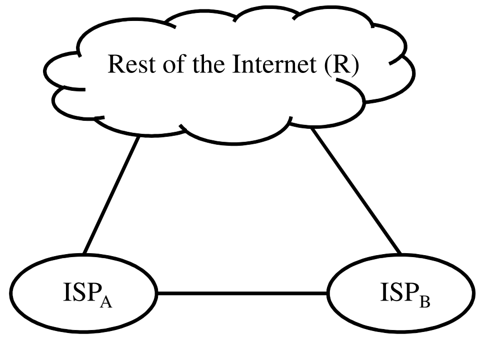


Fig. 1. Network model

is in use, and no money exchange between each other. Besides monetary cost, ISPs also suffer from link latency. We use ISPs' latency cost as the product of link latency and traffic on the link as in [16], and then the ISPs' costs with paid peering can be denoted as

$$\begin{aligned} J_A^{PP} &= \lambda(\tilde{t}_{AR} D_{AR}(\tilde{t}_{AR}) + \alpha \tilde{t}_{AB} D_{AB}(\tilde{t}_{AB})) \\ &\quad + (P_A \tilde{t}_{AR} + p_{AB} \tilde{t}_{AB}) \\ J_B^{PP} &= \lambda(\tilde{t}_{BR} D_{BR}(\tilde{t}_{BR}) + (1-\alpha) \tilde{t}_{AB} D_{AB}(\tilde{t}_{AB})) \\ &\quad + (P_B \tilde{t}_{BR} - p_{AB} \tilde{t}_{AB}). \end{aligned} \tag{2}$$

The first term is latency cost of transit link, the second term is latency cost of peering link, and the third term is monetary cost of transit and peering. The variable $\lambda > 0$ translates the latency cost into an appropriate monetary value. As ISP_A and ISP_B share the same peering link, and the latency of peering link is experienced by both users of the two ISPs, so that the latency cost of peering link is also shared by the two ISPs. We use α ($0 < \alpha < 1$) to measure the ratio of ISP_A's share, and $(1-\alpha)$ to measure ISP_B's share. If $p_{AB} = 0$, it implies that BK peering is used, and the ISPs' costs are

$$\begin{aligned} J_A^{BK} &= \lambda(\tilde{t}_{AR} D_{AR}(\tilde{t}_{AR}) + \alpha \tilde{t}_{AB} D_{AB}(\tilde{t}_{AB})) + P_A \tilde{t}_{AR} \\ J_B^{BK} &= \lambda(\tilde{t}_{BR} D_{BR}(\tilde{t}_{BR}) + (1-\alpha) \tilde{t}_{AB} D_{AB}(\tilde{t}_{AB})) + P_B \tilde{t}_{BR}. \end{aligned} \tag{3}$$

Analogously, we define the cost functions without peering as

$$\begin{aligned} J_A^{NP} &= \lambda(t_{AR} + t_{AB}) D_{AR}(t_{AR} + t_{AB}) + P_A(t_{AR} + t_{AB}) \\ J_B^{NP} &= \lambda(t_{BR} + t_{AB}) D_{BR}(t_{BR} + t_{AB}) + P_B(t_{BR} + t_{AB}). \end{aligned} \tag{4}$$

Sometimes it is useful to consider the total cost of the two ISPs. We denote the total cost of paid peering, BK peering and no peering as

$$\begin{aligned} J_{total}^{PP} &= J_{total}^{BK} = J_A^{BK} + J_B^{BK} \\ J_{total}^{NP} &= J_A^{NP} + J_B^{NP}. \end{aligned} \tag{5}$$

In order to reach paid peering agreement, ISPs have to negotiate to decide c_{AB} and corresponding p_{AB}. We suppose Nash bargaining solution is used for the negotiation. Nash bargaining is widely used for characterizing labor negotiations and a range of other bargaining situations. Bargaining power can be impacted by many factors. In this paper, we take α as the bargaining power of ISP_A, and $(1-\alpha)$ as the bargaining power of ISP_B, because the ISP who takes more cost of the peering link should also benefit more from it. The costs without peering are supposed as the breaking point of agreement. The optimal problem by Nash bargaining can be formulated as

$$\min \left(J_A^{NP} - J_A^{PP}\right)^{\alpha} \left(J_B^{NP} - J_B^{PP}\right)^{1-\alpha}.$$

We can transform it into an equivalent problem by taking the logarithm of the objective function. We then get the following equivalent problem

$$\min \left(\alpha \ln(J_A^{NP} - J_A^{PP}) + (1-\alpha) \ln(J_B^{NP} - J_B^{PP})\right).$$

The first order condition is

$$\frac{\partial \left(\alpha \ln(J_A^{NP} - J_A^{PP}) + (1-\alpha) \ln(J_B^{NP} - J_B^{PP})\right)}{\partial p_{AB}} = 0,$$

and the Nash solution is

$$p_{AB}^{Nash} = (1-\alpha)(J_A^{NP} - J_A^{BK}) - \alpha(J_B^{NP} - J_B^{BK}), \tag{6}$$

substituting (6) into (2), and we get the ISPs' costs determined by Nash bargaining as

$$\begin{aligned} J_A^{PP} &= (1-\alpha) J_A^{NP} - \alpha J_B^{NP} + \alpha(J_A^{BK} + J_B^{BK}) \\ J_B^{PP} &= \alpha(J_B^{NP} - (1-\alpha) J_A^{NP} + (1-\alpha)(J_A^{BK} + J_B^{BK}). \end{aligned} \tag{7}$$

We can see that paid peering provides a cost re-allocation mechanism for peering ISPs, while it cannot lead to additional cost reduction for the total welfare.

III. Traffic model with overlay routing

It is shown in the business model that ISPs' costs are closely related to traffic model. In this section, we study the traffic patterns composed of overlay routing and non-overlay routing in the network as in Figure 1. Non-overlay routing traffic is routed with policy routing strategy. In our model, traffic with source i and destination j ($i, j \in \{A, B, R\}$, $i \neq j$) is routed through the directed path l_{ij}, while overlay routing traffic generated by all overlay users are playing a non-atomic selfish routing game [17]. In this game, each unit of overlay routing traffic flow travels along the minimum-latency path available to it, where latency is measured with respect to the rest of the flow; otherwise, this flow would reroute itself on a path with smaller latency. In other words, all paths in use by an equilibrium flow have minimum-possible cost. In particular, all paths of a given commodity used by an equilibrium flow have equal latency. In our model, there are only three links, so we are able to analyze all the cases of overlay routing traffic patterns explicitly.

First, suppose at certain time, latencies of the three links are as follows:

$$D_{AR}(\tilde{t}_{AR}) + D_{BR}(\tilde{t}_{BR}) < D_{AB}(c_{AB}, \tilde{t}_{AB}),$$

which happens when c_{AB} is too small that the latency of path $A \leftrightarrow R \leftrightarrow B$ is less than path $A \leftrightarrow B$. Then overlay routing traffic with source-destination pair in ISP_A and ISP_B would choose the multi-hop path for better performance. Such process will continue until the latencies of the two paths become equal, or all the overlay routing traffic with source-destination pair in ISP_A and ISP_B has chosen path $A \leftrightarrow R \leftrightarrow B$. Then we have such situation:

$$D_{AR}(\tilde{t}_{AR}) + D_{BR}(\tilde{t}_{BR}) \leq D_{AB}(c_{AB}, \tilde{t}_{AB}). \tag{8}$$

Note that, given (8), we can also have

$$\begin{aligned} D_{AR}(\tilde{t}_{AR}) &< D_{BR}(\tilde{t}_{BR}) + D_{AB}(c_{AB}, \tilde{t}_{AB}) \\ D_{BR}(\tilde{t}_{BR}) &< D_{AR}(\tilde{t}_{AR}) + D_{AB}(c_{AB}, \tilde{t}_{AB}), \end{aligned} \tag{9}$$

which suggests that $t_{ABR}^o = t_{BAR}^o = 0$, and it is a traffic pattern of Nash equilibrium. Note that a peering link with too samll capacity will cause serious congestion status, so that it is not feasible in practice. Also, in order to make the analysis mathematical tractable, we set a lower bound for c_{AB} as the value that makes (8) an equation, and denote it as c_1^l. Then the properties of this pattern can be summarized as follows:

$$
\begin{aligned}
D_{AB}(c_{AB}, \tilde{t}_{AB}) &= D_{AR}(\tilde{t}_{AR}) + D_{BR}(\tilde{t}_{BR}) \\
\tilde{t}_{AR} &= t_{AR} + t^o_{ARB} \\
\tilde{t}_{BR} &= t_{BR} + t^o_{ARB} \\
\tilde{t}_{AB} &= t_{AB} - t^o_{ARB} \\
t^o_{ABR} &= t^o_{BAR} = 0, 0 \le t^o_{ARB} \le \rho t_{AB}.
\end{aligned} \tag{10}
$$

(10) suggests that given transit link capacities and latency functions, t^o_{ARB} is determined only by c_{AB}. So t^o_{ARB} can be seen as a function of c_{AB}, and it is decreasing with respect to c_{AB}. We denote the upper bound of c_{AB} that allows (10) to hold as c_1^h.

Next we discuss the situation when c_{AB} increases to certain value that makes

$$
\begin{aligned}
D_{AB}(c_{AB}, \tilde{t}_{AB}) &< D_{AR}(\tilde{t}_{AR}) + D_{BR}(\tilde{t}_{BR}) \\
D_{AB}(c_{AB}, \tilde{t}_{AB}) &> \left| D_{AR}(\tilde{t}_{AR}) - D_{BR}(\tilde{t}_{BR}) \right|.
\end{aligned} \tag{11}
$$

In this case no multi-hop overlay routing traffic exists. With the assumption $D_{AR}(t_{AR}) > D_{BR}(t_{BR})$, we can summarize the properties of this pattern as

$$
\begin{aligned}
D_{AR}(\tilde{t}_{AR}) - D_{BR}(\tilde{t}_{BR}) &< D_{AB}(c_{AB}, \tilde{t}_{AB}) \\
&< D_{AR}(\tilde{t}_{AR}) + D_{BR}(\tilde{t}_{BR}) \\
\tilde{t}_{AR} &= t_{AR} \\
\tilde{t}_{BR} &= t_{BR} \\
\tilde{t}_{AB} &= t_{AB} \\
t^o_{ABR} &= t^o_{BAR} = t^o_{ARB} = 0.
\end{aligned} \tag{12}
$$

We denote the lower bound and upper bound of c_{AB} that makes (12) hold as c_2^l and c_2^h, and note that $c_2^l = c_1^h$.

If c_{AB} continues increasing and exceeds c_2^h, then

$$
D_{AB}(c_2^h, t_{AB}) \le D_{AR}(t_{AR}) - D_{BR}(t_{BR}). \tag{13}
$$

If so, a portion of overlay routing traffic with source-destination pair in ISP_A and R will move to the path $A \leftrightarrow B \leftrightarrow R$ until the latencies of the two paths become equal, or all overlay routing traffic with source-destination pair in ISP_A and R have chosen the alternative multi-hop path. Note that c_{AB} can be increased infinitely in the theory, but it is not feasible in the practice. Also, as c_{AB} exceeds some very big value, the traffic pattern will become trivially complicated. In order to make the analysis practical and mathematical tractable, we set an upper bound for c_{AB} as a relatively large value that makes (13) an equation, and denote it as c_3^h. $t^o_{ABR}(c_3^h) \le \rho t_{AR}$. We also denote the lower bound of c_{AB} as c_3^l, and $c_3^l = c_2^h$. Then we summarize the properties of this pattern as follows:

$$
\begin{aligned}
D_{AB}(c_{AB}, \tilde{t}_{AB}) &= D_{AR}(\tilde{t}_{AR}) - D_{BR}(\tilde{t}_{BR}) \\
\tilde{t}_{AR} &= t_{AR} - t^o_{ABR} \\
\tilde{t}_{BR} &= t_{BR} + t^o_{ABR} \\
\tilde{t}_{AB} &= t_{AB} + t^o_{ABR} \\
t^o_{ARB} &= t^o_{BAR} = 0, 0 \le t^o_{ABR} \le \bar{t}^o_{ABR}.
\end{aligned} \tag{14}
$$

Note that ρt_{AR} may not be a tight upper bound of t^o_{ABR}. We denote the maximum of t^o_{ABR} as $\bar{t}^o_{ABR}$. The traffic traveling through the path $A \leftrightarrow B \leftrightarrow R$ is called free-riding traffic. ISP_A needs not pay for the transit service of the free-riding traffic, while ISP_B pays instead.

As in the three patterns discussed above, if the properties of two ISPs are given, the traffic patterns are independently determined by the peering link capacity. We identify the peering levels as low level, medium level and high level according to the three traffic patterns above. The peering level is an important factor for ISPs to make connecting decision.

IV. Economic issues on ISPs connecting

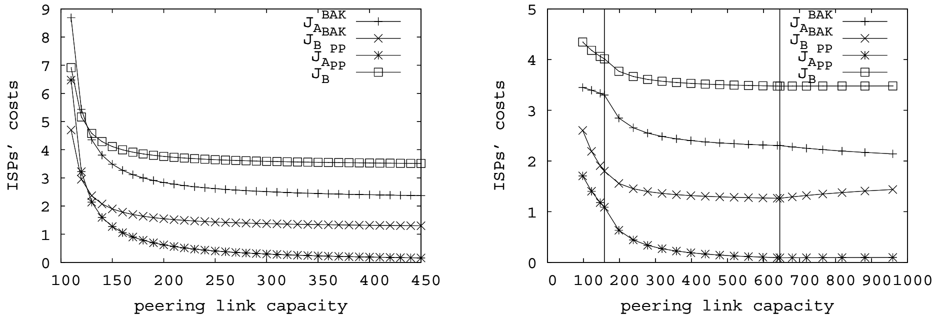
In this section, we combine the business model and the traffic patterns in the previous sections to obtain the ISPs' costs with different peering agreement and various peering capacities. First, we summarize the costs functions by combining (3), (10), (12) and (14) as follows:

$$
J_A^{BK} = \begin{cases}
\lambda((\tilde{t}_{AR} + \alpha \tilde{t}_{AB}) D_{AR} + \alpha \tilde{t}_{AB} D_{BR}) \\
+ P_A \tilde{t}_{AR}, \text{if } c_1^l \le c_{AB} \le c_1^h; \\
\lambda(t_{AR} D_{AR} + \alpha t_{AB} D_{AB}) + P_A t_{AR} \\
\text{else if } c_2^l < c_{AB} < c_2^h; \\
\lambda((\tilde{t}_{AR} + \alpha \tilde{t}_{AB}) D_{AR} - \alpha \tilde{t}_{AB} D_{BR}) \\
+ P_A \tilde{t}_{AR}, \text{else } c_3^l \le c_{AB} \le c_3^h;
\end{cases} \tag{15}
$$

$$
J_B^{BK} = \begin{cases}
\lambda((\tilde{t}_{BR} + (1-\alpha) \tilde{t}_{AB}) D_{BR} \\
+ (1-\alpha) \tilde{t}_{AB} D_{AR}) + P_B \tilde{t}_{BR}, \\
\text{if } c_1^l \le c_{AB} \le c_1^h; \\
\lambda(t_{BR} D_{BR} + (1-\alpha) t_{AB} D_{AB}) + P_B \tilde{t}_{BR}, \\
\text{else if } c_2^l < c_{AB} < c_2^h; \\
\lambda((\tilde{t}_{BR} - (1-\alpha) \tilde{t}_{AB}) D_{BR} \\
+ (1-\alpha) \tilde{t}_{AB} D_{AR}) + P_B \tilde{t}_{BR}, \\
\text{else } c_3^l \le c_{AB} \le c_3^h.
\end{cases} \tag{16}
$$

Costs of paid peering can be calculated from (7), (15) and (16).

We can see that all the cost functions with overlay routing traffic are of three-piece. Figure 2 shows two examples of ISPs' costs vs. peering link capacity with and without overlay routing traffic. In the examples, we assume two ISPs use the same latency model of M/M/1. For a M/M/1 queue, the latency can be expressed as $l(x) = \frac{1}{\mu - x} + prop$, where x is the traffic load, μ is the link capacity, and $prop$ is the propagation delay. This model satisfies all our assumptions of latency model. In the examples, we set $P_A = P_B = 0.0001$, $t_{AR} = 200$, $c_{AR} =$



(a) ρ = 0.0

(b) ρ = 0.5. The boundaries of different peering levels are indicated by the vertical lines.

Fig. 2. ISPs' costs

600, $t_{BR} = 150$, $c_{BR} = 300$, $t_{AB} = 100$. The propagation latencies are set as $prop_{AB} = prop_{BR} = 0.001$, $prop_{AR} = 0.008$. The bargaining power of ISP_A is $\alpha = 0.65$, $\lambda = 1$. In Figure 2(a), the ratio of overlay routing traffic is 0, and the ISPs' cost curves are smooth. In Figure 2(b), the ratio of overlay routing is 0.5, and the costs curve become three-piece curves corresponding to different peering levels. From the examples, we can see the significant impact of overlay routing on ISPs' cost functions.

A. *Incentives of upgrading peering link*

In this part, we assume that a peering link between ISP_A and ISP_B has been set up, and analyze the incentive of individual ISP to upgrade the peering link. We measure the incentive as derivative of cost to peering link capacity. If the derivative is negative, it indicates that ISP can reduce cost by increasing peering link capacity, and if the derivative is positive, it indicates that an ISP will suffer increases in cost by increasing peering link capacity. We have the following results:

Proposition 1: (1) ISP_A always has incentive to upgrade the peering link with BK peering when the peering level is medium or high.

(2) ISP_B always has incentive to upgrade the peering link with BK peering when the peering level is medium.

(3) Both ISPs always have incentive to upgrade the peering link with paid peering when the peering level is low or medium.

Proof: For ISP_A with BK peering, if the peering level is medium, from (15), we have

$$J_A^{BK'}(c_{AB}) = \lambda\alpha t_{AR} D'_{AB}(c_{AB}) < 0.$$

If the peering level is high, we can get from (14) that $\tilde{t}'_{AR}(c_{AB}) = -t^o_{ABR}{}'(c_{AB}) < 0$, $\tilde{t}'_{AB}(c_{AB}) = t^o_{ABR}{}'(c_{AB}) > 0$, $D'_{AR}(c_{AB}) = D'_{AR}(\tilde{t}_{AR})\tilde{t}'_{AR}(c_{AB}) < 0$, and $D'_{BR}(c_{AB}) = D'_{BR}(\tilde{t}_{BR})\tilde{t}'_{BR}(c_{AB}) > 0$. Substituting the results into $J_A^{BK'}(c_{AB})$ and we obtain $J_A^{BK'}(c_{AB}) < 0$. Also, as J_A^{BK} is continuous, we can say that ISP_A always has incentive to upgrade the peering link with BK peering when the peering level is medium or high.

For ISP_B with BK peering, if the peering level is medium, from (16), we have

$$J_B^{BK'}(c_{AB}) = \lambda\alpha t_{BR} D'_{AB}(c_{AB}) < 0.$$

So ISP_B always has incentive to upgrade the peering link with BK peering when the peering level is medium.

From (6), it is known that $\frac{\partial J_A^{PP}}{\partial c_{AB}} = \frac{\partial J_B^{PP}}{\partial c_{AB}} = \frac{\partial J_{total}^{BK}}{\partial c_{AB}}$. For J_{total}^{BK}, when peering level is low, we can get from (10) that $D'_{AR}(c_{AB}) = D'_{AR}(\tilde{t}_{AR})\tilde{t}'_{AR}(c_{AB}) < 0$ and $D'_{BR}(c_{AB}) = D'_{BR}(\tilde{t}_{BR})\tilde{t}'_{BR}(c_{AB}) < 0$. Substituting the results into $J_{total}^{BK'}(c_{AB})$, and we can have $J_{total}^{BK'}(c_{AB}) < 0$. If the peering level is medium, then $J_{total}^{BK'}(c_{AB}) = J_A^{BK'}(c_{AB}) + J_B^{BK'}(c_{AB}) < 0$. It indicates that both ISPs always have incentive to upgrade the peering link with paid peering when the peering level is low or medium. ■

In fact, for ISP_A with BK peering, if the peering is of low level, it is uncertain whether it is good to increase the peering link capacity. If the peering is of medium level, ISP_A can always reduce cost by increasing peering link capacity. If the peering is of high level, it can continue reducing the cost partly by free-riding ISP_B. For ISP_B with BK peering, if the peering is of low level, it is uncertain whether cost can be reduced by upgrade the peering link, which is just the same as ISP_A. If the peering is of medium level, ISP_B can reduce cost by increasing peering link capacity. If the peering is of high level, it is uncertain whether it is good to upgrade the peering link because of the free-riding effect by ISP_A. In the case of paid peering, both ISPs are with similar incentive on upgrading peering link. When the peering is of low level or medium level, they can both reduce cost by upgrading the peering link. But if the peering is of high level, it is uncertain whether it is good to upgrade the peering link. We can also conclude from the results above that free-riding is welcomed by the ISP who free-rides the other, while it is uncertain for the ISP being free-ridden. Also, free-riding might do harm to the total welfare of the two ISPs.

B. The conditions in which peering is better than no peering

If the cost of an ISP with certain peering agreement is less than the cost without peering, it is better for the ISP to reach peering agreement than no peering. Whether an ISP can reduce cost by peering is an important factor for the ISP to make connecting decision. Based on the upgrading incentive analysis we further study the conditions under which peering is better than no peering. We have the following results:

Proposition 2: (1) ISP_A can reduce cost with BK peering of any peering level, if the following condition holds

$$\max J_A^{BK}(c_{AB}) < J_A^{NP}, c_1^l \le c_{AB} \le c_1^h.$$

(2) ISP_B can reduce cost with BK peering of low and medium level, if the following condition holds

$$\max J_B^{BK}(c_{AB}) < J_B^{NP}, c_1^l \le c_{AB} \le c_1^h.$$

(3) Both ISP_A and ISP_B can reduce cost with paid peering of low and medium level.

Proof: As J_A^{BK} is continuous, it must have at least one maximum value when $c_{AB} \in [c_1^l, c_1^h]$. Denote the maximum value as $J_A^{BK}(c_A)$, we have $J_A^{BK}(c_A) \ge J_A^{BK}(c_1^h)$. As we have proved in Proposition 1 that $J_A^{BK}(c_{AB})$ is decreasing in $[c_2^l, c_3^h]$, and $c_1^h = c_2^l$, so $J_A^{BK}(c_A)$ is the maximum value in $[c_1^l, c_3^h]$. Then if $J_A^{BK}(c_A) < J_A^{NP}$, we have $J_A^{BK}(c_{AB}) < J_A^{NP}$ everywhere in $[c_1^l, c_3^h]$, which indicates ISP_A can reduce cost with BK peering of any peering level.

$J_B^{BK}(c_{AB})$ also has at least one maximum value in $[c_1^l, c_1^h]$ for the same reason as J_A^{BK}, and we denote it as $J_B^{BK}(c_B)$. Also $J_B^{BK}(c_B) \ge J_B^{BK}(c_1^h)$. As we have proved in Proposition 1 that $J_B^{BK}(c_{AB})$ is decreasing in $[c_2^l, c_2^h]$, and $c_1^h = c_2^l$, so $J_B^{BK}(c_B)$ is the maximum value in $[c_1^l, c_2^h]$. Then if $J_B^{BK}(c_B) < J_B^{NP}$, we have $J_B^{BK}(c_{AB}) < J_B^{NP}$ everywhere in $[c_1^l, c_2^h]$, which indicates that ISP_B can reduce cost with BK peering of low level and medium level.

In the case of paid peering, Nash bargaining solution gurantees that if $J_{total}^{PP} < J_{total}^{NP}$ (J_{total}^{PP}), then $J_A^{PP} < J_A^{NP}$ and $J_B^{PP} < J_B^{NP}$. For the total cost J_{total}^{BK}, if $c_{AB} \in [c_1^l, c_2^h]$, from (15) and (16), we have

$$\begin{aligned} J_{total}^{BK} &= \lambda((t_{AR}+t_{AB})D_{AR}(\tilde{t}_{AR}) \\ &\quad + (t_{BR}+t_{AB})D_{BR}(\tilde{t}_{BR})) \\ &\quad + P_A\tilde{t}_{AR} + P_B\tilde{t}_{BR} \\ &\le \lambda((t_{AR}+t_{AB})D_{AR}(t_{AR}+t_{AB}) \\ &\quad + (t_{BR}+t_{AB})D_{BR}(t_{BR}+t_{AB})) \\ &\quad + P_A(t_{AR}+t_{AB}) + P_B(t_{BR}+t_{AB}) \\ &= J_{total}^{NP}. \end{aligned}$$

Then it is proved that both ISPs can reduce cost with paid peering of low and medium level. ∎

We can see from the results above that the conditions in which individual ISP's cost can be reduced are closely dependent on the other ISP. If it is certain that ISP_A can reduce cost with BK peering of low level, then it can reduce more cost by upgrading to the medium level and high level. While for ISP_B, if it is certain to reduce cost with BK peering of low level, it can only guarantee that the cost can be further reduced in the medium level. The uncertainty of upgrading to high level is because of free-riding effect. With paid peering agreement, we have a different result that both ISPs can always be better with paid peering than no peering of both low level and medium level. However, the case with peering of high level is still in uncertainty.

TABLE I
GAME MATRIX

ISP_A/ISP_B	NP	BK	PP
NP	NP	NP	NP
BK	NP	BK	NP
PP	NP	NP	PP

C. Regime equilibria

In this part, we study the ISPs' connecting strategy choice directly with a simple game theoretic model. In this model, two ISPs have to choose among no peering, BK peering and paid peering strategies to make contract. The ISPs simultaneously announce the type of contractual agreement they intend to have. Define S_i, $i \in \{A, B\}$, as the strategy set of ISP_i, and $S_i = \{NP, BK, PP\}$. A strategy choice $s_i = BK$ indicates that ISP_i seeks a BK peering agreement. $s_i = PP$ indicates that ISP_i is interested in paid peering agreement. $s_i = NP$ indicates that ISP_i prefers no peering agreement. The outcomes of possible combinations of the decisions are give in Table I. A feasible contract requires consent of both ISPs, otherwise (NP, NP) is default output. To rule out any Pareto-inferior equilibrium, the paper uses the definition of BNE, which allows for coordinated two-person deviations. The formal definition follows:

Definition 1: A strategy profile $s^* = (s_i^*, s_j^*)$ is a BNE if the following conditions hold:

(1) for any $i \in N$, and every $s_i \in S_i, \pi_i(s_i^*, s_{-i}^*) \ge \pi_i(s_i, s_{-i}^*)$ and

(2) for $i, j \in N$, and every strategy pair (s_i^*, s_j^*) $\pi_i(s_i, s_j, s_{-i-j}^*) > \pi_i(s_i^*, s_j^*, s_{-i-j}^*) \Rightarrow \pi_j(s_i, s_j, s_{-i-j}^*) < \pi_j(s_i^*, s_j^*, s_{-i-j}^*)$

BNE suggests that at equilibrium, no player or a pair of players can deviate and benefit from the deviation. From this definition, we have the following results.

Proposition 3: (1) If $J_{total}^{BK} > J_{total}^{NP}$, (NP, NP) is the only strategy in BNE.

(2) If $J_{total}^{BK} < J_{total}^{NP}$, and $(J_A^{BK} - J_A^{NP})(J_B^{BK} - J_B^{NP}) > 0$, (BK, BK) and (PP, PP) are two strategies in BNE.

(3) If $J_{total}^{BK} < J_{total}^{NP}$, and $(J_A^{BK} - J_A^{NP})(J_B^{BK} - J_B^{NP}) < 0$, (PP, PP) is the only strategy in BNE.

Proof: (1) is straightforward because if $J_{total}^{BK} > J_{total}^{NP}$, there must be at least one ISP with more cost than no peering, and this ISP will never agree with BK agreement. Also, paid peering by Nash bargaining solution is meaningless in this case. If $J_{total}^{BK} < J_{total}^{NP}$, there are two possibilities as in (2) and (3). If both ISPs have less cost than no peering, then BK peering and paid peering by Nash bargaining are better

TABLE II
COST MATRIX 1

ISP_A/ISP_B	NP	BK	PP
NP	$(3.43, 5.28)$	$(3.43, 5.28)$	$(3.43, 5.28)$
BK	$(3.43, 5.28)$	$(3.44, 2.53)$	$(3.43, 5.28)$
PP	$(3.43, 5.28)$	$(3.43, 5.28)$	$(1.65, 4.31)$

TABLE III
COST MATRIX 2

ISP_A/ISP_B	NP	BK	PP
NP	$(3.43, 5.28)$	$(3.43, 5.28)$	$(3.43, 5.28)$
BK	$(3.43, 5.28)$	$(2.48, 1.36)$	$(3.43, 5.28)$
PP	$(3.43, 5.28)$	$(3.43, 5.28)$	$(0.27, 3.57$

TABLE IV
COST MATRIX 3

ISP_A/ISP_B	NP	BK	PP
NP	$(3.43, 5.28)$	$(3.43, 5.28)$	$(3.43, 5.28)$
BK	$(3.43, 5.28)$	$(2.22, 1.35)$	$(3.43, 5.28)$
PP	$(3.43, 5.28)$	$(3.43, 5.28)$	$(0.09, 3.48)$

TABLE V
COST MATRIX 4

ISP_A/ISP_B	NP	BK	PP
NP	$(5.60, 25.20)$	$(5.60, 25.20)$	$(5.60, 25.20)$
BK	$(5.60, 25.20)$	$(1.63, 29.99)$	$(5.60, 25.20)$
PP	$(5.60, 25.20)$	$(5.60, 25.20)$	–

off than no peering. If one ISP has less cost than no peering while the other ISP has more cost than no peering, BK can not be BNE because the ISP with more cost can never agree with a BK agreement. However, paid peering by Nash bargaining in this case can be better off than no peering, and it is the only strategy in BNE. ■

At last, we have the following corollary.

Corollary 1: Paid peering is always BNE if peering level is low or medium.

Proof: Combine the results in Proposition 3 and Proposition 2, it can be straightly proved. ■

By the analysis of the regime equilibria, we can find that if the peering level is low or medium, paid peering by Nash bargaining is always a strategy in BNE, while only in sometimes BK peering is strategy in BNE. No peering is never BNE. But if the peering level is high, too much uncertainties are caused by free-riding effect. If ISPs choose a high level peering relationship, they have to do calculation and bargaining process very carefully to avoid lost. Also, it would lose elasticity because a slight variation in traffic model or link capacity may lead to unknown risk to the ISPs.

Consider the example of Figure 2(b). In this example, $J_A^{NP} = 3.43$, $J_B^{NP} = 5.28$, and $J_{total}^{NP} = 8.71$. The bounds of levels are $c_1^l = 97.95$, $c_1^h = c_2^l = 158.25$, $c_2^h = c_3^l = 645.45$, and $c_3^h = 950.00$. If the ISPs choose to peering with $c_{AB} = 101.68$, which is of the low level, we can get the cost matrix as Table II. Paid peering by Nash bargaining is the only BNE strategy. If the ISPs decide to peering with $c_{AB} = 318.25$, which is of the medium level, the cost matrix is as Table III. Both BK peering and paid peering by Nash bargaining are BNE strategies. If the ISPs decide to peering with $c_{AB} = 764.50$ which is of the high level, the cost matrix is as Table IV, both BK peering and paid peering by Nash bargaining are BNE strategies. If we make some changes of the example in Figure 2(b) as $P_A = 0.001$, $P_B = 0.060$, $t_{AR} = 300$, $c_{AR} = 500$, $t_{BR} = 300$, $c_{BR} = 900$, $prop_{AB} = prop_{BR} = 0.001$, $\alpha = 0.7$, and $prop_{AR} = 0.003$. Then $J_A^{NP} = 5.60$, $J_B^{NP} = 25.20$, $c_1^l = 109.50$, $c_1^h = c_2^l = 203.45$, $c_3^l = c_2^h = 330.77$, and $c_3^h = 1000.00$. The cost matrix is as Table V. Note that in practice, P_B could not be as big as 60 times of P_A. We just show an extreme condition here in the theory. Then if the ISPs decide to peering with $c_{AB} = 996.15$ which is of the high level, no peering is the only strategy in BNE. Although the examples above may not include all the possibilities, we can see intuitively our analytical results about peering level choices and BNE strategies.

V. CONCLUSION

In this paper, we studied the economic issues in ISPs connecting with the advent of overlay routing. We obtained the overlay routing traffic patterns in Nash equilibrium with a simple network model, and revealed how does peering link capacity affect the traffic pattern. Based on the effect on different traffic patterns, we identified the peering level as three levels: low level, medium level, and high level, each of which is corresponding to a certain traffic pattern. Combining the traffic patterns and business model, we studied the economic issues in ISPs' peering. We showed that with BK peering, the ISP that may free-ride the other ISP prefers peering of medium and high level, while the ISP being free-ridden prefers only medium level. With paid peering determined by Nash bargaining solution, it is preferred by both ISPs with peering of low level and medium level. However, the peering of high level still has much uncertain factors caused by free-riding. We also proposed a regime equilibria analysis with BNE theory, and showed that paid peering by Nash bargaining is always a BNE strategy when the peering is of low level and medium level.

A shortcoming of this paper is that the model analyzed is quite stylized. Although this model is quite informative, we would like to extend the model to include more realistic features. First, we would like to incorporate more complicated network. Second, we plan to use various overlay routing applications. Finally, we would like to incorporate implementing issues.

REFERENCES

[1] W. B. Norton, "Internet Service Providers and Peering," 2001. [Online]. Available: http://www.equinix.com

[2] G. Huston, *ISP Survival Guide: Strategies for Running a Competitive ISP*. John Wiley and Sons, 1999.

[3] G. Shrimali and S. Kumar, "Paid Peering Among Internet Service Providers," in *Proc. GameNets workshop on Game theory for communications and networks*, 2006.
[4] E. Jahn and J. Prüfer, "Interconnection and Competition Among Asymmetric Networks in the Internet Backbone Market," *Information Economics and Policy*, vol. 20, pp. 243–256, 2008.
[5] J. J. Laffont, S. Marcus, P. Rey, and J. Tirole, "Internet Interconnection and the Off-Net-Cost Pricing Principle," *RAND Journal of Economics*, vol. 34, no. 2, pp. 370–390, 2003.
[6] S. Shakkottai and R. Srikant, "Economics of Network Pricing With Multiple ISPs," *IEEE/ACM Transactions on Networking*, vol. 16, pp. 1233–1245, 2006.
[7] G. Shrimali and S. Kumar, "Can Bill-and-Keep Peering Be Mutually Beneficial?" *Internet and Network Economics*, vol. 3828, pp. 738–747, 2005.
[8] G. Fudenberg and J. Tirole, *Game Theory*. MIT Press, 2000.
[9] J. H. Wang, D. M. C. Chiu, and J. C. S. Lui, "Modeling the Peering and Routing Tussle Between ISPs and P2P Applications," in *Proc. IEEE IWQoS'06*, 2006, pp. 51–59.
[10] J. H. Wang, D. M. Chiu, and J. C. S. Liu, "A Game-Theoretic Analysis of the Implications of Overlay Network Traffic on ISP Peering," *Computer Networks*, vol. 52, pp. 2961–2974, 2008.
[11] O. Saleh and M. Hefeeda, "Modeling and Caching of Peer-to-Peer Traffic," in *Proc. IEEE ICNP'06*, 2006, pp. 249–258.
[12] H. Y. Xie, Y. R. Yang, A. Krishnamurthy, Y. G. Liu, and A. Silberschatz, "P4P: Provider Portal For Applications," in *Proc. ACM SIGCOMM'08*, vol. 38, 2008.
[13] G. Hasegawa, M. Kobayashi, M. Murata, and T. Murase, "Free-Riding Traffic Problem in Routing Overlay Network," in *Proc. IEEE ICON'07*, 2007, pp. 118–123.
[14] S. Goyal and V. Redondo, "Structural Holes in Social Networks," *Journal of Economic Theory*, vol. 137, no. 1, pp. 460–492, 2007.
[15] J. F. Nash, "Two-Person Cooperative Games," *Econometrica*, vol. 21, pp. 128–140, 1953.
[16] T. Basar and R. Srikant, "Revenue-Maximizing Pricing and Capacity Expansion in a Many-User Regime," in *Proc. IEEE INFOCOM'02*, vol. 1, 2002, pp. 294–301.
[17] T. Roughgarden and E. Tardos, "How Bad is Selfish Routing?" *Journal of the ACM*, vol. 49, pp. 236–259, 2002.