Transit versus (Paid) Peering: Interconnection and Competition in the Internet Backbone Market*

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Abstract

We examine the strategic interaction between interconnection and competition in the Internet backbone market. Networks asymmetric in size choose among different interconnection regimes, IP-Transit, Bill-and-Keep Peering, and Paid Peering, and compete for end-users. We show that sufficiently symmetric networks enter a Peering agreement while otherwise use an intermediary network for exchanging traffic. This is structurally in line with considerations of a non-US policy maker. In contrast, US policy makers prefer Peerings among relatively asymmetric networks.

Keywords: Internet Backbone, Network Interconnection, (Paid) Peering, Two-Way Access Pricing

JEL Classification: *L10, L96, D43*

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1 Introduction

The Internet as a communications industry is subject to network externalities. These forced Internet Backbone Providers (IBPs) to interconnect with each other in order to provide their customers with "world-wide connectivity", hence increasing consumers' benefits and willingness-to-pay for Internet access. However, from an economic perspective, there are several ways to interconnect with other networks. The specific type of interconnection influences competition for end-users though, and vice versa. Hence, interconnection becomes strategic.

This paper introduces a first attempt to endogenize both networks' interconnection and competition decisions. We address the following questions: What determines networks' choice of interconnection? How do different types of interconnection affect competition for end-users? Are networks' decisions in line with policy considerations?

We suggest to consider a new interconnection regime, Paid Peering, and derive ranges within which it constitutes a unique subgame-perfect equilibrium. If feasible at all, Paid Peering always dominates regular Bill-and-Keep Peering in equilibrium as long as Paid Peering incurs no extra bargaining costs, i.e. networks can raise profits in comparison to a situation where they were restricted to the choice of Bill-and-Keep Peering versus Transit. We find that networks which are sufficiently symmetric in size peer while otherwise buy IP-Transit from an intermediary network. Our model suggests that this interconnection behaviour is not desirable from a welfare point of view. Finally, taking into account that the market for IP-Transit is dominated by US carriers, a non-US trade policy oriented regulator would find that there is too much Peering and would seek to restrict Peering of networks which are sufficiently asymmetric in size.

Unlike in telecommunications, interconnection in the Internet backbone market is not subject to regulation.[1] That is, cash flows associated with interconnection on the Internet do not depend on the direction of traffic but may be negotiated

[1]For two seminal articles on interconnection and two-way access pricing in telecommunications, refer to Armstrong (1998) and Laffont et al. (1998). For a recent survey on access price regulation in telecommunications, see Vogelsang (2003).

freely in the market.[2] Second, destination based price discrimination is usual in telecommunications, while it is practically impossible on the Internet.[3] Therefore, the economic implications derived from the literature on telecommunications do not necessarily apply to the Internet.

Laffont et al. (2003) study the strategic behaviour of Internet backbone operators in an environment of reciprocal access pricing. They divide the market into traffic senders and traffic receivers and assume Bertrand competition over both sides of the market. As one result of their study they find that networks are pricing Internet usage as if their customers' traffic were entirely off-net. Furthermore, they conclude that the level of access charges determines the allocation of communication costs between traffic senders and receivers. Extending this framework to consumer delay costs and capacity decisions, Mendelson and Shneorson (2003) conclude that the presence of traffic delay does have a substantial impact on competition and interconnection in the Internet backbone market. Crémer et al. (2000) analyse whether dominant network operators have incentives to lower the interconnection quality to rival networks. By extending the Katz and Shapiro (1985) network competition model they show that a network with a large installed base of customers is likely to degrade its interconnection quality with smaller networks.

The papers connected most closely to our's are Baake and Wichmann (1999) and Besen et al. (2001). The former studies the Transit vs. Peering decision in the context of quality differentials while the latter provides a bargaining process of Peering partners (implicitly introducing the option for Paid Peering). Both do not consider effects on competition for end-users. Kende (2000) and Atkinson and Barnekov (2004) provide non-formal studies of the Internet backbones' market environment pointing on currently important issues and open questions. To the best of our knowledge, our paper is a first attempt to endogenize both networks' intercon-

[2] In telecommunications, regularly the data sending network has to pay the receiving network for terminating a call. Moreover, policy makers often require such termination charges or "access charges" to be set reciprocally.

[3] It is standard for consumers to pay more for long-distance or international phone calls than for local ones. To imitate such price discrimination on the Internet, a consumer would have to be asked before each click on a Web link whether she would be willing to pay a specific price depending on the network distance to a specific target Web site's location.

nection and competition decisions while taking into account the economic differences between the Internet backbone and telecommunications markets.

Our model has the following timing: Firstly, two networks, which are ex ante connected via an intermediary backbone, negotiate their interconnection regime. In case of Paid Peering, they bargain for a settlement-fee that could flow either direction on stage two. Thirdly, they compete in prices for consumers with heterogeneous preferences in a Hotelling model. Finally, consumers choose the network maximizing their net benefits.

The paper is organised as follows. Section 2 describes the most widely used interconnection regimes in more detail. Section 3 sets the stage for the model and derives networks' equilibrium prices, market shares, and profits under Intermediary and Bill-and-Keep Peering regimes, respectively. Section 4 introduces the Nash bargaining game used under the Paid Peering regime. Section 5 examines incentives to peer and defines parameter ranges of subgame-perfect equilibria. Section 6 takes a welfare perspective. Section 7 derives subgame-perfect equilibria for cases where Paid Peering incurs bargaining costs. Section 8 provides empirical implications while section 9 offers an outlook on the Internet backbone market's future.

2 Interconnection practice in the Internet backbone market

The market for interconnection between network operators on the Internet has developed rapidly during the last years and is expected to do so in the future, too. According to one forecast (IDC, 2003), the volume of global Internet traffic should nearly double annually, increasing from 180 petabits per day in 2002 to 5,175 petabits per day by the end of 2007.

Up to the mid-1990's, large parts of the Internet were owned by governmental agencies, for instance the National Science Foundation (NSF) in the US. Along with deregulation of telecommunications markets, these steadily withdrew from managing the infrastructure which was followed by a rapid technological and commercial development. As is common knowledge, the Internet itself is a network of networks playing an intermediary role in connecting consumers who are connected to it via Internet Service Providers (ISPs). Traditionally, ISPs have formed regional networks that exchange traffic generated by their customers via Internet Backbone Providers (IBPs). Nowadays, however, more and more ISPs are vertically integrated into IBPs.

Users could be assigned to two segments, traffic senders (e.g. Web sites) and traffic receivers (e.g. end-users). But due to the emergence of new broadband services, for instance Voice over IP (VoIP) or video conferencing, the distinction blurs and consumers become senders and receivers at the same time. Therefore, the direction of traffic flows cannot be attributed clearly to distinct utility levels, anymore.[4]

How does traffic get from consumer 1 to consumer 2? Suppose, for instance, 1 and 2 are video conferencing and are connected to different networks. These have two main options to exchange traffic, Transit and Peering.

IP-Transit/Intermediary: If a direct connection is not feasible or desirable, two networks can buy so-called Transit services from a third network. Under such an arrangement, both networks pay a variable charge per unit of traffic to the intermediary network which obligates to deliver the traffic to any specified destination and from a certain origination. For being able to fulfil this obligation networks offering Transit mostly have a large physical network and are connected to many other networks via Peering or further Transit sales. The IP-Transit market is dominated by so-called Tier-1 networks which are mainly US based.[5]

Peering:[6] *Bill-and-Keep Peering*, also called settlement-free Peering, has evolved as the regular type of direct interconnection regime between two networks since privatisation. Networks exchange traffic without charging any fees to each other. How-

[4]A widely-used billing mechanism for Transit services is the so-called 95th Percentile Billing which does only account for traffic volume, but not for traffic direction.

[5]A network is regarded to have Tier-1 status, if it is connected to the whole Internet while never paying for interconnection itself.

[6]In the industry, there is a difference between "Private Peering" where exactly two networks build or lease lines to interconnect, and "Public Peering" where several networks interconnect their lines in a node, a so-called Internet Exchange Point (IXP). Since economic differences are not very significant and more and more networks use Private Peering, we only consider this type in our model. See Kende (2000) for more details.

ever, under such a Peering agreement, no participating network has the obligation to terminate traffic to or from a third party. Each network must only process traffic from the Peering partner to its own customers (and the customers of their customers, and so on, if existent), but not to the rest of the Internet. This constitutes a major difference between IP-Transit and Peering. In our example, customers 1 and 2 can exchange traffic without causing any interconnection costs to the networks they have subscribed to, if those are peering. A necessary requirement for Peering in general is the exact routing of traffic in order to control the flow of traffic. Otherwise, a third network which has been denied Peering by one of the participating networks could free-ride on the existing Peering arrangement.

A *Paid Peering* regime between two networks implies the same rights concerning their exchange of traffic. However, in contrast to a Bill-and-Keep arrangement, one network charges the other for exchanging traffic. We may emphasize that Paid Peering is a relatively new type of interconnection regime and has only recently begun to be employed.[7] In our example, suppose the network of customer 1 pays for exchanging traffic with the network which 2 belongs to. When exchanging traffic, 1's network, for instance, pays 2's network for exchanging traffic, regardless of the direction of the traffic flow. However, since this is no Transit contract, 2's network will not proceed traffic from 1 to a third party which is not a customer of 2's network.[8]

3 The model

3.1 Key assumptions

There are two networks $i \in \{A, B\}$ each having a fixed installed base of customers α_i that is not subject to competition.[9] Without loss of generality we assume $\alpha_A > \alpha_B$.

[7] A Paid Peering settlement could appear in several different forms of payment, either fixed amount payments or a variable charge per unit of traffic (or a combination of both). The previous type of payment could involve asymmetric cost sharing regarding the technological fixed costs of installing traffic exchange points between Peering partners.

[8] For more details on Internet traffic, see Giovanetti and Ristuccia (2003) or Kende (2000).

[9] Internet Service Providers (ISPs) selling Internet access to those consumers are integrated into the networks.

On top, $\bar{\alpha}$ consumers are situated in a *battlezone*, where networks A and B compete in prices.[10] Ex ante both networks are connected to the rest of the Internet by using an intermediary, thereby offering their customers world-wide connectivity.[11] I.e. we assume global excess capacity, since this reflects the current infrastructure environment. As there is Bertrand price competition in the market for IP-Transit, we assume the intermediary to be the cheapest tier-one network available, by definition offering access to all remaining consumers connected to the Internet, κ. It is not important, whether the intermediary directly serves the κ consumers as ISP, or connects other networks' consumers via its backbone to networks A and B. There is a continuum of consumers, of mass 1, so $\alpha_A + \alpha_B + \bar{\alpha} + \kappa = 1$. Figure 1 charts the competition set-up.

Networks' cost structure:

- Technical marginal cost of sending data are zero.[12]
- Costs of connecting customers to a network within the battlezone are symmetric and, for simplicity, normalized to zero.
- In case of a Peering arrangement, each network has to bear a fixed cost $F_i > 0$.[13]

[10] The most intuitive explanation is of a geographic nature: the locked customers of network i can only be connected directly to network j for prohibitively high costs, e.g. because they live in a rural area. The battlezone, however, consists of consumers living in large cities where both networks have a point of presence (POP). Another interpretation is that A and B compete in new services, e.g. Voice over IP, in the battlezone, but also have legacy customers who are not interested in such services.

[11] In line with this, we model no quality differentials among Peering and Transit, unlike as in Crémer et al. (2000) or Baake and Wichmann (1998), since, according to industry representatives, there is no clear relationship between interconnection quality and regimes. Consequently, demand-side network effects do not play a role in the model, since customers enjoy world-wide connectivity on a constant quality level regardless of the networks' interconnection decision or competition.

[12] Unlike modelled in previous papers that assumed positive marginal cost, industry representatives assured us that these are negligible. See Atkinson and Barnekov (2004) for support of our approach and more detailed information.

[13] F_i encompasses all fixed-step costs for setting up a physical interconnection, buying routers, etc. and organisational costs for managing a Peering agreement.

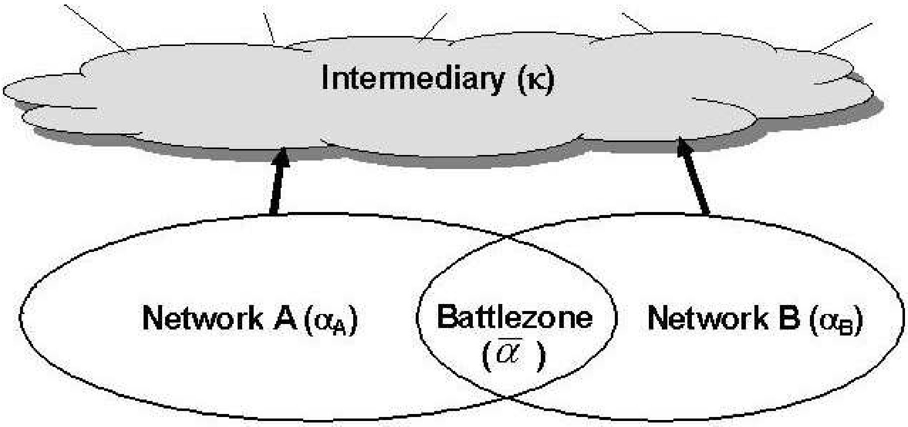

Figure 1: Network Interconnection via an Intermediary

- Networks are faced with an exogenous market price for upstream Transit, t_u, per unit of data.

Since top-level backbones do not charge different fees for upstream or downstream traffic, we merely assume that each consumer sends one unit of data to each other consumer, and receives one unit of data from each other consumer, thereby not taking into account which network the other consumer is connected to. This yields each consumer a gross benefit, v. Finally, we assume that prices p_i^L in the locked areas are not affected by competition in the battlezone where both networks charge each customer a price p_i.

3.2 The game

The timing of the game is as follows:

1. Networks A and B decide non-cooperatively about the interconnection regime between them, *Intermediary*, *Bill-and-Keep Peering* or *Paid Peering*. If networks cannot agree on a specific Peering regime, both are forced to Intermediary.

2. In case of Paid Peering, networks bargain for a fixed settlement which could flow either direction.

3. Networks A and B set prices p_i for consumers in the battlezone. Consumers have heterogeneous preferences, so networks compete à la Hotelling.[14]

4. Consumers in the battlezone choose the network maximizing their net benefits.

We will derive equilibrium profits of both networks under Bill-and Keep Peering (BK) and Intermediary regimes at the third stage of the game first, derive Paid Peering (PP) profits at the second stage, and compare them at the first stage afterwards to yield incentives for choosing the regimes. Then we derive parameter constellations under which Bill-and-Keep Peering, Paid Peering, and Intermediary are equilibrium strategies for both networks.

3.3 Price competition under the Intermediary regime

Consider a standard Hotelling (1929) model. Consumers are indexed by x and uniformly distributed on the interval $[0, 1]$ with increasing preference for network B. The network differentiation parameter (transportation cost parameter) is $\tau > 0$, so that a consumer's utility function is given by

$$U = \begin{cases} v - \tau x - p_A & \text{if buying from network A} \\ v - \tau(1-x) - p_B & \text{if buying from network B} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

We assume $v \geq \frac{3}{2}\tau + 2\kappa t_u$ to assure the market is covered. It is easy to calculate the standard marginal consumer who is indifferent between A and B and denoted by

$$\hat{x} = \frac{1}{2} + \frac{p_B - p_A}{2\tau}. \tag{2}$$

Hence $\hat{x}$ also specifies A's market share within the battlezone, while $(1 - \hat{x})$ is B's battlezone market share. Profit functions[15] under the Intermediary regime are given

[14] Heterogeneous consumer preferences could depend on different complementary services offered by the networks, e.g. specific Web content or software applications certain consumers are already used to.

[15] Since $p_i \neq p_i^L$ is feasible, we assume that networks are able to discriminate prices between locked consumers and the battlezone. If that was not possible, there would be an infinite set of

by

$$\Pi_A^I = \hat{x}\bar{\alpha}(p_A - 2\kappa t_u) + \alpha_A(p_A^L - 2\kappa t_u) - 2t_u(\hat{x}\bar{\alpha} + \alpha_A)((1-\hat{x})\bar{\alpha} + \alpha_B) \quad (3)$$
$$\Pi_B^I = (1-\hat{x})\bar{\alpha}(p_B - 2\kappa t_u) + \alpha_B(p_B^L - 2\kappa t_u) - 2t_u(\hat{x}\bar{\alpha} + \alpha_A)((1-\hat{x})\bar{\alpha} + \alpha_B) \quad (4)$$

The first term of each function describes a network's direct profits from customers in the battlezone net of Transit costs which stem from sending data to or receiving data from customers of the other network. The second term denotes the same for its locked customers, while the third term adjusts for the traffic that is exchanged between A and B. This term has to be paid to the intermediary by each network, is of equal size for both firms and will become a main formal driver of the model. Note that traffic has to be paid twice for each consumer, since we assume that all consumers both send data to and receive data from all other consumers. The first-order-condition of network A is given by

$$\frac{\partial \Pi_A^I}{\partial p_A} = \frac{\bar{\alpha}}{2\tau^2}(\tau(p_B - 2p_A + \kappa 2t_u - \alpha_A 2t_u + \alpha_B 2t_u + \tau) + p_A 2t_u\bar{\alpha} - p_B 2t_u\bar{\alpha}) = 0,$$

while B's is analogous. We derive reaction functions as

$$p_A(p_B) = \frac{2t_u\bar{\alpha} - \tau}{2(t_u\bar{\alpha} - \tau)}p_B + \frac{2\tau t_u(\alpha_A - \alpha_B - \kappa) - \tau^2}{2(\bar{\alpha}t_u - 2\tau)}$$
$$p_B(p_A) = \frac{2t_u\bar{\alpha} - \tau}{2(t_u\bar{\alpha} - \tau)}p_A + \frac{2\tau t_u(\alpha_B - \alpha_A - \kappa) - \tau^2}{2(\bar{\alpha}t_u - 2\tau)}.$$

Second-order-conditions are satisfied for $\tau > 2\bar{\alpha}t_u$. This yields the following equilibrium prices

$$p_A^* = \tau + \frac{2t_u(\kappa(3\tau - 4t_u\bar{\alpha}) - \Delta\tau)}{3\tau - 4t_u\bar{\alpha}} = \tau(1-z) + 2\kappa t_u \quad (5)$$
$$p_B^* = \tau + \frac{2t_u(\kappa(3\tau - 4t_u\bar{\alpha}) + \Delta\tau)}{3\tau - 4t_u\bar{\alpha}} = \tau(1+z) + 2\kappa t_u, \quad (6)$$

where $\Delta = \alpha_A - \alpha_B > 0$ and $z = \frac{2t_u\Delta}{(3\tau - 4t_u\bar{\alpha})}$. Hence, A's equilibrium market share is

$$\hat{x} = \frac{1}{2} + \frac{2t_u\Delta}{(3\tau - 4t_u\bar{\alpha})} = \frac{1}{2} + z. \quad (7)$$

price Nash-equilibria as long as networks are symmetric. In case $\alpha_A \neq \alpha_B$, however, there is no price Nash-equilibrium in pure strategies. Therefore, and because we believe in the feasibility of price discrimination based on the sender's—not the receiver's—location in the Internet, we restrict our analysis to this case.

Equilibrium profits under the Intermediary regime are given by

$$\Pi_A^I = \frac{1}{2}\tau\bar{\alpha}(1 + \frac{2t_u\Delta(3\tau - 4t_u\bar{\alpha}) - 8t_u^2\Delta^2}{(3\tau - 4t_u\bar{\alpha})^2}) + \frac{4t_u^2\Delta^2\bar{\alpha}(3\tau - 2t_u\bar{\alpha})}{(3\tau - 4t_u\bar{\alpha})^2} - 2[t_u\frac{\bar{\alpha}}{2}(\alpha_A + \alpha_B + \frac{\bar{\alpha}}{2}) + \alpha_A\alpha_B t_u] + \alpha_A(p_A^L - 2\kappa t_u) \quad (8)$$

$$\Pi_B^I = \frac{1}{2}\tau\bar{\alpha}(1 - \frac{2t_u\Delta(3\tau - 4t_u\bar{\alpha}) + 8t_u^2\Delta^2}{(3\tau - 4t_u\bar{\alpha})^2}) + \frac{4t_u^2\Delta^2\bar{\alpha}(3\tau - 2t_u\bar{\alpha})}{(3\tau - 4t_u\bar{\alpha})^2} - 2[t_u\frac{\bar{\alpha}}{2}(\alpha_A + \alpha_B + \frac{\bar{\alpha}}{2}) + \alpha_A\alpha_B t_u] + \alpha_B(p_B^L - 2\kappa t_u). \quad (9)$$

It is obvious that A's direct profits from the battlezone, $\frac{1}{2}\tau\bar{\alpha}(1+\frac{2t_u\Delta(3\tau-4t_u\bar{\alpha})-8t_u^2\Delta^2}{(3\tau-4t_u\bar{\alpha})^2})$, increase while B's direct profits sink with growing asymmetry Δ. Besides, total Transit costs of each network, $2(t_u\frac{\bar{\alpha}}{2}(\alpha_A+\alpha_B+\frac{\bar{\alpha}}{2})+\alpha_A\alpha_B t_u+\alpha_i\kappa t_u)-\frac{4t_u^2\Delta^2\bar{\alpha}(3\tau-2t_u\bar{\alpha})}{(3\tau-4t_u\bar{\alpha})^2}$, are maximized for symmetry ($\Delta = 0$). Recall our assumption that $\alpha_A > \alpha_B$. It follows directly that $\Delta > 0 \Rightarrow z > 0$. Then, we find

Proposition 1 *Under the Intermediary regime of interconnection, network A prices more aggressively leading to a higher market share and larger profits of A in the battlezone.*

The key to understanding this proposition is that Transit payments of A and B to the intermediary decrease with growing network asymmetry. Thus, the larger network A has higher incentives to increase its market share than the smaller one. B faces an extra trade-off: if acquiring a marginal customer within the battlezone, its income would increase, but Transit costs would increase in line. In contrast, if A could sell to a marginal consumer, its income would increase, but Transit costs would sink. Therefore, A's marginal profit from acquiring another customer is larger than B's making A more aggressive. Alike, A's ex-post profits increase with growing ex ante asymmetry, which also minimizes both networks' Transit payments, since more traffic is exchanged "on-net", i.e. if sender and receiver are customers of the same network.

3.4 Price competition under Bill-and-Keep Peering

If networks peer with each other, their profit functions show two differences in relation to the case without Peering: Peering's upside is that networks do not have to pay the intermediary for traffic that is exchanged solely between the two networks involved, anymore. Its downside is that the Peering partners have to set up direct lines, buy new equipment such as routers, and have to bear Peering management costs. All these types of costs are compiled in the variable F_i which is not, according to various industry talks, correlated with network size or the amount of traffic transmitted, however. For simplicity, we assume $F_A = F_B = F$.

This leads to the following profit functions under Peering:

$$\Pi_A^P = \hat{x}\bar{\alpha}(p_A - 2\kappa t_u) + \alpha_A(p_A^L - 2\kappa t_u) - F, \tag{10}$$

$$\Pi_B^P = (1-\hat{x})\bar{\alpha}(p_B - 2\kappa t_u) + \alpha_B(p_B^L - 2\kappa t_u) - F. \tag{11}$$

Equilibrium prices can be derived as

$$p_A^* = \tau + 2\kappa t_u \tag{12}$$

$$p_B^* = \tau + 2\kappa t_u, \tag{13}$$

leading to an equilibrium market share for A (and for B, respectively) of

$$\hat{x} = \frac{1}{2}. \tag{14}$$

Equilibrium profits under the Peering regime are given by

$$\Pi_A^P = \frac{1}{2}\tau\bar{\alpha} + \alpha_A(p_A^L - 2\kappa t_u) - F \tag{15}$$

$$\Pi_B^P = \frac{1}{2}\tau\bar{\alpha} + \alpha_B(p_B^L - 2\kappa t_u) - F. \tag{16}$$

These equations yield

Proposition 2 *Under the Peering regime of interconnection, (i) Regardless of asymmetries in installed bases, networks' pricing behaviour is symmetric. (ii) Market shares in the battlezone are symmetric. (iii) Leaving out profits from the installed bases, profits from competition in the battlezone are symmetric. (iv) If installed bases were symmetric ($\Delta = z = 0$), then equilibrium prices and battlezone market shares were the same under Intermediary and Peering regimes.*

The intuition for (i) through (iii) is that, since under a Peering regime Transit costs for traffic between the two parties are waived, the larger network has no extra incentives to undercut the smaller one, anymore. Therefore, incentive structures, behaviour, and profits are symmetric. This intuition is confirmed by (iv) stating that symmetric networks always behave in the same way regardless of the interconnection regime.

4 Bargaining under Paid Peering

Given networks decided to interconnect under the Paid Peering regime, on the second stage of the game we should calculate the settlement-fee, S, one network has to pay the other to make the latter agree to Peering.[16] If they opted for Intermediary or BK, this stage would be waived.

It facilitates further analysis, if we first derive the networks' relative individual incentives to accept Bill-and-Keep Peering.

Proposition 3 *The smaller network always has higher incentives to reach a Bill-and-Keep Peering relative to Intermediary than the larger network.*

Proof: Network A's incentives to BK—the gains from Peering—are smaller than B's, if $\Pi_A^P - \Pi_A^I < \Pi_B^P - \Pi_B^I$, or (15) − (8) < (16) − (9). This expression is equivalent to $-2t_u\Delta(3\tau - 4t_u\bar{\alpha}) < 2t_u\Delta(3\tau - 4t_u\bar{\alpha})$ which is true for all defined parameter realisations. $\square$

Because of Proposition 3 it is clear that network B always has to pay network A under Paid Peering, not vice versa. Let

$$S \equiv \frac{1}{2}(\Pi_B^P - \Pi_B^I - (\Pi_A^P - \Pi_A^I)) = \frac{\tau\bar{\alpha}t_u}{3\tau - 4t_u\bar{\alpha}}\Delta \tag{17}$$

[16]Here, the transfer payment or *access charge* between networks, unlike in most papers on interconnection in telecommunications, is of a lump-sum type, not a per unit of data fee. The two are structurally similar as long as they do not influence pricing behaviour in the retail market. Given that and our assumption of perfect information, S could be interpreted as the sum of all per unit fees in a given period. In contrast, inclusion of access charges that influence retail competition on the third stage of the game is not the focus of our more fundamental paper. Therefore, we follow Besen et al. (2001) in assuming a lump-sum payment.

be this settlement B has to pay A. I.e. we assume equal bargaining power and use the respective equilibrium profits under the Intermediary regime as threat points.[17] At a non-cooperative bargaining outcome, the networks share equally any gains relative to their threat points. This formulation ensures that each player obtains (or keeps) profits from the Intermediary case, at least, while only "excess" profits are shared. Therefore, the assumption of equal bargaining power is not crucial here since it does not affect absolute incentives to agree to Paid Peering relative to Intermediary.

In general, A's equilibrium profits under Paid Peering are $\Pi_A^{PP} = \Pi_A^P + S$ while B's are $\Pi_B^{PP} = \Pi_B^P - S$. Using (17) yields

$$\Pi_A^{PP} = \frac{1}{2}\tau\bar{\alpha} + \alpha_A(p_A^L - 2\kappa t_u) - F + \frac{\tau\bar{\alpha}t_u}{3\tau - 4t_u\bar{\alpha}}\Delta \tag{18}$$

$$\Pi_B^{PP} = \frac{1}{2}\tau\bar{\alpha} + \alpha_B(p_B^L - 2\kappa t_u) - F - \frac{\tau\bar{\alpha}t_u}{3\tau - 4t_u\bar{\alpha}}\Delta. \tag{19}$$

5 Regime equilibria

Being aware of Nash equilibria in prices given the respective regimes, we now proceed to analyse incentives on the first stage: When do networks wish to peer with a specific competitor? What form of Peering would prevail, if side payments were feasible?

Proposition 4 *Bill-and-Keep Peering can never be an equilibrium outcome for asymmetric networks, since network A always has incentives to deviate from Bill-and-Keep to Paid Peering.*

Proof: To reach BK both networks have to agree to it. As (18) > (15) for all defined realisations, A will never agree, since PP always yields BK profits plus a positive settlement.[18] □

[17] This formulation is analogous to Besen et al. (2001) whose approach is based on the Nash bargaining model of Binmore et al. (1986). It can be applied, if we assume that the lack of Peering is sustained only temporarily during bargaining until an agreement is reached, since this resembles the bargaining result according to the non-cooperative bargaining theory with short times between offers.

[18] If network B had all bargaining power, A would be indifferent between BK and PP, but B would prefer PP. The same happens vice versa.

Therefore, to find the level of asymmetry up to which Paid Peering is an equilibrium, we need to compare joint profits under the Intermediary and the Paid Peering regimes. Because of our assumption that under Paid Peering "excessive" profits can be perfectly exchanged, networks will peer, if $\sum \Pi_i^{PP} > \sum \Pi_i^I$. Rearranging this relation based on equations (8), (9), (18), and (19) yields that networks A and B will peer under Paid Peering if

$$\Delta < \sqrt{\frac{(3\tau - 4t_u\bar{\alpha})^2(t_u\bar{\alpha}(\alpha_A + \alpha_B + \frac{\bar{\alpha}}{2}) + 2\alpha_A\alpha_B t_u - F)}{8\bar{\alpha}t_u^2(\tau - t_u\bar{\alpha})}} \equiv \Delta_P. \tag{20}$$

This is only a feasible solution for $F < t_u\bar{\alpha}(\alpha_A+\alpha_B+\frac{\bar{\alpha}}{2})+2\alpha_A\alpha_B t_u$, i.e. if Peering costs are sufficiently low. Otherwise, either form of Peering will never be reached in equilibrium. (20) emphasizes that networks will interconnect via an Intermediary, if the difference in size of two networks is relatively large.

Before checking the existence of Δ_P, we are to specify the support of Δ in general. (7) explicates that to receive interior solutions for $\hat{x}$ so that $\hat{x} \in [0, 1]$, it is necessary that $\Delta \in [-\frac{3\tau-4t_u\bar{\alpha}}{4t_u}, \frac{3\tau-4t_u\bar{\alpha}}{4t_u}]$. If Δ lies outside of these boundaries, the larger network's aggressiveness in the price competition is so strong that the smaller network will be driven out of the (battlezone) market. There would be no competition and no negotiation whether to peer, or not. Thus, as $\Delta > 0$, we find that $\Delta_{max} \equiv \frac{3\tau-4t_u\bar{\alpha}}{4t_u}$, where $t_u \geq \frac{3\tau}{4(1+\bar{\alpha})}$ which is always true for defined values.

There exists an interval in which Paid Peering is *not* an equilibrium, but yields an interior solution, if and only if $\Delta_P < \Delta < \Delta_{max}$.[19] This is equivalent to

$$F > t_u\bar{\alpha}(\alpha_A + \alpha_B + \frac{\bar{\alpha}}{2}) + 2\alpha_A\alpha_B t_u - \frac{\bar{\alpha}}{2}(\tau - t_u\bar{\alpha}). \tag{21}$$

Summarizing, if F is sufficiently low, Paid Peering is the regime outcome, so a defined interval $[0, \Delta_P]$ exists. If F is sufficiently large within this range, Peering is not feasible but an interior solution letting both networks enter the battlezone, so an interval $[\Delta_P, \Delta_{max}]$ exists. For clarity, let $w \equiv \bar{\alpha}(\alpha_A + \alpha_B + \frac{\bar{\alpha}}{2}) + 2\alpha_A\alpha_B$. Thus from the above we obtain

[19]If Paid Peering always was an equilibrium by definition, the analysis would not be very interesting.

Proposition 5 *Assume $t_u w - \frac{\bar{\alpha}}{2}(\tau - t_u\bar{\alpha}) < F < t_u w$. (i) For all $\Delta \in (0, \Delta_P)$, Paid Peering is a unique subgame-perfect equilibrium. (ii) For all $\Delta \in (\Delta_P, \Delta_{max}]$, Intermediary is a unique subgame-perfect equilibrium.*

For $\Delta = 0$, Bill-and-Keep Peering and Paid Peering are equal. Hence both are equilibria. For $\Delta = \Delta_P$ both Paid Peering and Intermediary are equilibria.

6 Welfare

Now we know which interconnection regime networks will choose given exogenous parameter realisations. But are market outcomes beneficial for consumers and total welfare, as well?

6.1 Consumer surplus

We restrict the analysis to the $\bar{\alpha}$ consumers residing in the battlezone, since consumer surplus within the locked regions is neither a function of the networks' interconnection regime nor of their battlezone prices. Hence aggregate consumer surplus is the integral over individual net benefit (according to (1)) using the marginal consumer as boundary. As under (Paid) Peering, equilibrium prices of networks A and B are equal and each one gets a market share of 0.5, we can calculate consumer surplus as

$$CS^P = 2\bar{\alpha}\int_0^{0.5}(v - \tau x - p_A)dx = \bar{\alpha}(v - \frac{5}{4}\tau - 2\kappa t_u). \tag{22}$$

In contrast, consumer surplus under Intermediary is denoted by

$$\begin{aligned} CS^I &= \bar{\alpha}\left(\int_0^{\hat{x}}(v - \tau x - p_A)dx + \int_{\hat{x}}^{1}(v - \tau(1-x) - p_B)dx\right) \\ &= \bar{\alpha}(v - \frac{5}{4}\tau - 2\kappa t_u) + \frac{4\bar{\alpha}\tau t_u^2}{(4\bar{\alpha}t_u - 3\tau)^2}\Delta^2 = CS^P + \frac{4\bar{\alpha}\tau t_u^2}{(4\bar{\alpha}t_u - 3\tau)^2}\Delta^2. \end{aligned} \tag{23}$$

Analogous to section 3, $CS^P = CS^I$, if networks are symmetric ($\Delta = 0$). But for all $\Delta \neq 0$ consumer surplus is larger under the Intermediary regime. This is intuitive, since in the Intermediary case the larger network competes more aggressively in prices than in the Peering case, but it also obtains a higher market share within the battlezone. Hence a majority of consumers enjoys extra surplus which is not offset completely by higher prices that are paid by the fewer customers of the smaller network. It is straightforward to observe from (23) that consumer surplus under Intermediary relative to Peering increases even further with growing network asymmetry.

6.2 Total welfare

Up to which asymmetry should networks peer from a social perspective? Clearly, we can find this point, Δ_P^{Soc}, where a social planner including both consumer surplus and producer surplus (i.e. profits of networks A and B and the intermediary network) into his calculation would be indifferent between Peering and Intermediary. As $\sum \Pi_i^P = \sum \Pi_i^{PP}$, we can find this level via setting

$$CS^P + \Pi_A^P + \Pi_B^P + \Pi_{Int}^P = CS^I + \Pi_A^I + \Pi_B^I + \Pi_{Int}^I \tag{24}$$

where profits of the intermediary are denoted by $\Pi_{Int}^P = 2\kappa t_u(\alpha_A + \alpha_B + \bar{\alpha})$ and $\Pi_{Int}^I = \Pi_{Int}^P + 4(t_u \frac{\bar{\alpha}}{2}(\alpha_A + \alpha_B + \frac{\bar{\alpha}}{2}) + \alpha_A \alpha_B t_u + \alpha_A \kappa t_u) - \frac{8t_u^2 \Delta^2 \bar{\alpha}(3\tau - 2t_u\bar{\alpha})}{(3\tau - 4t_u\bar{\alpha})^2}$ respectively. Employing equations (22), (15), and (16) as well as (23), (8), and (9) yields that from a social perspective networks should peer, if

$$\Delta > \sqrt{\frac{F\,(4t_u\bar{\alpha} - 3\tau)^2}{2\bar{\alpha}\tau t_u^2}} \equiv \Delta_P^{Soc}. \tag{25}$$

However, since currently all major intermediary backbones are US based firms, one might also be interested in the ranges of asymmetry where a non-US regulator would like networks to peer, i.e. without taking into account the profits of the intermediary network. Therefore, we set

$$CS^P + \Pi_A^P + \Pi_B^P = CS^I + \Pi_A^I + \Pi_B^I \tag{26}$$

and find that in this "trade policy" case, a regulator would want networks to peer as long as

$$\Delta < \sqrt{\frac{(3\tau - 4t_u\bar{\alpha})^2(t_u\bar{\alpha}(\alpha_A + \alpha_B + \frac{\bar{\alpha}}{2}) + 2\alpha_A\alpha_B t_u - F)}{2\bar{\alpha}t_u^2(5\tau - 4t_u\bar{\alpha})}} \equiv \Delta_P^{TP}. \tag{27}$$

It might be startling that both a trade policy regulator and the independent networks prefer Peering for more symmetric networks, while a social planner prefers Peering for more asymmetric networks. The intuition is that, with increasing Δ, under the Intermediary regime network A prices more aggressively leading to decreasing direct profits from the battlezone. The smaller network B's higher prices cannot offset this effect in total, hence total network profits from the battlezone decrease in Δ. However, this is more than offset by the networks' savings through less Transit expenditures because of higher asymmetry. None of these effects exists under Peering. Therefore, with increasing Δ, networks are less motivated to peer.

A "trade policy" regulator, including consumers but not the intermediary into his optimization problem, profits from less Transit expenditures because of higher Δ, just as the networks do. On top, he observes that decreasing network profits from the battlezone are offset by larger consumer surplus. But there is also a negative effect from competition in the battlezone under the Intermediary regime onto consumers: the higher Δ the lower network A's price the more consumers buy from A. But these extra consumers (with preferences $x > \frac{1}{2}$) also have to bear high transportation costs when buying from A. Since increasing asymmetry does not affect the situation under Peering, the trade policy regulator would want networks to stop Peering for large Δ.

A social planner, in contrast, does not observe the effect of decreasing Transit costs for larger asymmetry, as this money flows to the intermediary backbone which is included in his optimization calculus. But the social planner also observes increasing transportation costs of the consumers with increasing Δ which makes the Intermediary regime increasingly unattractive with growing network asymmetry.

Proposition 6 *(i) Excess Peering: The level of asymmetry of network sizes up to which a "trade policy" regulator would prefer Peering, Δ_P^{TP}, is smaller than the asymmetry up to which networks peer without regarding consumer welfare, Δ_P. (ii) Within the range where networks peer but where it is suboptimal from a "trade policy" viewpoint, the loss increases with growing asymmetry.*

Proof: see appendix.

Now we know that always $\Delta_P^{TP} < \Delta_P$. However, Δ_P^{SOC} is not fixed within this range. What happens for low, medium, and large realisations of Δ_P^{SOC}, and when do those cases occur? We distinguish among three possible realisations. Please, recall that the minimum level of F is $wt_u - \frac{\bar{\alpha}}{2}(\tau - t_u\bar{\alpha})$ and its maximum level is wt_u:

- Case I: $\Delta_P^{Soc} \leq \Delta_P^{TP} \quad \forall \quad F \in (wt_u - \frac{\bar{\alpha}}{2}(\tau - t_u\bar{\alpha}), \frac{\tau}{6\tau - 4t_u\bar{\alpha}}wt_u]$
- Case II: $\Delta_P^{TP} < \Delta_P^{Soc} \leq \Delta_P \quad \forall \quad F \in (\frac{\tau}{6\tau-4t_u\bar{\alpha}}wt_u, \frac{\tau}{5\tau-4t_u\bar{\alpha}}wt_u]$
- Case III: $\Delta_P < \Delta_P^{Soc} \quad \forall \quad F \in (\frac{\tau}{5\tau-4t_u\bar{\alpha}}wt_u, wt_u)$

By checking these cases with the respective definitions of Δ_P, Δ_P^{Soc}, and Δ_P^{TP}, we easily observe

Proposition 7 *(i) Within cases I and III, but not in case II, there exist ranges where the equilibrium interconnection regime is in line with the views of both a social regulator and a "trade policy" regulator. In case I (III) Peering (Intermediary) is optimal from these three perspectives as long as* $\Delta_P^{Soc} < \Delta < \Delta_P^{TP}$ *(*$\Delta_P < \Delta < \Delta_P^{SOC}$*). (ii) If Peering costs are sufficiently large, Peering never occurs where it is socially efficient (*$\Delta_P < \Delta_P^{SOC}$*). (iii) If Peering costs are sufficiently large, "trade policy regulators" only support Peering where it is socially inefficient (*$\Delta_P^{TP} < \Delta_P^{SOC}$*).*

Proof: see appendix.

Figure 2 provides a graphical intuition for Propositions 6 and 7. Peering is preferred by (a) the networks themselves (b) a "trade policy" regulator (c) a total welfare maximizer.

Therefore, it is possible that both types of regulators are content with networks' actions, but it is also feasible that they would like to intervene into the market. As a general rule we can derive that networks always peer excessively from a "trade policy" regulator's point of view.

7 Positive Bargaining Costs

According to Proposition 4, Bill-and-Keep Peering never occurs in equilibrium. In practice, however, it is widely observable. This could be explained by the fact that the bargaining process associated with Paid Peering may involve extra transaction

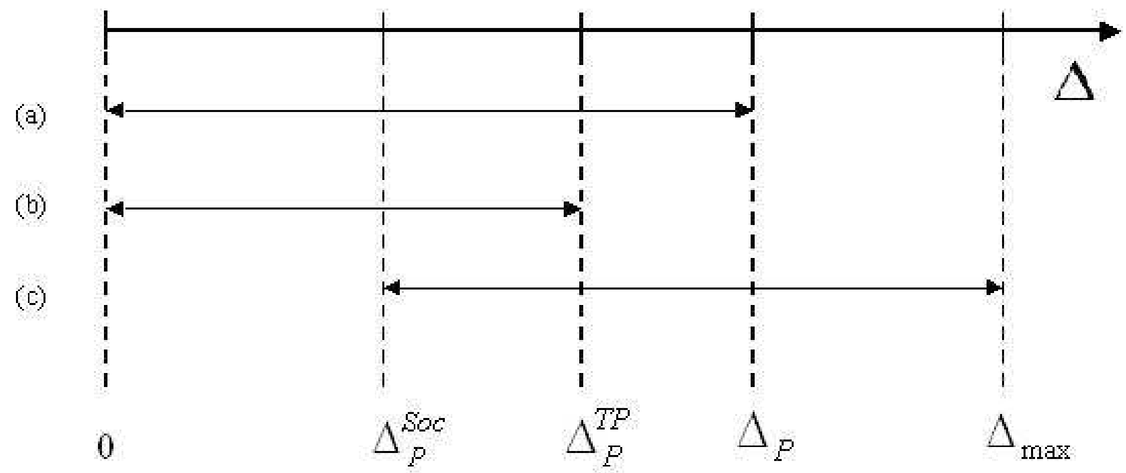

Figure 2: Welfare considerations for $\Delta_P^{Soc} \leq \Delta_P^{TP}$ (Case I)

costs in comparison to Bill-and-Keep Peering.[20] Suppose there are positive bargaining costs $C > 0$. This would change (18) and (19) to

$$\Pi_A^{PP} = \frac{1}{2}\tau\bar{\alpha} + \alpha_A(p_A^L - 2\kappa t_u) - F - C + \frac{\tau\bar{\alpha}t_u}{3\tau - 4t_u\bar{\alpha}}\Delta \tag{28}$$

$$\Pi_B^{PP} = \frac{1}{2}\tau\bar{\alpha} + \alpha_B(p_B^L - 2\kappa t_u) - F - C - \frac{\tau\bar{\alpha}t_u}{3\tau - 4t_u\bar{\alpha}}\Delta. \tag{29}$$

Since network A, according to Proposition 3, has lower incentives for Bill-and-Keep Peering and network B always prefers Bill-and-Keep to Paid Peering, network A de facto sets the type of interconnection.

Proposition 8 *For all $C > 0$ and Δ sufficiently low, there exists a range where Bill-and-Keep Peering is the unique subgame-perfect equilibrium.*

Proof: see appendix.

[20]Another explanation could be *legacy* which is questionable from an economic point of view, however. The argument claims that, at the beginning of the commercial Internet era, networks did not focus on the strategic aspects of interconnection but strived for reaching world-wide connectivity fast. Nowadays, they find themselves in the resource consuming process of reviewing their existing Peering policies.

Besides these remarks, it is questionable whether Paid Peering does in practice involve higher costs than Bill-and-Keep Peering. This would be yet another reason to expect more Paid Peering agreements in the future.

8 Empirical Implications

Our main objective was to study IBPs' optimal interconnection decisions which are strategically linked to competition for end-users. Based on our results we derive the following main empirical implications:

1. If, besides Intermediary and Bill-and-Keep, networks also consider Paid Peering as a possible type of interconnection, we expect to observe more Paid Peering in the future. This translates to more Peering agreements in general which, in turn, leads to higher profits of IBPs.

2. This development harms consumer surplus, however.

3. Since the emergence of Paid Peering also lowers demand for IP-Transit, top level backbones will lose revenues.

4. As all top level backbones are US-based, non-US policy makers do not include profits from IP-Transit in their calculus. Instead of considering to punish large networks who refuse (Bill-and-Keep) Peering to smaller ones, these policy makers should review to restrict Peering, since networks do not care about the fact that fiercer competition under Intermediary benefits consumers, and peer excessively. In contrast, since US-based policy makers do account for profits from IP-Transit, they favour Peerings among networks sufficiently asymmetric in size. Hence, they should seek to discourage large networks from refusing to peer with smaller ones.

These results could also be applied to a telecommunications market which was both unregulated in terms of inter-carrier compensation fees and not subject to price discrimination regarding destinations of calls.

9 Discussion

We verified three possible sources of revenues for IBPs: end-user charges (p_i), Paid Peering revenues (S), and IP-Transit fees (t_u).

Given that IP-Transit is a homogenous good, as long as this market is characterised by (i) perfect competition, (ii) the absence of bottlenecks, and (iii) excess capacity, we should expect to observe Transit charges equalling marginal costs ($t_u = MC = 0$). This view is supported by empirical data: OECD (2002) states that prices for IP-Transit had fallen by up to 55 percent annually from 1998-2000. According to Band-X (2003), "the average price of IP across all speeds on the Band-X IP Transit Exchange has fallen by 30% from £135 per Mbps in August 2002 to £96 per Mbps in July 2003."

As a consequence of this development, we should expect revenues from IP-Transit to vanish. Moreover, according to (17) settlement-fees in case of Paid Peering should follow the direction of Transit fees, i.e. they should approach zero, too. Thus, profits from Bill-and-Keep and Paid Peering would converge. (20) shows that as a boundary solution we obtain $\Delta_P \to 0$ meaning that Intermediary would become the dominant interconnection regime.[21] Alike, we find that $\Delta_{max} \to (+\infty)$ encouraging market entry by small IBPs.

This leaves networks with equilibrium profits of $\Pi_i = \frac{1}{2}\tau\bar{\alpha} + \alpha_i p_i^L$, according to (8) and (9). These profits heavily depend on τ, i.e. IBPs should exert any effort to differentiate themselves in the retail market, for instance by introducing new, specific services for end-users.

Since this paper adopts a new approach to network interconnection on the Internet, it could be extended in various directions in future research. One option is to analyse thoroughly the implications of different Paid Peering contracts, e.g. an ex ante lump-sum settlement (as assumed here) vs. ex post payment of a price $p^P < t_u$ per unit of data that influences networks' competitive retail pricing. Another interesting issue would be to study the impact of one (or both) networks being a Tier-1 on our analysis. This could include endogenization of the Transit charge t_u.

[21] Technically, $\Delta_P \to (-\infty)$.

A Appendix

A.1 Proof of Proposition 6

Ad (i): Δ_P and Δ_P^{TP} both have the same denominator. Therefore $\Delta_P^{TP} < \Delta_P$ if $2\bar{\alpha}t_u^2(5\tau - 4t_u\bar{\alpha}) > 8\bar{\alpha}t_u^2(\tau - t_u\bar{\alpha})$, which is true for all defined parameter realisations.
Ad (ii): The loss (L) accumulates to

$$L = \{TP^I - TP^P | \Delta_P^{TP} \leq \Delta \leq \Delta_P\}. \tag{A.1}$$

$\Leftrightarrow CS^P + \frac{4\bar{\alpha}\tau t_u^2}{(4\bar{\alpha}t_u - 3\tau)^2}\Delta^2 + \sum \Pi_i^I(\Delta^2) - CS^P - \sum \Pi_i^P$. Since $\frac{\partial}{\partial \Delta^2}\left(\frac{4\bar{\alpha}\tau t_u^2}{(4\bar{\alpha}t_u - 3\tau)^2}\Delta^2\right) > 0$ and $\frac{\partial(\sum \Pi_i^I(\Delta^2))}{\partial \Delta^2} > 0$, it follows that

$$\frac{\partial L}{\partial \Delta^2} > 0. \quad \square \tag{A.2}$$

A.2 Proof of Proposition 7

Ad (i): This follows directly from the respective definitions.
Ad (ii): Peering occurs if $\Delta < \Delta_P$. It is efficient if $\Delta > \Delta_P^{SOC}$. It never occurs when it is efficient if $\Delta_P < \Delta_P^{SOC}$. This is true for all $F \in (\frac{\tau}{5\tau - 4t_u\alpha_c}wt_u, wt_u)$.
Ad (iii): A "trade policy" regulator supports Peering if $\Delta < \Delta_P^{TP}$. Peering is efficient if $\Delta > \Delta_P^{SOC}$. It is never supported by a "trade policy" regulator when it is efficient if $\Delta_P^{TP} < \Delta_P^{SOC}$. This is true for all $F \in (\frac{\tau}{6\tau - 4t_u\alpha_c}wt_u, wt_u)$. $\square$

A.3 Proof of Proposition 8

Bill-and-Keep Peering being a subgame-perfect equilibrium requires that BK dominates both Paid Peering and Intermediary from network A's perspective.
Network A prefers BK to Intermediary if $\Pi_A^P > \Pi_A^I$. This is given as long as

$$\Delta < \frac{3\tau - 4t_u\bar{\alpha}}{16t_u(\tau - t_u\bar{\alpha})}\left(\sqrt{\frac{\tau^2\bar{\alpha} + 32(\tau - t_u\bar{\alpha})(t_uw - F)}{\bar{\alpha}}} - \tau\right) \equiv \Delta_{BK}. \tag{A.3}$$

$\Delta_{BK} > 0$ exists if $(A.3) > 0$. This is true for all $F < t_uw$. I.e. if $\Delta_P > 0 \rightarrow \Delta_{BK} > 0$.
Network A prefers BK to PP if $\Pi_A^P > \Pi_A^{PP}$. This equals $C > S$. Rearranging yields

$$\Delta < \frac{3\tau - 4t_u\bar{\alpha}}{\tau\bar{\alpha}t_u}C. \tag{A.4}$$

Bill-and-Keep Peering is a unique subgame-perfect equilibrium if the level of asymmetry fulfils both inequalities (A.3) and (A.4) which is true for all $C > 0$ and Δ sufficiently small. $\square$

References

Armstrong, M. (1998), Network Interconnection in Telecommunications, *Economic Journal* 108, 545-564.

Atkinson, J. and C. Barnekov (2004), A Coasian Alternative to Pivogian Regulation of Network Interconnection, *mimeo, Federal Communications Commission*, Washington DC.

Baake, P. and T. Wichmann (1999), On the Economics of Internet Peering, *Netnomics* 1, 89-105.

Band-X (2003), Press Release 02-10-2003, http://www.band-x.com/en/press_release/story.php?news_id=1398.

Besen, S., P. Milgrom, B. Mitchell and P. Srinagesh (2001), Advancing in Routing Technologies and Internet Peering Arrangements, *American Economic Review Papers and Proceedings* 91, 292-296.

Binmore, K., A. Rubinstein and A. Wolinsky (1986), The Nash Bargaining Solution in Economic Modeling, *RAND Journal of Economics* 17(2), 176-188.

Crémer, J., P. Rey and J. Tirole (2000), Connectivity in the Commercial Internet, *Journal of Industrial Economics* 48(4), 433-472.

Giovannetti, E. and C. Ristuccia (2003), Estimating Market Power in the Internet Backbone Using Band-X Data, *DAE Working Paper No. 0332, University of Cambridge*, UK.

Hotelling, H. (1929), Stability in Competition, *Economic Journal 39*, 41-57.

IDC (2003), Worldwide Bandwidth End-User Forecast and Analysis 2003-2007.

Katz, M. and C. Shaprio (1985), Network Externalities, Competition, and Compatibility, *American Economic Review* 75, 424-440.

Kende, M. (2000), The Digital Handshake: Connecting Internet Backbones, *OPP working paper No. 32, Federal Communications Commission*, Washington DC.

Laffont, J.-J., S. Marcus, P. Rey and J. Tirole (2003), Internet Interconnection and the Off-Net-Cost Pricing Principle, *RAND Journal of Economics* 34(2), 370-390.

Laffont, J.-J., P. Rey and J. Tirole (1998), Network Competition: I. Overview and Nondiscriminatory Pricing, *RAND Journal of Economics* 29, 1-37.

Mendelson, H. and S. Shneorson (2003), Internet Peering, Capacity and Pricing, *mimeo, Stanford University.*

OECD (2002), Internet Traffic Exchange and the Development of End-to-end International Telecommunication Competition.

Vogelsang, I. (2003), Price Regulation of Access to Telecommunications Networks, *Journal of Economic Literature* 41, 830-62.