Competition Schemes and Investment in Network Infrastructure under Uncertainty*

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October 2007

Abstract

This paper compares two specific types of competition schemes—service-based and facility-based competition—by focusing on a firm's incentive to invest in network infrastructure. We show that when monopoly rent is large, facility-based competition means that the initial introduction of infrastructure is made earlier than under service-based competition. However, when monopoly rent and the degree of uncertainty are both small, service-based competition brings about an earlier initial introduction of infrastructure than under facility-based competition. The paper includes discussion of the policy implications of these findings.

Keywords: Service-based competition, Facility-based competition, Real options, Preemption.

JEL classification: D92; G13; L43; L51

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*We would like to thank the editor Michael Crew and two anonymous referees for their valuable comments. We also thank conference participants at Kyoto University and the 32nd Conference of the European Association for Research in Industrial Economics (EARIE) for useful comments and suggestions on an earlier version of this paper titled "Promoting Competition with Open Access under Uncertainty". The financial support of the Zengin Foundation for Studies on Economics and Finance is gratefully acknowledged.

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1 Introduction

This paper addresses how infrastructure investments in network industries, such as telecommunications, electricity, natural gas and railroads, can be promoted. In particular, we examine the effect of the choice of a competition scheme on a firm's incentive to invest in network infrastructure. To this end, we focus on two specific types of competition schemes: service-based competition and facility-based competition. In service-based competition, entrants can enter the market by accessing an incumbent's network facility if and when they desire. On the other hand, facility-based competition requires entrants to construct their own network facilities in order to enter the market. In this paper, we attempt to clarify the conditions under which one competition scheme would induce a firm to invest earlier in network infrastructure than another competition scheme.

As a matter of fact, promoting investment in network infrastructure is an important concern in a regulator's choice of competition scheme. This is because the adoption of a new type of network infrastructure with innovative technology (e.g., broadband in telecommunications) may lead to price reductions or the provision of better quality products. Furthermore, the construction of a bypass (i.e., an additional network built by a potential entrant) may not only enhance the size but also upgrade the existing network. It may also introduce a positive network externality by reducing congestion, which in turn contributes to welfare enhancement.

There are several studies comparing competition schemes in an open access environment. A closely related study to this paper on the issue of open access policy is Bourreau and Doğan (2005). By focusing on an incumbent's incentive for unbundling and the incentive to set an access charge, Bourreau and Doğan (2005) show that an incumbent has an incentive to set too low an access charge. As a result, the entrant builds its own network too late from a welfare viewpoint.[1] Em-

[1] However, Bourreau and Doğan (2005) do not appear to pay sufficient attention to the dynamic

pirical research by Kaserman and Ulrich (2002) shows the effects of facility-based vs. resale entry on competition. According to the results presented in their Table 3, resale entry seemingly has a more drastic effect on competition than facility-based entry, in the sense that resale entry reduces the incumbents' shares in the long-distance telecommunication market more than with facility-based entry. Guthrie (2006) also provides valuable discussion about the two competition schemes, with an emphasis on their effects on the firm's timing of investment.

Our paper differs from previous work in two main ways. First, most earlier studies on open access policy do not deal with uncertainty and irreversibility, whereas we examine the firm's incentive for irreversible investment under uncertainty.[2] Uncertainty and irreversibility are decisive for firms in network industries. Both of these elements are commonly recognized by those involved in network industries, including researchers and policy makers. For example, Guthrie (2006) states that the dynamics, investment irreversibility, and uncertainty are all essential features of regulated competition. Alleman and Noam (1999) suggest the application of the real options approach to the telecommunications industry. Indeed, the net present value rule, which states that an investment should be undertaken only if its net present value is positive, is inappropriate for firms operating under uncertainty and irreversibility. This is why we employ a real options approach to discuss the above-mentioned issue.[3] We then examine how uncertainty affects the priority of the two competition schemes in terms of a firm's incentive to invest in network infrastructure.

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perspective of the policy consequences, even though they suggest that they employ a dynamic model. In fact, they normalize the discount rate to unity, implying that a dollar today has the same value as a dollar in the future.

[2] The effect of uncertainty on retail-price or access-price regulation has been formally examined by Biglaiser and Riordan (2000) and Pindyck (2005), with a focus on the irreversibility of investments. However, neither analyzes an investment game between an incumbent and an entrant, and an entrant is not allowed to build an additional network. Both of these dimensions are included in our paper.

[3] The real options approach applies option concepts to the valuation of real assets under uncertainty. It has become an important growth area in investment theory. See Dixit and Pindyck (1994) for a basic treatment of the tools employed. See also Smits and Trigeorgis (2004) for a real options approach to game-theoretic models.

Second, while previous studies assume that firms' positions in a market are exogenously given, in our model they are endogenously determined. This is because we would like to consider the firm's preemption incentive in an open access environment. The preemption effect was originally examined by Fudenberg and Tirole (1985) and Katz and Shapiro (1987). An open access environment gives a follower an advantage in the sense that a follower can avoid the network sunk cost by accessing a leader's network with payment of an access charge. This follower advantage may weaken a firm's preemption incentive (i.e., it may deter the introduction of new network infrastructures in a market). By analyzing the effect of allowing access on the preemption incentive in an open access environment, we can consider the priority of the two competition schemes in terms of the rapidity of the initial construction of network infrastructure.

Hori and Mizuno (2006) have already analyzed the effect of access charges on firms' incentives for preemption and investment with stochastically growing demand. However, comparison of the competition schemes has not been hitherto attempted. This paper extends the analysis to suggest the optimal choice of competition scheme in order to promote investment in network infrastructure. In particular, using the model developed in Hori and Mizuno (2006), this paper derives the conditions for one competition scheme to give the firm more incentive to invest in network infrastructure than another competition scheme.

We firstly show that service-based competition makes the construction of a bypass by an entrant (or a follower) later than under facility-based competition, so long as the entrant accesses the incumbent's (or the leader's) network in service-based competition. We then examine the incumbent's incentive to invest in network infrastructure. In particular, we show that when monopoly rent is large, facility-based competition provides for the earlier initial introduction of infrastructure than service-based competition. In addition, we clarify the conditions for the level of access charge where facility-based competition ensures the earlier initial introduction of infrastructure than service-based competition. On the other hand, when both the monopoly rent and the degree of uncertainty are small, service-based competition makes for the earlier initial introduction of infrastructure than facility-based competition. We then discuss the policy implications of these analytical results by applying them to the situation where the Federal Communications Commission (FCC) adopted new rules concerning network unbundling in 2003.

The remainder of the paper is organized as follows. Section 2 presents a model based on Hori and Mizuno (2006). Section 3 describes the equilibria of the two competition schemes. Section 4, which is the main part of the paper, analyzes the conditions that affect the priority of competition schemes in terms of a firm's incentive to invest in network infrastructure. Section 5 provides the case where firms with heterogeneous technology play the investment game as an extension of the model. In addition, it also discusses some policy implications derived from the analysis. Some concluding remarks are made in Section 6.

2 The model

The model presented here is based on Hori and Mizuno (2006). In order to incorporate the dynamics, investment irreversibility, and uncertainty as essential features of regulated competition, the model uses a simplified representation of its static aspect, as explained below.

There are two risk-neutral identical firms with the same production technology, $i = 1, 2$, that plan to enter a market. No firm establishes its facility at the beginning. The firms require two types of facilities to serve consumers in the market: a production facility and a network facility. Investment in these facilities may be undertaken simultaneously or sequentially. A firm builds a production facility at cost I^p, while a network facility (hereafter a network) is built at cost I^n. These investments are irreversible, hence I^p and I^n are sunk costs.

In service-based competition, however, not all firms must invest in a network. In particular, the firm without a network may utilize the existing network for production by paying a usage access charge, $v\,(>0)$, determined by the regulator and taken as given in this analysis.[4] Let us call the firm that initially invests in both kinds of facilities a leader. The other firm, which may or may not have a network, is called a follower. When a follower uses a leader's existing network, the leader incurs an access cost, c. For simplicity, production costs other than access costs are assumed to be zero. On the other hand, in facility-based competition, a follower needs to invest not only in a production facility but also in a network.

The profit flows of the firms are uncertain because the firms face a common exogenous industry shock. We represent the industry shock by Y. Y evolves stochastically according to a geometric Brownian motion given by the following expression:

$$dY_t = \alpha Y_t dt + \sigma Y_t dW, \tag{1}$$

where $\alpha \in [\sigma^2/2,\ r)$ is the drift parameter measuring the expected growth rate of Y,[5] r is the risk-free interest rate, $\sigma > 0$ is a volatility parameter, and dW is the increment of a standard Wiener process where $dW \sim N\,(0, dt)$.

As we focus on investment or entry timing, we represent each firm's profit flow by a reduced form of $\pi = Y\Pi\,(N)$, where $\Pi\,(N)$ is the nonstochastic part of a firm's profit flow at the industry equilibrium with active firms ($N = 0, 1, 2$). Note that in service-based competition, we need to distinguish two duopolistic market structures: access duopoly, where the follower has access to the leader's network; and bypass duopoly, where the follower has its own network, called a bypass. Let

[4] We restrict our attention in this study to a one-way access environment.

[5] Note that by means of $\alpha \geq \sigma^2/2$, we implicitly assume that the firm's profit flow is enhanced stochastically.

$Y\Pi(2)$ represent the profit flow of each firm in the bypass duopoly equilibrium. As the profit flow of a firm in an access duopoly depends on the level of the access charge, we represent the profit flows of a leader and a follower in the access duopoly equilibrium by $Y\Pi^L(2; v)$ and $Y\Pi^F(2; v)$, respectively. In facility-based competition where a follower invests not only in a production facility, but also in a network, the relevant profit flow of each firm in duopoly is $Y\Pi(2)$.

We assume the following relationship among the nonstochastic parts of a firm's reduced profit flow.

Assumptions (i) $\Pi(1) > \Pi(2)$ and $\Pi(1) > \Pi^j(2; v)$ for $j = L, F$, (ii) $\Pi(2) \geq \Pi^F(2; v)$, (iii) $\Pi^L(2; v) \underset{(<)}{\geq} \Pi^F(2; v)$ if $v \underset{(<)}{\geq} c$, (iv) $\frac{\partial \Pi^L(2;v)}{\partial v} > 0$, $\frac{\partial \Pi^F(2;v)}{\partial v} < 0$.

Assumption (i) is natural. In a service-based competition scheme, (iii) and (iv) are also natural. Assumption (ii) comes from the idea that the additional supply of network generally improves the quality of goods or causes a positive externality, thereby increasing the consumers' willingness to pay.[6] Accordingly, (ii) states that these kinds of positive externality are reflected in an increase in each firm's profit flow. This can exceed the profit flow of a follower in an access duopoly when the level of access charge lies in a reasonable range.

Within each instant $[t, t + dt]$, the timing of the game is the following. In the model, we take a competition scheme and the level of v as given. First, each firm decides whether to invest, given the realization of Y. Second, when entering the market, a firm decides the output level in the production stage, and the market clears. In our framework, the equilibrium profits in the second stage are represented by the reduced profits presented earlier.

We focus on the Markov strategies. That is, the firms' investment and quantity decisions depend only on the current value of Y. The relevant equilibrium concept

[6] For example, as the construction of an additional broadband cable can increase the speed of information flows, it benefits the population of Internet users.

is a Markov-perfect equilibrium.

3 Equilibria in the two competition schemes

Let us examine the equilibria of the game described in Section 2. At first, we characterize the equilibrium in facility-based competition. We then examine the equilibrium in service-based competition.

3.1 Facility-based competition equilibrium

As usual in dynamic game contexts, the game is solved backwards. We start by considering a follower's strategy (i.e., when to enter by building a bypass). A leader's strategy is then examined, given the follower's strategy. [7]

First, a follower's strategy is examined. In a facility-based competition scheme, to serve consumers, the follower must invest not only in a production facility but also in a bypass, so that the total investment cost is $I^p + I^n$. The follower's profit flow is $Y\Pi(2)$.

Given the fact that the other firm has already entered the market, the optimal investment policy for a follower is formulated as follows:

$$V_t^F(Y_t) = \max_T E\left\{ e^{-r(T-t)} \left(\int_T^\infty e^{-r\tau} Y_\tau \Pi(2)\, d\tau - (I^p + I^n) \right) \middle| Y_t \right\}, \qquad (2)$$

where E denotes expectations conditional on Y_t, and T is the future time at which the investment is made.

Equation (2) is the same as the simultaneous investment case described in Section 3 of Hori and Mizuno (2006). Following the procedure explained therein, we obtain

[7] The following procedure is standard in the real options literature concerning strategic investment. See Ch. 9 of Dixit and Pindyck (1994) and Smit and Trigeorgis (2004). See Nielsen (2003) and Weeds (2003) for applications.

each firm's value function as follows:

$$V_F^B(Y)=\begin{cases} CY^{\beta} & if \quad Y<Y^B \\ \frac{Y\Pi(2)}{r-\alpha}-(I^p+I^n) & if \quad Y\geq Y^B, \end{cases} \tag{3}$$

where $C{=}\left(Y^B\right)^{-\beta}\left[\frac{Y^B\Pi(2)}{r-\alpha}-(I^p+I^n)\right]$ and $\beta=\frac{1}{2}\left\{1-\frac{2\alpha}{\sigma^2}+\sqrt{\left(1-\frac{2\alpha}{\sigma^2}\right)^2+\frac{8r}{\sigma^2}}\right\}(>1)$.
The trigger point is given by:

$$Y^B=\frac{\beta}{\beta-1}\frac{r-\alpha}{\Pi(2)}(I^p+I^n). \tag{4}$$

CY^{β} in (4) is the value of delaying the investment, which corresponds to the value of the call option.

Secondly, we consider a leader's value. If $Y<Y^B$, the leader enjoys the monopoly profit before the follower invests. If $Y\geq Y^B$, it obtains a duopoly profit. Hence, its value function is represented as follows.

$$V_L^B(Y)=\begin{cases} \frac{Y\Pi(1)}{r-\alpha}\left[1-\left(\frac{Y}{Y^B}\right)^{\beta-1}\right]+\left(\frac{Y}{Y^B}\right)^{\beta}\frac{Y^B\Pi(2)}{r-\alpha}-(I^p+I^n) & if \quad Y<Y^B \\ \frac{Y\Pi(2)}{r-\alpha}-(I^p+I^n) & if \quad Y^B\leq Y \end{cases} \tag{5}$$

Finally, we can derive the *facility-based competition equilibrium* from (4) and (5).[8] In the equilibrium, the two firms do not enter the market when $Y\in[0,Y_L)$, where Y_L is the trigger point at which the leader enters the market. Y_L is defined as the smallest value of Y that satisfies $V_L^B(Y)=V_F^B(Y)$. When $Y\in\left[0,Y^B\right)$, the leader enjoys a monopoly profit. When $Y\in\left[Y^B,+\infty\right)$, the follower also serves its customers by building a bypass (i.e., a duopoly). The facility-based competition

[8] Put more precisely, two equilibria exist in facility-based competition. We shall, however, make use of the term "equilibrium" rather than "equilibria", because the number of equilibria is unimportant. In fact, there are two facility-based competition equilibria that differ only in the identities of the two firms—firm 1 is the leader in the first equilibrium, and firm 2 is the leader in the second equilibrium. The equilibrium outcome is the same for the two equilibria.

equilibrium is depicted in Figure 1.

[Insert Figure 1]

3.2 Service-based competition equilibrium

Next, we derive the equilibrium in service-based competition. When a follower is allowed to access a leader's network, several types of equilibria can occur, depending on the follower's strategy. For example, an equilibrium occurs where a follower enters the market by building a bypass, in spite of the access opportunity. In a stochastically growing demand environment, however, it is natural to examine the situation where a follower enters with access to a leader's network, and in the future, the follower will build a bypass itself. We call the follower's strategy an "access-to-bypass" strategy.

Hori and Mizuno (2006) have already derived the conditions for the existence of *the access-to-bypass equilibrium* where a leader first enters the market by building a network, and a follower takes the access-to-bypass strategy. The access-to-bypass equilibrium has two features: it is a leader–follower equilibrium, and a follower undertakes sequential investment. From this point onwards, we restrict our attention to the access-to-bypass equilibrium.[9]

Let us denote a follower's trigger point above which it enters the market with access by Y^{A*} and the trigger point above which it builds a bypass by Y^{B*}, respectively. In the access-to-bypass equilibrium, Y^{A*} and Y^{B*} are characterized as follows:

$$Y^{A*} = \frac{\beta}{\beta - 1} \frac{r - \alpha}{\Pi^F (2; v)} I^p \tag{6}$$

$$Y^{B*} = \frac{\beta}{\beta - 1} \frac{r - \alpha}{\Delta\Pi (2; v)} I^n, \tag{7}$$

[9] See Hori and Mizuno (2006) for the details of the derivation of the access-to-bypass equilibrium.

where $\Delta\Pi(2;v) \equiv \Pi(2) - \Pi^F(2;v)$. In fact, Hori and Mizuno (2006) showed that, under $\Delta\Pi(2;v) > 0$ of Assumption (ii), the follower adopts the access-to-bypass strategy (i.e., when it undertakes a sequential investment) if and only if the following condition holds.

$$\Pi(2) \leq \left(1 + \frac{I^n}{I^p}\right)\Pi^F(2;v) \tag{8}$$

When the follower chooses the access-to-bypass strategy, its value function is as follows.

$$V_F^{AB}(Y) = \begin{cases} \left(\frac{Y}{Y^{A*}}\right)^\beta \left\{\frac{Y^{A*}\Pi^F(2;v)}{r-\alpha} - I^p + \left(\frac{Y^{A*}}{Y^{B*}}\right)^\beta \left[\frac{Y^{B*}\Delta\Pi(2;v)}{r-\alpha} - I^n\right]\right\} & if\ Y < Y^{A*} \\ \frac{Y\Pi^F(2;v)}{r-\alpha} - I^p + \left(\frac{Y}{Y^{B*}}\right)^\beta \left[\frac{Y^{B*}\Delta\Pi(2;v)}{r-\alpha} - I^n\right] & if\ Y^{A*} \leq Y < Y^{B*} \\ \frac{Y\Pi(2)}{r-\alpha} - (I^p + I^n) & if\ Y^{B*} \leq Y \end{cases} \tag{9}$$

Similarly, we can derive the leader's value function when the follower adopts the access-to-bypass strategy.

$$V_L^{AB}(Y) = \begin{cases} \frac{Y\Pi(1)}{r-\alpha}\left[1 - \left(\frac{Y}{Y^{A*}}\right)^{\beta-1}\right] + \left(\frac{Y}{Y^{A*}}\right)^\beta \left\{\frac{Y^{A*}\Pi^L(2;v)}{r-\alpha}\left[1 - \left(\frac{Y^{A*}}{Y^{B*}}\right)^{\beta-1}\right]\right. \\ \quad \left. + \left(\frac{Y^{A*}}{Y^{B*}}\right)^{\beta_1} \frac{Y^{B*}\Pi(2)}{r-\alpha}\right\} - (I^p + I^n) & if\ Y < Y^{A*} \\ \frac{Y\Pi^L(2;v)}{r-\alpha}\left[1 - \left(\frac{Y}{Y^{B*}}\right)^{\beta-1}\right] + \left(\frac{Y}{Y^{B*}}\right)^\beta \frac{Y^{B*}\Pi(2)}{r-\alpha} - (I^p + I^n) \\ \quad & if\ Y^{A*} \leq Y < Y^{B*} \\ \frac{Y\Pi(2)}{r-\alpha} - (I^p + I^n) & if\ Y^{B*} \leq Y \end{cases} \tag{10}$$

[Insert Figure 2]

Figure 2 depicts the access-to-bypass equilibrium. For $Y \in [0, Y_L^*)$, neither of the firms enters. For $Y \in \left[Y_L^*, Y^{A*}\right)$, only one of the firms enters the market and earns a monopoly profit. For $Y \in [Y^{A*}, Y^{B*})$, the other firm as a follower has access to a leader's network (access duopoly). For $Y \in [Y^{B*}, +\infty)$, the follower builds its own network (bypass duopoly).

4 Comparison of the two competition schemes

We are now in a position to examine the priority of the competition schemes in terms of the firms' investment decisions. The following section discusses the policy implications.

4.1 A follower's investment decision

We first can confirm that in service-based competition, a follower enters the market earlier and builds a bypass later than in facility-based competition.

Proposition 1 *In the access-to-bypass equilibrium, (i) a follower enters the market earlier than a follower in the facility-based competition equilibrium, and (ii) a follower builds a bypass later than a follower in the facility-based competition equilibrium. That is,* $Y^{A*} < Y^{B} < Y^{B*}$.

Proof. See Appendix. ■

The first inequality in Proposition 1 shows that a follower's entry in service-based competition can be earlier than that in facility-based competition. This holds as long as the access charge is in the range where the follower adopts the access-to-bypass strategy. The second inequality in Proposition 1 states that a follower in the service-based competition builds a bypass later than one in facility-based competition.

The second result is explained by the replacement effect: the follower that already gains profit through access to the leader's network has less incentive to build a bypass than the potential follower that now intends to enter the market. The replacement effect also appears in Lemma 6 of Bourreau and Doğan (2005). They argue that when there is unbundling, a follower builds its bypass later than when there is no unbundling. While there are a few differences in the setting of the model between the two studies, the replacement effect is robust.

From Proposition 1, we can immediately verify the effect of uncertainty on a follower's investment decisions in the two competition schemes.

Proposition 2 *As the degree of uncertainty increases, the difference of a follower's investment timing gets larger between the two competition schemes.*

Proof. As is already known, β gets small as σ gets large.[10] Then, from the forms of Y^{A*}, Y^{B}, and Y^{B*} and the fact that $Y^{A*} < Y^{B} < Y^{B*}$, the claim in the proposition holds automatically. ■

Proposition 2 implies that as uncertainty increases, the difference in a follower's entry timing gets larger, in turn causing a significant impact on social welfare. This point will be discussed in the next section.

4.2 A leader's investment decision

We next compare the entry timing of a leader in the two competition schemes. The following proposition states the necessary and sufficient condition for a leader in the access-to-bypass equilibrium to enter earlier than in the facility-based competition equilibrium.

Proposition 3 *A leader enters earlier (later) in the facility-based competition equilibrium than in the access-to-bypass equilibrium (i.e., $Y_L^* > (<) Y_L$) if and only if:*

$$Q^{AB}(Y_L) < (>)\, 0,$$

[10] See p. 144 of Dixit and Pindyck (1994).

where $Q^{AB}(Y) \equiv V_L^{AB}(Y) - V_F^{AB}(Y)$ *is the difference in firm value between the leader and the follower in the access-to-bypass equilibrium.*

Proof. Y_L^* is the smallest value of Y that satisfies $Q^{AB}(Y) = 0$. Therefore, $Q^{AB}(Y_L)$ is negative (positive) if and only if $Y_L^* > (<) Y_L$. ■

However, substituting (9) and (10) directly into $Q^{AB}(Y_L)$ yields too complicated an expression to obtain an intuitive interpretation. Hence, we instead attempt to seek a sufficient condition for one competition scheme to make a leader's entry earlier than the other. In fact, we show that three elements (i.e., monopoly rent, the level of access charge, and the degree of uncertainty) are key factors in determining the priority of competition schemes in terms of a leader's investment timing.

First, we show that when monopoly rent is large, facility-based competition induces a leader to invest earlier than in service-based competition.

Proposition 4 *If* $\Pi(1)$ *is sufficiently large, a leader in the facility-based competition equilibrium invests in both production and network facilities earlier than in the access-to-bypass equilibrium (i.e.,* $Y_L < Y_L^*$*).*

Proof. See Appendix. ■

Note that $\Pi(1)$ does not affect the follower's decision on access to the leader's network and the construction of a bypass. Hence, when $\Pi(1)$ is sufficiently large, service-based competition decelerates introduction of new infrastructure in a region which is not yet covered, without any influence on competition in the product market.

[Insert Figure 3]

The intuitive reasoning of Proposition 4 is simple. See Figure 3. According to Proposition 1, $Y^{A*} < Y^B$, which means a leader in the facility-based competition equilibrium enjoys monopoly rent for a longer period than in the access-to-bypass equilibrium. Hence, the preemption incentive of a leader in the facility-based competition equilibrium is larger than that in the access-to-bypass equilibrium.

We next examine the effect of a change in the level of access charge on investment decisions in the two competition schemes. Concerning the follower's investment decision, Proposition 1 already discusses this effect: when the level of access charge lies in the range where the access-to-bypass equilibrium exists, a follower's entry in service-based competition is earlier than in facility-based competition, with a bypass being built later.[11] What then is its effect on a leader's investment timing?

Because the effect of the access charge on $Q^{AB}(Y_L)$ works nonlinearly, it is difficult to derive analytically a necessary and sufficient condition for one competition scheme to make one leader's entry earlier than the other's. Hence, we again seek a sufficient condition for one competition scheme to do so. The next proposition provides a sufficient condition for a leader in facility-based competition to invest earlier than in service-based competition.

Proposition 5 *(i) A leader in the facility-based competition equilibrium invests in both kinds of facilities earlier than in the access-to-bypass equilibrium (i.e., $Y_L < Y_L^*$) when the level of access charge satisfies the following condition.*

$$\frac{\Pi(1) - \Pi^L(2;v)}{\Pi^F(2;v)} \geq \frac{\Pi(1) - \Pi(2)}{\Pi(2)} \tag{11}$$

(ii) The timing of the leader's investment in the access-to-bypass equilibrium becomes later as the access charge gets smaller, as long as (11) holds.

Proof. See Appendix. ■

[11] If the access charge is above this range, the follower builds a bypass, so that the follower's investment timing is the same in the two competition schemes.

The intuitive meaning of the condition (11) is as follows. The numerator on the left-hand side represents the profit or loss a leader incurs when the market structure changes from a monopoly to an access duopoly, while the denominator represents the profit a follower obtains in an access duopoly. Hence, the left-hand side is the relative cost a leader incurs from structural change in the market in the service-based competition scheme. The right-hand side has exactly the same meaning as in the case of facility-based competition. Therefore, condition (11) states that when the relative cost a leader incurs from structural change in a facility-based competition scheme is less than in service-based competition, the preemption effect is larger for the facility-based competition scheme.

Note that condition (11) also implies the range of monopoly rent $\Pi(1)$ that induces a leader in facility-based competition to invest in both kinds of facilities earlier than one in the access-to-bypass equilibrium. In fact, rearranging (11) gives us the following.

$$\Pi(1) \geq \frac{\Pi(2)\left(\Pi^L(2;v) - \Pi^F(2;v)\right)}{\Pi(2) - \Pi^F(2;v)} \tag{12}$$

The difference between (12) and Proposition 4 is that (12) refers to the relationship between the monopoly rent and the level of access charge or the network externality, whereas Proposition 4 mentions only the degree of monopoly rent. The intuitive meaning of (12) is the same as Proposition 4.

So far, we provide only sufficient conditions for facility-based competition to cause a leader to invest earlier than in service-based competition. The following proposition, which highlights not only the monopoly rent but also the degree of uncertainty, gives a sufficient condition for service-based competition to cause a leader to invest earlier than facility-based competition.

Proposition 6 *If the monopoly rent is small such that* $\Pi(1) \leq \frac{\Pi^F(2;v)(I^p+I^n)}{I^p}$*, a leader in the access-to-bypass equilibrium invests earlier than a leader in the facility-*

based competition equilibrium (i.e., $Y_L^* < Y_L$) as σ approaches to zero.

.

Proof. See Appendix. ■

Proposition 6 states that when both monopoly rent and uncertainty are small, the preemption effect in the access-to-bypass equilibrium is stronger than in the facility-based competition equilibrium. This is explained as follows.

Remember that $Y^{A*} < Y^B$. (See Figure 3 again.) This implies that a leader in the facility-based competition equilibrium can earn a monopoly rent for a longer period than in the access-to-bypass equilibrium. According to Proposition 2, a decrease in σ makes Y^{A*} closer to Y^B. That is, the difference in the period in which the leader can earn the larger rent in the facility-based competition equilibrium than in the access-to-bypass equilibrium (i.e., $\Pi(1) > \Pi^L(2; v)$) becomes shorter as uncertainty is reduced.[12]

Moreover, for $Y \in [Y^B, Y^{B*}]$, the leader in the access-to-bypass equilibrium can obtain higher profit than in the facility-based competition equilibrium (i.e., $\Pi^L(2; v) > \Pi(2)$), when the access-to-bypass equilibrium exists. The access profit can then compensate for the loss caused by a shorter period of monopoly rent in the access-to-bypass equilibrium where the monopoly rent is smaller. Therefore, a leader in the access-to-bypass equilibrium has a greater incentive to enter than a leader in the facility-based competition equilibrium, when both the monopoly rent and uncertainty are small.

[12] However, note that the effect of uncertainty on a leader's entry timing in a *given* competition scheme in our model is still ambiguous. This ambiguity stems from the conflict between the preemption effect and the real options effect. Because a follower enters later when uncertainty is higher, the incentive to become a leader becomes larger. This is because a leader can enjoy a monopoly rent for a longer period. Hence, the preemption motive is a countervailing force to the real options effect. This point is also illustrated by Mason and Weeds (2003). They demonstrate that if monopoly profits are large, an increase in uncertainty hastens the leader's entry.

5 Discussion

5.1 An investment game of firms with heterogeneous technology

So far we have assumed that there are two identical firms with the same production technology. In a real business environment, however, different firms may have different technologies. Hence, we extend our model to deal with the case where there are two firms with heterogeneous technology. In this section, we derive an access-to-bypass equilibrium where the cost of the network facility, I^n, differs among the firms.

Let I_1^n and I_2^n denote the respective costs for firms 1 and 2. Without loss of generality, we assume that I_1^n is smaller than I_2^n. Furthermore, I_1^n is specified as $I^n - \epsilon$, while I_2^n is specified as $I^n + \epsilon$ where $\epsilon > 0$. Under these assumptions, we can show the following proposition.

Proposition 7 *Assume that there are two identical firms, save the cost of the network facility, and the investment game begins with a sufficiently low level of Y. In the access-to-bypass equilibrium, (i) a firm with a lower cost of the network facility does not construct a bypass later than a firm with a higher cost, (ii) the difference in the cost of the network facility does not matter for the timing of access by the entrant, and (iii) the firm with the lower cost enters the market earlier than one with a higher cost.*

Proof. See Appendix ■

If the investment game begins with a sufficiently low level of Y, firm 1 becomes a leader in service-based competition, while firm 2 becomes a follower. This suggests that firms with advanced technology or lower costs crowd out other firms and so enter the market as leaders. Moreover, the larger the ϵ, implying a wider discrepancy in technology, the longer the expected period of monopoly and access duopoly.

The results of (i) and (iii) of Proposition 7 can apply to the facility-based competition equilibrium. Therefore, the heterogeneous technology would only identify the incumbent and the entrants but would not alter the implications obtained from Propositions 1 to 6.[13]

5.2 Policy implications

In the above analysis, we took the competition scheme and level of access charge as given, and examined the relationship between the choice of a competition scheme and the investment decisions of both the leader and the follower. Although all of the propositions derived above concern which particular competition scheme can achieve earlier investment timing, earlier timing is not necessarily better from a welfare viewpoint. In fact, it is difficult to determine which of the two competition schemes is better from a welfare viewpoint. This point is explained as follows.

Denoting the social surplus flow in the monopoly and in the (bypass) duopoly by $SS(1)$ and $SS(2)$ respectively, we can derive the socially optimal investment timing in our stochastic environment as follows:

$$Y_L^{**} = \frac{\beta}{\beta-1}\frac{r-\alpha}{SS(1)}\left(I^p + I^n\right), \text{ and } Y^{B**} = \frac{\beta}{\beta-1}\frac{r-\alpha}{\Delta SS}\left(I^p + I^n\right), \tag{13}$$

where $\Delta SS \equiv SS(2) - SS(1)$. Then, it is easy to verify that comparison of these socially optimal timings with the investment timings in the equilibrium of each competition scheme is difficult. The bottom line is that the comparison depends on various factors, including the shape of the inverse demand function, the invest-

[13] Another possible heterogeneity is profitability. As both the stochastic and nonstochastic parts of a firms' profit flow can differ between firms, a firm with higher profits would be the incumbent while one with lower profits would be the entrant.

ment costs of the production and network facilities, the preemption incentive, and the parameters of (1) that define the geometric Brownian motion. This reasoning also works when we try to compare the two competition schemes from a welfare viewpoint.

Nevertheless, we can obtain some policy implications for the choice of competition scheme. According to Proposition 1, a follower under service-based competition is more proactive in entering a market than under facility-based competition, because it need not incur the large sunk costs of building its own network. In this respect, service-based competition realizes a competitive environment in the product market earlier than facility-based competition. This, in turn, contributes to the enhancement of social welfare.[14] This is consistent with a crucial aspect of service-based competition that has been pointed out in the literature. That is, a competitive environment can be achieved earlier under service-based competition because of nonduplication in the network investment's sunk cost.[15] In fact, this provided a partial rationale for the unbundling provisions of the 1996 Telecommunications Act.

However, service-based competition simultaneously entails the late construction of a bypass. This implies the later introduction of a positive externality generated by the prevalence of infrastructure. Because consumers also obtain benefit from the positive externality, service-based competition may be harmful. In sum, service-based competition includes benefits and costs from a welfare viewpoint when focusing on the follower's entry. Note also that the magnitude of the benefits and costs becomes larger as uncertainty increases (Proposition 2).

On the other hand, according to Propositions 4 and 5, service-based competition

[14] One may speculate whether a *follower*'s entry timing can be too early from a welfare perspective. Because a firm's incentive to enter a market depends only on the profit motive, the possibility of a follower's entry timing being too early appears to be low.

[15] When an entrant captures some customers by already providing a different service other than a new service, service-based competition may immediately achieve a competitive environment in the new service market. This idea is related to the existence of consumers' switching costs with multiple markets. Although our analysis can include this idea by changing a firm's profit flow in the case of service-based competition, the main qualitative results would be unchanged.

may deter the initial construction of network infrastructure, which depends on the environment surrounding firms. Therefore, we cannot confirm whether service-based competition enhances social welfare in regard to a leader's entry.

In reality, the negative effect of service-based competition on social welfare already appears to be recognized, particularly in telecommunications. For example, it has been argued that the U.S. is not necessarily a well-developed country in the field of broadband networks such as fiber optics. Several aspects of the regulatory regime in the 1996 Telecommunications Act, such as asymmetric regulation between cable TV companies and incumbent local exchange companies (ILEC), have already been considered as elements that deter investment in broadband networks.[16] We can give another explanation for this phenomenon by applying our analytical results. According to our analysis, this is because the monopoly rent has been large in the US telecommunication industry. In fact, because cable TV networks were prevalent in the US broadband market, the advantage of the leader introducing a fiber optic cable network with a higher-speed internet service would be large. In addition, the demand for broadband services has not been readily estimated (i.e., its demand is uncertain), because wireless and the Internet have changed the way people communicate. Hence, in that situation, facility-based competition has been superior to service-based competition in terms of the early investment in new infrastructure. As a result, in 2003, the Federal Communications Commission (FCC) adopted new rules regarding the network unbundling obligations of incumbent local phone carriers, with the aim of providing incentives for the carriers to invest in broadband (i.e., the change in the competition scheme toward facility-based competition).

[16] See Crandall and Alleman (2003) for details of the policy debate on the development of US broadband networks.

6 Concluding remarks

This paper compared two specific types of competition schemes (i.e. service-based competition and facility-based competition) by focusing on a firm's incentive to invest in network infrastructure. To address this issue, we employed a real options approach, because the uncertainty and irreversibility of investment are influential factors when considering investment problems.

The analysis showed that service-based competition makes the construction of a bypass, by either an entrant or a follower, later than facility-based competition so long as an entrant accesses an incumbent's network in service-based competition. We then examined the leader's (i.e., the first entrant) incentive to invest in network infrastructure. In particular, we showed that when monopoly rent is large, facility-based competition means that the introduction of a new type of infrastructure is made earlier than in service-based competition. In addition, we clarified the conditions concerning the level of access charge where facility-based competition provides for the introduction of a new type of infrastructure earlier than under service-based competition. On the other hand, when both the monopoly rent and the degree of uncertainty are small, service-based competition means that the introduction of a new type of infrastructure is made earlier than under facility-based competition. These findings indicated the relationship between the timing of the building of infrastructure and the degree of competitiveness in product markets. We also discussed other policy implications of the analytical results.

Appendix

Proof of Proposition 1

(i) In the access-to-bypass equilibrium, the relationship that $Y^{A*} < Y^{B*}$ holds. We show that $Y^{A*} < Y^{B}$ if and only if $Y^{A*} < Y^{B*}$. This is because:

$$
\begin{aligned}
Y^{A*} &\equiv \frac{\beta}{\beta-1}\frac{r-\alpha}{\Pi^{F}(2;v)}I^{p} < \frac{\beta}{\beta-1}\frac{r-\alpha}{\Delta\Pi(2;v)}I^{n} \equiv Y^{B*} \\
&\Leftrightarrow \left(\Pi(2)-\Pi^{F}(2;v)\right)I^{p} < \Pi^{F}(2;v)\,I^{n} \\
&\Leftrightarrow Y^{A^{*}} \equiv \frac{\beta}{\beta-1}\frac{r-\alpha}{\Pi^{F}(2;v)}I^{p} < \frac{\beta}{\beta-1}\frac{r-\alpha}{\Pi(2)}\left(I^{p}+I^{n}\right) \equiv Y^{B}.
\end{aligned}
$$

(ii) Similarly, it is easy to show that $Y^{B} < Y^{B*}$ if and only if $Y^{A*} < Y^{B*}$. In fact:

$$
\begin{aligned}
Y^{A*} &\equiv \frac{\beta}{\beta-1}\frac{r-\alpha}{\Pi^{F}(2;v)}I^{p} < \frac{\beta}{\beta-1}\frac{r-\alpha}{\Delta\Pi(2;v)}I^{n} \equiv Y^{B*} \\
&\Leftrightarrow \left(\Pi(2)-\Pi^{F}(2;v)\right)I^{p} < \Pi^{F}(2;v)\,I^{n} \\
&\Leftrightarrow Y^{B} \equiv \frac{\beta}{\beta-1}\frac{r-\alpha}{\Pi(2)}\left(I^{p}+I^{n}\right) < \frac{\beta}{\beta-1}\frac{r-\alpha}{\Delta\Pi(2;v)}I^{n} \equiv Y^{B*}.
\end{aligned}
$$

Therefore, we have $Y^{B} < Y^{B*}$. ■

Proof of Proposition 4

Substituting (9) and (10) for $\forall Y \in \left(0, Y^{A*}\right)$ into $Q^{AB}(Y) \equiv V_{L}^{AB}(Y) - V_{F}^{AB}(Y)$ and rearranging it, we have:

$$
\begin{aligned}
Q^{AB}(Y) &= \frac{Y\Pi(1)}{r-\alpha} - \left(I^{p}+I^{n}\right) \\
&\quad + \left(\frac{Y}{Y^{A*}}\right)^{\beta}\left\{I^{p} + \frac{Y^{A*}\Pi^{LF}(2;v)}{r-\alpha} - \frac{Y^{A*}\Pi(1)}{r-\alpha}\right\} \\
&\quad + \left(\frac{Y}{Y^{B*}}\right)^{\beta}\left\{I^{n} - \frac{Y^{B*}\Pi^{LF}(2;v)}{r-\alpha}\right\}. \qquad (14)
\end{aligned}
$$

To prove the proposition, we check the sign of $Q^{AB}(Y_{L})$ where Y_{L} is the trigger point of the leader under facility-based competition equilibrium.

Note that Y_L is characterized by $V_L^B(Y_L) = V_F^B(Y_L)$, so that we have:

$$\begin{aligned} & \frac{Y_L \Pi(1)}{r-\alpha}\left[1-\left(\frac{Y_L}{Y^B}\right)^{\beta-1}\right]+\left(\frac{Y_L}{Y^B}\right)^{\beta}\frac{Y^B \Pi(2)}{r-\alpha}-(I^p+I^n) \\ = & \left(\frac{Y_L}{Y^B}\right)^{\beta_1}\left[\frac{Y^B \Pi(2)}{r-\alpha}-(I^p+I^n)\right], \end{aligned}$$

or:

$$\frac{Y_L \Pi(1)}{r-\alpha}-(I^p+I^n)=\left(\frac{Y_L}{Y^B}\right)^{\beta}\left[\frac{Y^B \Pi(1)}{r-\alpha}-(I^p+I^n)\right]. \tag{15}$$

Substituting (15) into $Q^{AB}(Y_L)$ gives:

$$Q^{AB}(Y_L) = (Y_L)^{\beta}\chi(\mathbf{x}),$$

where:

$$\begin{aligned} \chi(\mathbf{x}) \equiv & \left(Y^B\right)^{-\beta}\left[\frac{Y^B \Pi(1)}{r-\alpha}-(I^p+I^n)\right] \\ & +\left(Y^{A*}\right)^{-\beta}\left[I^p+\frac{Y^{A*}\Pi^{LF}(2;v)}{r-\alpha}-\frac{Y^{A*}\Pi(1)}{r-\alpha}\right] \\ & +\left(Y^{B*}\right)^{-\beta}\left[I^n-\frac{Y^{B*}\Pi^{LF}(2;v)}{r-\alpha}\right], \end{aligned} \tag{16}$$

and $\mathbf{x} \equiv (v, \Pi(1), \Pi(2), I^p, I^n)$.

Hence, $Q^{AB}(Y_L) < 0$ if $\chi(\mathbf{x}) < 0$. Note that the terms in the bracket of the third term of (16) are negative under the condition of (8). Hence, $\chi(\mathbf{x}) < 0$ if:

$$\left(Y^B\right)^{-\beta}\left[\frac{Y^B \Pi(1)}{r-\alpha}-(I^p+I^n)\right]+\left(Y^{A*}\right)^{-\beta}\left[I^p+\frac{Y^{A*}\Pi^{LF}(2;v)}{r-\alpha}-\frac{Y^{A*}\Pi(1)}{r-\alpha}\right]<0, \tag{17}$$

or:

$$\left(Y^B\right)^{-\beta}(I^p+I^n)\left[\frac{\beta}{\beta-1}\frac{\Pi(1)}{\Pi(2)}-1\right]$$
$$+\left(Y^{A*}\right)^{-\beta}I^p\left[1+\frac{\beta}{\beta-1}\frac{\Pi^{LF}(2;v)}{\Pi^F(2;v)}-\frac{\beta}{\beta-1}\frac{\Pi(1)}{\Pi^F(2;v)}\right]<0. \tag{18}$$

We will show (18) holds if $\Pi(1)$ is sufficiently large.

Define $\Gamma[\Pi(1)] \equiv [m\Pi(1)-l]/[j\Pi(1)-k]$ where $m \equiv \frac{\beta}{\beta-1}\frac{I^p}{\Pi^F(2;v)}$, $l \equiv I^p + \frac{\beta}{\beta-1}\frac{\Pi^{LF}(2;v)}{\Pi^F(2;v)}$, $j \equiv \frac{\beta}{\beta-1}\frac{I^p+I^n}{\Pi(2)}$, and $k \equiv (I^p+I^n)$. Note that (8) ensures $j \geq m$ as long as the access-to-bypass equilibrium exists. In addition, $l > k$ holds if (8) holds. Hence:

$$\frac{d\Gamma[\Pi(1)]}{d\Pi(1)}=\frac{jl-km}{[j\Pi(1)-k]^2}>0. \tag{19}$$

Equation (19) shows that $\Gamma[\Pi(1)]$ is an increasing function of $\Pi(1)$ and that $\Gamma[\Pi(1)]$ monotonically converges to m/j as $\Pi(1)$ goes to infinity.

Let us compare $\left(Y^{A*}/Y^B\right)^\beta$ with $\Gamma[\Pi(1)]$. Because $Y^{A*}/Y^B = m/j < 1$ and $\beta > 1$, there exists a threshold of $\Pi(1)$ above which $(m/j)^\beta < \Gamma[\Pi(1)]$ or:

$$\left(\frac{Y^{A*}}{Y^B}\right)^\beta<\frac{m\Pi(1)-l}{j\Pi(1)-k}. \tag{20}$$

Because $\Pi(1) > \Pi(2)$, we have $j\Pi(1)-k > 0$. Hence, rearranging (20) gives (18). That is, if $\Pi(1)$ is sufficiently large, a leader enters earlier in the facility-based competition equilibrium than in the access-to-bypass equilibrium. ■

Proof of Proposition 5

Substituting Y_L into Y in (19) and using $I^p = (\beta/(\beta-1))\left(\Pi^F(2;v)/(r-\alpha)\right)Y^{A*}$ and $I^n = (\beta/(\beta-1))\times(\Delta\Pi(2;v)/(r-\alpha))\,Y^{B*}$, $Q^{AB}(Y_L)$ is rewritten as follows:

$$Q^{AB}(Y_L)=\frac{Y_L\Pi(1)}{r-\alpha}-(I^p+I^n)-(Y_L)^\beta[B_F+B_L],$$

where $B_F \equiv \frac{1}{\beta(r-\alpha)} \left[\Pi^F(2;v) \left(Y^{A*}\right)^{1-\beta} + \Delta\Pi(2;v) \left(Y^{B*}\right)^{1-\beta} \right]$,
and $B_L \equiv \frac{1}{(r-\alpha)} \left[\left(\Pi(1) - \Pi^L(2;v)\right) \left(Y^{A*}\right)^{1-\beta} + \left(\Pi^L(2;v) - \Pi(2)\right) \left(Y^{B*}\right)^{1-\beta} \right]$. Differentiating $Q^{AB}(Y_L)$ with respect to v gives:

$$\frac{\partial Q^{AB}(Y_L)}{\partial v} = -(Y_L)^\beta \frac{\partial [B_F + B_L]}{\partial v}.$$

To prove (i) and (ii) of the proposition, we firstly show that, under condition (11), $Q^{AB}(Y_L)$ is a monotone increasing function of v. Then we show that, at the upper limit of v that guarantees the existence of the access-to-bypass equilibrium, $Q^{AB}(Y_L) = 0$.

In fact, we have:

$$\frac{\partial B_F}{\partial v} = \frac{\beta}{\beta - 1} \frac{\partial \Pi^F(2;v)}{\partial v} \left[\left(Y^{A*}\right)^{-\beta} \frac{I^p}{\Pi^F(2;v)} - \left(Y^{B*}\right)^{-\beta} \frac{I^n}{\Delta\Pi(2;v)} \right], \tag{21}$$

$$\begin{aligned} \frac{\partial B_L}{\partial v} &= \frac{-1}{r-\alpha} \frac{\partial \Pi^L(2;v)}{\partial v} \left[\left(Y^{A*}\right)^{1-\beta} - \left(Y^{B*}\right)^{1-\beta} \right] + \beta \frac{\partial \Pi^F(2;v)}{\partial v} \times \\ & \left[\left(Y^{A*}\right)^{-\beta} \frac{\left(\Pi(1) - \Pi^L(2;v)\right) I^p}{\left(\Pi^F(2;v)\right)^2} - \left(Y^{B*}\right)^{-\beta} \frac{\left(\Pi^L(2;v) - \Pi(2)\right) I^n}{\left(\Delta\Pi(2;v)\right)^2} \right] \end{aligned} \tag{22}$$

Because $Y^{A*}/Y^{B*} = \Delta\Pi(2;v) I^p / \Pi^F(2;v) I^n$ (< 1), both the square bracket of (21) and the one in the first term of (22) are positive. Hence, a sufficient condition for $\partial [B_F + B_L] / \partial v < 0$ is:

$$\left(Y^{A*}\right)^{-\beta} \frac{\left(\Pi(1) - \Pi^L(2;v)\right) I^p}{\left(\Pi^F(2;v)\right)^2} \geq \left(Y^{B*}\right)^{-\beta} \frac{\left(\Pi^L(2;v) - \Pi(2)\right) I^n}{\left(\Delta\Pi(2;v)\right)^2}. \tag{23}$$

Because $\left(Y^{A*}\right)^{-\beta} \frac{I^p}{\Pi^F(2;v)} > \left(Y^{B*}\right)^{-\beta} \frac{I^n}{\Delta\Pi(2;v)}$, the sufficient condition for $\partial [B_F + B_L] / \partial v < 0$ or $\partial Q^{AB}(Y_L) / \partial v > 0$ is:

$$\frac{\Pi(1) - \Pi^L(2;v)}{\Pi^F(2;v)} \geq \frac{\Pi^L(2;v) - \Pi(2)}{\Delta\Pi(2;v)}. \tag{24}$$

Rearranging it, we have

$$\frac{\Pi(1) - \Pi^L(2; v)}{\Pi^F(2; v)} \geq \frac{\Pi(1) - \Pi(2)}{\Pi(2)},$$

which is the condition of (11).

Next, let us examine the upper limit, $\overline{v}$, of the access charge that guarantees the existence of the access-to-bypass equilibrium. It is apparent that (8) defines $\overline{v}$. That is, $\Pi(2) = \left(1 + \frac{I^p}{I^n}\right) \Pi^F(2; \overline{v})$. It is then easy to check that $Q^{AB}(Y_L) = 0$ at $\overline{v}$.

Hence, for $v \leq \overline{v}$, $Q^{AB}(Y_L) < 0$. This means that, under condition (11), a leader in the facility-based competition equilibrium enters earlier than the one in the access-to-bypass equilibrium. ■

Proof of Proposition 6

Let us rewrite $Q^{AB}(Y_L)$ as follows:

$$Q^{AB}(Y_L) = \left(\frac{Y^L}{Y^{A*}}\right)^\beta \widetilde{\chi}(\mathbf{x}),$$

where $\widetilde{\chi}(\mathbf{x}) \equiv \left(Y^{A*}\right)^\beta \chi(\mathbf{x})$ and $\chi(\mathbf{x})$ is defined in the proof of Proposition 3.

Using $Q^{AB}\left(Y^{A*}\right) = \frac{Y^{A*}\Pi^{LF}(2;v)}{r-\alpha} - I^n + \left(\frac{Y^{A*}}{Y^{B*}}\right)^\beta I^n \left[1 - \frac{\beta}{\beta-1}\frac{\Pi^{LF}(2;v)}{\Delta\Pi(2;v)}\right]$, $\widetilde{\chi}(\mathbf{x})$ is rewritten as:

$$\begin{aligned}
\widetilde{\chi}(\mathbf{x}) &= \left(\frac{Y^{A*}}{Y^B}\right)^\beta (I^p + I^n)\left[\frac{\beta}{\beta-1}\frac{\Pi(1)}{\Pi(2)} - 1\right] \\
&\quad + I^p\left[1 - \frac{\beta}{\beta-1}\frac{\Pi(1)}{\Pi^F(2; v)}\right] + I^n + Q^{AB}\left(Y^{A*}\right) \\
&= (I^p + I^n)\left[\left(1 - N^\beta\right) - \frac{\beta}{\beta-1}\frac{\Pi(1)}{\Pi(2)} N\left(1 - N^{\beta-1}\right)\right] + Q^{AB}\left(Y^{A*}\right), \qquad (25)
\end{aligned}$$

where $N \equiv \frac{\Pi(2) I^p}{\Pi^F(2;v)(I^p+I^n)} \left(= \frac{Y^{A*}}{Y^B}\right) < 1$. Let us denote the bracket part of the first term of (25) by $\Omega(N,\beta)$:

$$\Omega(N,\beta) \equiv \left(1-N^{\beta}\right) - \frac{\beta}{\beta-1}\frac{\Pi(1)}{\Pi(2)} N\left(1-N^{\beta-1}\right).$$

Because $Q^{AB}\left(Y^{A*}\right) > 0$, a sufficient condition for $\widetilde{\chi}(\mathbf{x}) > 0$ is $\Omega(N,\beta) > 0$. Then, as $\beta \to \infty$, $\Omega(N,\beta) \to 1 - \frac{\Pi^F(2;v)(I^p+I^n)}{\Pi(1)I^p}$.[17] Therefore, when $\Pi(1) \leq \frac{\Pi^F(2;v)(I^p+I^n)}{I^p}$, $\Omega(N,\beta) > 0$ as $\beta \to \infty$ or $\sigma \to 0$. ■

Proof of Proposition 7

(i) A trigger point where firm 1 builds a bypass is represented by Y_1^{B*}, and the one for firm 2 is represented by Y_2^{B*}. It is easy to verify that $Y_1^{B*} < Y_2^{B*}$ because $I_1^n < I_2^n$.

(ii) A trigger point at which an entrant accesses the incumbent's network facility for both firms remains as Y^{A*}. This is obvious, because Y^{A*} does not depend on the cost of the network facility.

(iii) We show that $Y_{L1}^* < Y_{L2}^*$ where Y_{L1}^* is a trigger point at which firm 1 enters the market as a leader, and Y_{L2}^* is the one for firm 2. Firm 1 is assumed to enter the market as a leader at which $Y = Y_{L1}^*$ is defined by $V_F^{AB}(Y_{L1}^*) = V_L^{AB}(Y_{L1}^*)$, or:

$$B_F\left(Y_{L1}^*\right)^{\beta} = \frac{\Pi(1)}{r-\alpha}Y_{L1}^* - B_L\left(Y_{L1}^*\right)^{\beta} - \left(I^p + I^n - \varepsilon\right), \tag{26}$$

where $B_F \equiv \frac{\Pi^F(2;v)}{\beta(r-\alpha)}\left(Y^{A*}\right)^{1-\beta} + \frac{\Delta\Pi(2;v)}{\beta(r-\alpha)}\left(Y_2^{B*}\right)^{1-\beta}$ and $B_L \equiv \frac{\Pi(1)-\Pi^F(2;v)}{r-\alpha}\left(Y^{A*}\right)^{1-\beta} - \frac{\Delta\Pi(2;v)}{r-\alpha}\left(Y_2^{B*}\right)^{\beta}$. Differentiating this, we have:

$$CdY_{L1}^* + \left[\frac{\partial\left(B_F+B_L\right)}{\partial\epsilon}\left(Y_{L1}^*\right)^{\beta} - 1\right]d\epsilon = 0, \tag{27}$$

[17] Notice that, as $\sigma \to 0$, $\beta \to \frac{r}{\alpha}$ for $\alpha > 0$. (See p.144 of Dixit and Pindyck.) Hence, the claim in this sentence holds when α is sufficiently small when compared with r.

where $C \equiv V_F^{AB\prime}(Y_{L1}^*) - V_L^{AB\prime}(Y_{L1}^*) < 0$. As $\partial Y_2^{B*}/\partial \epsilon > 0$, we have:

$$
\begin{aligned}
\frac{\partial (B_F + B_L)}{\partial \epsilon} &= \frac{\partial (B_F + B_L)}{\partial Y_2^{B*}} \frac{\partial Y_2^{B*}}{\partial \epsilon} \\
&= \left[\frac{(1-\beta)\, \Delta\Pi(2;v)}{\beta(r-\alpha)} \left(Y_2^{B*}\right)^{-\beta} - \frac{\beta \Delta\Pi(2;v)}{r-\alpha} \left(Y_2^{B*}\right)^{\beta-1} \right] \frac{\partial Y_2^{B*}}{\partial \epsilon} < 0.
\end{aligned}
$$

Because $\partial Y_{L1}^*/\partial \epsilon < 0$, we can show that $Y_{L1}^* < Y_L^*$.

On the other hand, we examine the case where firm 2 enters the market as a leader. Through similar calculations, it can be easily shown that $Y_L^* < Y_{L2}^*$. Therefore, $Y_{L1}^* < Y_{L2}^*$. ■

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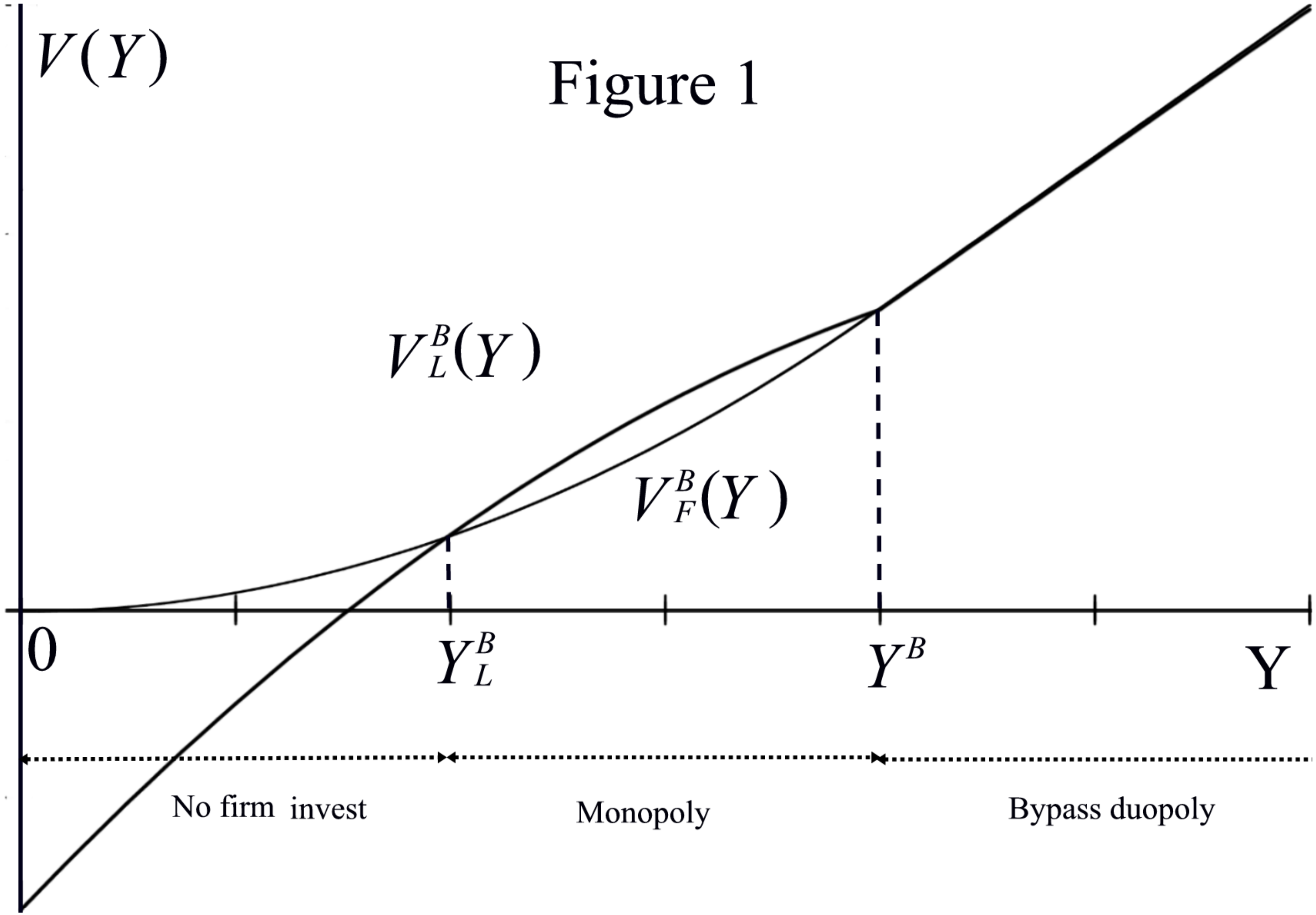
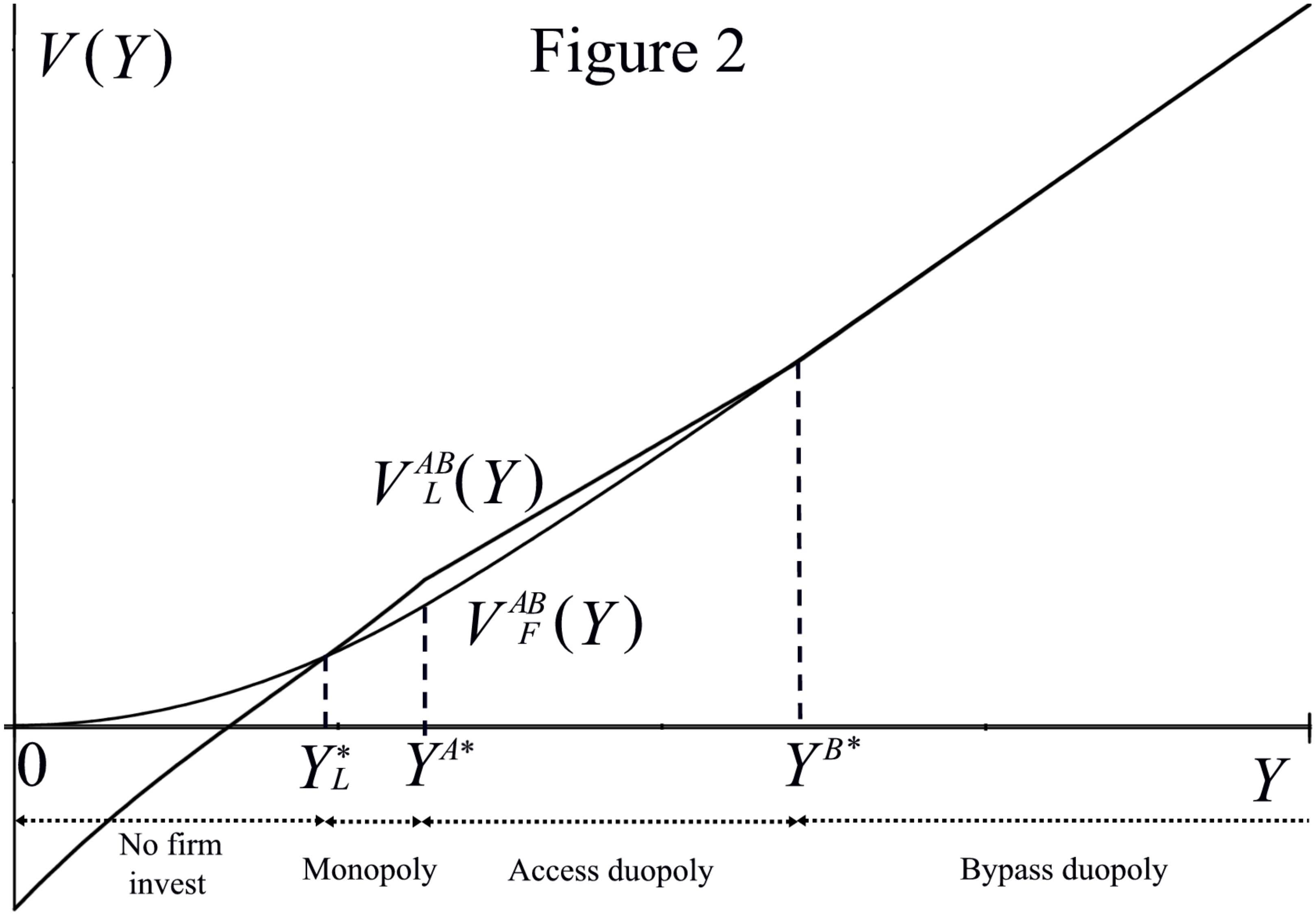
Figure 1

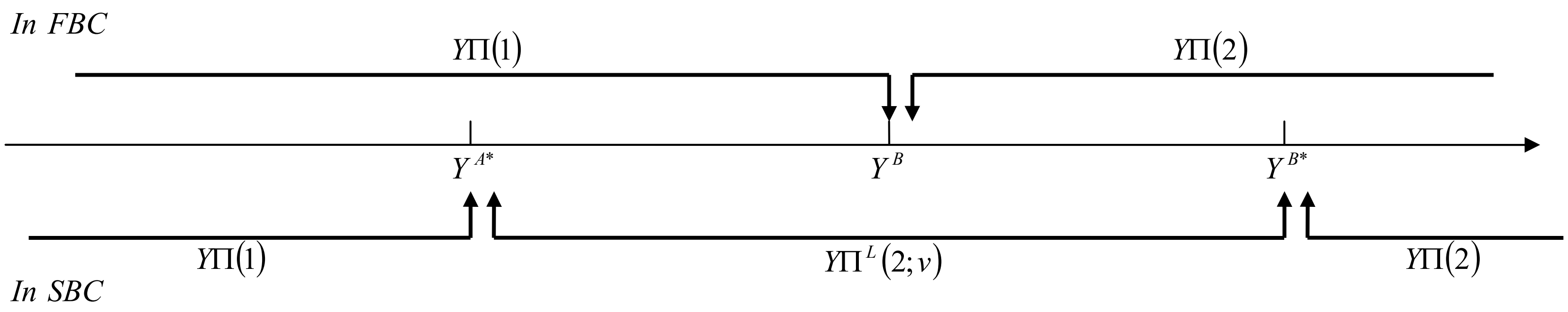


$V(Y)$
$V_L^B(Y)$
$V_F^B(Y)$
0
Y_L^B
Y^B
Y
No firm invest
Monopoly
Bypass duopoly



$V(Y)$
$V_L^{AB}(Y)$
$V_F^{AB}(Y)$
0
Y_L^*
Y^{A*}
Y^{B*}
Y
No firm invest
Monopoly
Access duopoly
Bypass duopoly

Figure 2



Note: *FBC* and *SBC* stand for a facility-based competition and a service-based competition, respectively.

Figure 3: A Leader's Profit in the Two Competition Schemes