Unbundling the Local Loop*

Marc BOURREAU[†] and Pınar DOĞAN[‡]

May 13, 2002

Abstract

We study competition for high bandwidth services in the telecommunications industry by introducing the possibility of unbundling the local loop, where leased lines permit the entrant to provide services without building up its own infrastructure. We use a dynamic model of technology adoption and study the incentives of the entrant to lease loops and compete "service-based", and/or to build up a new and more efficient infrastructure and compete "facility-based", given the rental price.

We show that the incumbent sets *too low* a rental price for its loops; hence, the entrant adopts the new technology *too late* from a social welfare perspective. The distortion may appear not only on the timing of technology adoption but also on the type (quality) of the new technology to be adopted. We also show that while regulating the rental price may suffice to achieve socially desirable outcomes, a sunset clause does not improve social welfare.

Keywords: Unbundling; Technology adoption; Regulation

JEL Classification: I9; L1; L5

*The authors would like to thank Jacques Crémer, Jean-Jacques Laffont, Bruno Jullien, Serdar Dalkir and David Sappington for their helpful comments. Bourreau wishes to thank IDEI, and Doğan thanks the Transportation Center at Northwestern University for their hospitality during the time part of this research was conducted. The authors would also like to thank France Télécom for financial support. The views expressed in this paper are not necessarily those of France Télécom. Last, but not least, we thank two anonymous referees for very useful comments and suggestions.

[†]ENST, Paris, FRANCE. E-mail: marc.bourreau@enst.fr

[‡]GREMAQ, UT-1, Toulouse, FRANCE, and PURC, University of Florida, USA. E-mail: pinar.dogan@univ-tlse1.fr

1 Introduction

In this paper we construct a dynamic framework to analyze the effect of unbundling on building alternative infrastructures to provide high bandwidth services. Using a dynamic model of technology adoption, we study the incentives of the entrant to lease loops and compete "service-based", and/or to build up a new and more efficient infrastructure and compete "facility-based", given the rental price determined by the incumbent. We show that the incumbent sets *too low* a rental price for its loops; hence, the entrant adopts the new technology *too late* from a social welfare perspective. The distortion may appear not only in the timing of technology adoption but also in the type (quality) of the new technology that it adopts. This distortion is related to a 'replacement effect' which has been studied in the R&D, licensing and technology adoption literature.[1] The novelty of this paper is to introduce the replacement effect in a regulated environment, and hence, to provide a new link between innovation and regulation of interconnection in the telecommunications industry.[2]

Unbundling provides entrants with access to the local loop of the incumbent operator so that they do not incur large fixed and sunk costs to build their own infrastructure. It is expected to improve service-based competition and increase the variety of new services. Without unbundling, competitors have limited access to the essential facility, which is reached through interconnection. For the same reason, however, many policy discussions conclude that unbundling undermines the incentives for building alternative networks. For instance, Kahn et al. (1999, p. 360) argue that the regulation of unbundled elements by the Federal Communications Commission (FCC) in the United States has "ignored or downplayed the likely discouraging effect on those competitors supplying their own needs and on risk-taking innovation by the ILECs (Incumbent Local Exchange Carriers) themselves". Sidak and Spulber (1998, p. 411) state that "pricing network services below economic cost is likely to discourage the building of competing facilities".

Facility-based competition in the telecommunications industry is perceived as a necessary condition for long-term efficiency. For the full functioning of competition, it is necessary that each operator control its supply chain to the largest possible extent. The benefits from flexibility and innovation obtainable under this state of affairs exceed by far those achievable under facility-sharing settlements. This is because consumers have varying needs best satisfied with competing and different technologies. As Oftel writes, "competition at the infrastructure level should in turn feed through to competition in the provision of services, providing consumers with a choice of packages, pricing structures and customer service options".[3]

[1] See for example, Arrow (1962), Reinganum (1983), and Gallini (1984).

[2] See Bourreau and Dogan (2001) for a general discussion on regulation and innovation in the telecommunications industry, and Prieger (2001) for an econometric study of how regulatory delays affect service innovation in the telecommunications industry.

[3] "Delivering a competitive broadband market - Oftel's regulatory strategy for broadband", Oftel, 19 December 2001.

"Build or buy" decisions of the entrants depend on the supply conditions at which the unbundled loops are provided. In particular, rental prices of the loops assume predominance in the efforts to achieve desirable outcomes. The optimal price for the local loops reflects the trade-off between short-run benefits from service-based competition and long-run benefits of improved facility-based competition. A price too low deters (or delays) investment in alternative networks, and a price too high would discourage entrants from joining service-based competition.[4]

Local loop unbundling in Europe has proven to be a complex and slow process, as in the United States where it has been mandatory since 1996. Following the liberalization of the European telecommunications market, the possibility of local loop unbundling was considered by only a few countries (e.g., Austria, Denmark, Finland and Germany). The European Commission's decision to mandate local loop unbundling in all E.U. member countries is very recent (January 2001). That decision (EC/2887/2000) requires incumbent operators to provide access to their copper lines on a 'reasonable' request. A reasonable rate should both ensure that the incumbent recovers its costs, and also should foster fair and sustainable competition in the local loop. In addition, the commission has also decided that the rental schemes should take into account the need for investment in alternative technologies. Although various policy studies discussed the possible effects of unbundling on building alternative technologies,[5] to our knowledge, no formal analysis in this respect has been provided.[6] This paper is an attempt to provide formal analysis of the issue.

The paper is organized as follows. We begin by setting up the basics of the model in Section 2. We devote Section 3 to the analysis of service-based competition and facility-based competition. In Section 4 we study the technology choice of the entrant, both with and without unbundling. In Section 5, we study the decision of the incumbent with respect to unbundling and the rental price. In Section 6 we provide a social welfare analysis whereby a comparison with the unregulated outcome is given. We also discuss the role of sunset clauses for improving socially desirable outcomes. In Section 7 we discuss some extensions to our analyis prior to our conclusions.

2 The Model

In this model, we assume that the incumbent, who owns and operates the local loop, is making all the decisions regarding unbundling. Hence, if it decides to unbundle its local loop, it sets the rental rate for it. Later, we introduce a social welfare maximizing regulator in order to compare the unregulated outcome with the socially efficient one. We also discuss regulatory tools to achieve desirable

[4] See Kahn et al. (1999).

[5] See Sidak and Spulber (1998), Kahn et. al (1999), and Dumont (1999). See also Harris and Kraft (1997) for the regulation of unbundled elements in the US.

[6] Kim et al. (2000) examine economic effects of local loop unbundling; however, they do not address the incentives to invest in alternative facilities.

outcomes when the local loop is unbundled.

We distinguish between two types of entry to the high bandwidth services market. *Service-based* entry takes place when the local loop is unbundled and the entrant decides to lease loops. In this type of entry, we assume that the incumbent and the entrant are restricted to providing horizontally differentiated products, as it is less likely that firms using the same infrastructure achieve different quality of services. Conversely, we assume that the entrant obtains a quality advantage over the services provided with the traditional local loops in case of *facility-based* entry, i.e., when the entrant invests in an alternative technology (e.g., wireless local loop, cable networks or fiber optic networks). A proper interpretation of quality in this context is the *bandwidth*.

Service-based entry occurs only if the local loop is unbundled, whereas facility-based entry can take place whether the local loop is unbundled or not. Furthermore, if the local loop is unbundled, the entrant may lease loops and compete on the basis of services, prior to its adoption of a new technology.

Finally, we assume that the incumbent uses some Digital Subscriber Line (DSL) technology, and cannot invest in alternative technologies. This may be either because of its previous sunk investments in the copper loop or because of a regulatory ban.[7]

Firms The incumbent (I) has a constant marginal cost of providing high bandwidth services, which is normalized to zero. If the incumbent unbundles the local loop, it sets the rental rate r, and receives a marginal revenue of r per line if the entrant decides to lease loops.[8]

When the entrant leases loops, there is a sunk cost of entry, f, attributable to co-location and order handling. The quality of service that is provided with the existing local loop is normalized to zero, but the new technology brings a superior quality of service,[9] q_F. In this basic model, we consider a single new technology that is available for adoption. At the end of Section 4 we extend the model with two different new technologies that bring different quality levels.

[7] For example, the incumbent operators in Austria and Portugal were excluded from the tendering process for wireless local loop licences. In France, where the incumbent operator was not excluded from the beauty contest for wireless local loop licences, the most important criteria was the ability of the applicant to enhance competition in the local loop. Hence, the incumbent was at a disadvantage. As for cable networks, the European Commission established rules in 1999 that require incumbent operators to legally separate their cable operations from their traditional phone services.

[8] Here, we don't consider any credibility issues. We assume that the incumbent is able to commit to a rental price with long-term contracts. This assumption is a strong one, but enables us to focus on the effects of a fixed rental price on the adoption of alternative technologies.

[9] In reality, incumbents can make upgrading investments that increase the bandwidth (here the quality) of their local loop. What is essential to our analysis is that the new technology brings a sufficiently superior quality to the maximum of what can be achieved through the copper lines. Indeed, it seems unlikely that in the future DSL copper lines will achieve the same bandwidth as fiber optic loops. In Section 7 we argue that the nature of our results does not change when we consider the possibility of the incumbent to upgrade the quality of its loops.

Adoption cost for the new technology is

$$A(\Delta) = \frac{a}{2}\Delta^2,$$

where $\Delta \in [0,1)$ is the discount factor determined by the adoption date.[10] Here we use the same notation and interpretation as Riordan (1992): $\Delta = \exp(-\delta t)$, where δ is the discount rate, and t denotes time. We normalize δ to 1.[11] Throughout the paper we refer to Δ as the adoption date. Note that higher Δ corresponds to an earlier adoption date. We have $A'(\Delta) \geq 0$, and $A''(\Delta) > 0$.

Consumers Consumers are uniformly distributed on the unit square $[0,1] \times [0,1]$. A consumer of type (x,θ) has a taste x for variety (its location on the horizontal segment) and a valuation θ for quality (location on the vertical segment), with $x, \theta \in [0,1]$.

The indirect utility function of the consumer of type (x,θ) who purchases a unit of service (an access line) from firm i is

$$U = v + \theta q_i - (x - y_i)^2 - p_i,$$

where $v > 3$ is the fixed utility derived by using high-bandwidth services. The horizontal location of firm i on the unit segment is denoted by y_i, whereas its price is denoted by p_i, with $i = I, E$. The quality of the service provided by the incumbent is q_I, and $q_I = 0$. The quality of service provided by the entrant is q_E, and depends on the technology it uses. If it leases loops and competes on the basis of services, it has the same quality as the incumbent, $q_E = 0$. If it adopts the new technology and competes on the basis of facilities, its quality is q_F, and is given in the interval $q_F \in \left(\underline{q}_F, \overline{q}_F\right)$.[12]

The assumption on the lower bound of v ensures market coverage for all possible cases: i) when the incumbent operates alone, ii) when firms compete on the basis of services, iii) when firms compete on the basis of facilities.

Finally, we assume that both a and f are bounded from below and above, i.e., $a \in (\underline{a}, \overline{a})$ and $f \in \left(\underline{f}, \overline{f}\right)$.[13] This rules out the uninteresting cases for our analysis, i.e., the case under which the entrant never leases loops (even when the rental price is set at zero) and the case in which the incumbent never unbundles its loops. Hence, the lower bound on a together with the upper bound on f ensure that if the rental price is set at marginal cost (zero), the entrant is willing to lease loops. The upper bound on a excludes the case in which the

[10] We a employ quadratic cost function, as it provides us with closed form solutions. Most of our results would hold with any convex adoption cost function.

[11] Note that a very low discount rate may change some of our findings. See the end of Section 5 for a discussion on low discount rates.

[12] See the Appendix for values of $\underline{q}_F$ and $\overline{q}_F$. Upper bound on q_F guarantees the existence of a price equilibrium when firms compete on the basis of facilities. The lower bound on q_F is determined for the sake of computational ease, as for lower q_F, linear segment of the demand curves may change. In Section 4, we consider another new technology with $q_F \in \left(0, \underline{q}_F\right)$.

[13] The values of $\underline{a}, \overline{a}, \underline{f}$, and $\overline{f}$ can be found in the Appendix.

incumbent never unbundles its loops.[14] Finally, given the lower bound on f, the entrant obtains non-positive profits for relatively high rental prices, and hence, we restrict our attention to the competitive and corner equilibria.

The Timing The timing of the game is as follows.

1. The incumbent decides whether to unbundle or not.
2. The incumbent commits to the rental rate of the loop, r, if it unbundles the local loop.
3. At any time t, the entrant decides whether to rent loops if the local loop is unbundled, and compete on the basis of services, and/or decides to adopt a new technology. The entrant can compete on the basis of services by leasing loops before it decides to adopt the new technology.

We have assumed that the entrant never adopts the technology at time zero, and that the adoption cost has no fixed component and declines over time. Furthermore, as seen in the next section, competing on the basis of facilities brings a higher profit flow to the entrant than when it competes on the basis of services, thus it always ends up by adopting a new technology. As a consequence, we find that either entry takes place with an alternative technology *only,* or, before adopting any new technology, the entrant leases local loops and competes on the basis of services. Once it adopts the new technology, it stops leasing loops.

3 Service-based Competition vs. Facility-based Competition

In this section, we determine the equilibrium profit flows of the firms for both the phase of service-based and facility-based competition, deriving the properties of the profit flows with the help of our structural model (see Appendix B - C) and we use the reduced form throughout the analysis.

Since immediate technology adoption is assumed away, prior to the adoption of the new technology (or lease of loops, if available) the incumbent is the monopolistic provider of high-bandwidth services. It locates at the middle of the horizontal unit line, charges p_I^M, and obtains a profit flow of $\pi_I^M(p_I^M)$ during this phase.

Service-based competition As already stated, firms compete on the basis of services when they use the same infrastructure (i.e., the traditional local loops),

[14] Later we show that if the adoption cost of a new technology is sufficiently high, which implies that there is no threat of facility-based entry, the incumbent is better off by not unbundling and maintaining its monopoly profits. However, we include the possibility of unbundling to be a favorable strategy for the incumbent.

and provide the same quality of service (i.e., bandwidth).[15] We assume that firms choose maximum horizontal differentiation, and hence are located at the two extremes of the unit line. In the phase of service-based competition, firm i obtains the following profit flow

$$\pi_i^S(r, p_i^S(r), p_j^S(r)),$$

where $i, j = I, E$, and $i \neq j$.

Value of r determines whether service-based competition yields competitive equilibrium, corner equilibrium, or quasi-monopolistic equilibrium. Note that our assumption on the lower bound of f means that service-based competition never results in quasi-monopolistic profit flows for firms.

Lemma 1 *For all r, $\partial\pi_I^S(r)/\partial r \geq 0$, and $\pi_E^S(r)/\partial r \leq 0$.*

Proof. See Appendix B2. ■

Intuitively, the higher the rental price, the lower the profit flow of the entrant, as it leases loops for providing services. However, for sufficiently low r, service-based competition yields competitive equilibrium; hence, firms charge exactly the same price and share the market equally. Nevertheless, the incumbent obtains higher profits compared to the entrant, as it receives a rental revenue from the lease of its loops. As the entrant transfers the entire r to the consumers, its profit flow does not depend on the rental price.

Facility-based competition If the entrant adopts the new technology, competition is facility-based. In this phase, firm i obtains the following profit flow

$$\pi_i^F(q_F, y_i^F, y_j^F, p_i^F, p_j^F),$$

where $i, j = I, E$, and $i \neq j$.

Lemma 2 *When firms compete on the basis of facilities, they obtain minimum horizontal differentiation.*

Proof. See Appendix C1. ■

Quality differentiation between the services provided by the incumbent and the entrant is sufficiently large so that firms obtain minimum variety differentiation. Of course, this is a direct implication of our assumption on q_F. If a new technology brings a lower quality than what we have assumed, it is possible that firms maintain maximum horizontal differentiation. However, general properties of the profit functions, which we provide with the following, do not

[15] Consider for example "bit stream access" to the unbundled local loop. In this case, any quality improvement as a result of an upgrade investment made by the incumbent is equally enjoyed by the entrant as a leaser. In other types of unbundling schemes (e.g. raw copper unbundling), we claim that the quality differentiation obtained by using the same technology is pretty much restricted compared to one that can be obtained with different technologies.

change as long as the new technology brings forth some quality advantage.[16] Although q_F is determined exogenously (once the new technology is adopted), we keep the notation $\pi_E^F(q_F)$, as in Section 4 we introduce another technology (with lower quality) that is available for adoption.

Lemma 3 *$\partial\pi_E^F(q_F)/\partial q_F > 0$, and for all r and q_F, $\pi_E^F(q_F) > \pi_E^S(r)$.*

Proof. See Appendix C2. ■

The entrant obtains higher profit flows in the phase of facility-based competition than in the phase of service-based competition. Furthermore, its profit flows from facility-based competition increases with the quality of service it provides.

Lemma 4 *For all r, $\pi_I^M > \pi_I^S(r) > \pi_I^F(q_F)$.*

Proof. See Appendix D1. ■

The incumbent is better off by operating as a monopolist, which suggests that, if there were no other technologies available for the entrant, the incumbent would deter entry by denying unbundled access to its local loop. Nevertheless, the incumbent obtains higher profit flows when it competes on the basis of services than when it competes on the basis of facilities. Note that this would be the case even if the new technology did not provide the entrant with a quality advantage, simply because the incumbent obtains additional revenues from the leased loops (for any $r > 0$) which are non-existent in facility-based competition, however, for the ultimate preference of the incumbent for unbundling, we cannot make a conclusive statement yet. Therefore, we proceed by studying optimal date of adoption for cases with and without unbundling.

4 Adoption of New Technology

In our setting, regardless of whether the local loop is unbundled, the entrant eventually builds its own facility. However, the date of adoption and the technology type adopted (when other technologies are available) may change with the rental price. Indeed, we show that when the entrant leases local loops prior to its technology adoption, the adoption date is retarded compared to the case in which local loops are not available for lease. This is not surprising, and similar types of 'replacement effect' have already been mentioned in several studies.[17]

[16] We have assumed that the new technology improves the quality. However, one can also consider a new technology that reduces cost but does not bring a superior quality. The nature of our results does not change whether the improvement is in terms of quality or cost. The essentials of the analysis rely on the observation that innovation in dynamic industries like telecommunications entails development of more efficient new technologies.

[17] The 'replacement effect' was introduced in the R&D literature by Arrow (1962), who states that an incumbent firm has less incentive to invest in R&D because, by increasing its R&D investment, it hastens its own replacement (see Tirole (1988)). The 'replacement effect' in our model is very similar to the 'replacement effect' considered in the licensing literature. Indeed, by licensing its technology, an incumbent reduces the entrants' incentives to innovate (see Gallini (1984), Katz and Shapiro (1987)).

No Unbundling of the Local Loop When the local loop is not unbundled (or, equivalently, if the rental price is set sufficiently high so that the entrant chooses not to lease local loops), the entrant maximizes its discounted profits net of the adoption cost, and the problem can be defined as

$$\max_{\Delta\in[0,1]} \left\{\Delta\pi_E^F(q_F) - a\Delta^2/2\right\}.$$

Note that, given our assumption on the lower bound of a, adoption does not occur at $\Delta = 1$. The optimal date of adoption is defined by the first-order condition,

$$\Delta^* = \pi_E^F(q_F)/a. \tag{1}$$

A higher quality advantage, and hence a higher profit flow from facility-based competition, results in the entrant's adoption of the new technology at an earlier date (a higher Δ^*). We denote the discounted profits when firms compete only on the basis of facilities by Π_i^F, with $i = I, E$. The discounted profit of the entrant is

$$\Pi_E^F(\Delta^*) = \Delta^*\pi_E^F(q_F) - A(\Delta^*) = \pi_E^F(q_F)^2/2a,$$

and is also increasing with q_F.

Since the entrant has no access to the loops, the incumbent obtains monopoly profits, π_I^M, until the entrant adopts the new technology, Δ^*, and obtains $\pi_I^F(q_F)$ thereafter. Hence, the discounted profit of the incumbent is

$$\Pi_I^F(\Delta^*) = (1-\Delta^*)\,\pi_I^M + \Delta^*\pi_I^F(q_F).$$

Unbundled Local Loop If the entrant has an access to the unbundled loop, we find ourselves in one of the two following cases.

Case 1 *The entrant adopts the new technology without first competing on the basis of services.*

This case is the same as if the local loop was not unbundled, hence the adoption date and the discounted equilibrium profits are the same as in the previous section.

Case 2 *The entrant leases local loops, then adopts the new technology at $\Delta_S(r)$.*[18]

[18] This is the only case in which firms change their horizontal locations. Although we do not consider any re-location cost, we have checked the robustness of our analysis by introducing a positive cost of re-location. Existence of a one-time cost of re-location, $c_r > 0$, does not change our results, for the following reason. When c_r is sufficiently small, it is optimal for the firms to choose minimum differentiation, as opposed to keeping their initial locations at the extremities of the unit line. The profit flows when the new technology is adopted are $\pi_I^F(q_F) - c_r$ and $\pi_E^F(q_F) - c_r$; for the remaining time they are $\pi_I^F(q_F)$ and $\pi_E^F(q_F)$. As c_r is sufficiently small, this does not affect our analysis. When c_r is sufficiently high, firms may choose not to relocate and maintain maximum differentiation during the phase of facility-based competition. It is easy to show that in this case firms obtain exactly the same profit flows, i.e., $\pi_I^F(q_F)$ and $\pi_E^F(q_F)$. Hence, all our results remain exactly the same (except for the statement in Lemma 2). Note that, when the entrant adopts the new technology, there is no equilibrium in which one firm stays at the initial location while the other re-locates. We thank an anonymous referee for pointing this out.

We denote the discounted profits in this case with Π_i^{S+F}, with $i = I, E$. Clearly, in this case the adoption date depends on r, as its profit flows from service-based competition depend on the rental price. When the entrant leases loops prior to technology adoption, during $1 - \Delta_S(r)$, it obtains $\pi_E^S(r)$ from service-based competition. When it adopts the new technology, it obtains $\pi_E^F(q_F)$. Therefore, given its technology choice, it has the following problem

$$\max_{\Delta_S(r) \in [0,1]} \Pi_E^{S+F}(\Delta_S(r), q_F, r)$$

where

$$\Pi_E^{S+F}(\Delta_S(r), q_F, r) = \Delta_S(r)\, \pi_E^F(q_F) - \frac{a}{2}(\Delta_S(r))^2 + (1 - \Delta_S(r))\, \pi_E^S(r) - f.$$

The optimal adoption date is

$$\Delta_S^*(r) = \left(\pi_E^F(q_F) - \pi_E^S(r)\right)/a. \tag{2}$$

One can observe that $\partial\left(\Delta_S^*(r)\right)/\partial r \geq 0$, as $\partial \pi_E^S(r)/\partial r \leq 0$, which means that a higher rental price set by the incumbent implies an earlier adoption date. Now we proceed by studying the entrant's incentives to lease loops prior to technology adoption, for any rental price set by the incumbent.

Lemma 5 *There exists a threshold $\overline{r}$ such that for all $r > \overline{r}$, the entrant does not rent local loops before adopting a new technology.*

Proof. With unbundling, the optimal adoption date is defined by equation (2). The entrant chooses to rent loops before building its own infrastructure if and only if it gets higher profit when it leases loops than when it does not:

$$\Pi_E^{S+F}(q_F, r)^* \geq \Pi_E^F(q_F)^*.$$

Replacing for $\Pi_E^{S+F}(r)^*$ and $\Pi_E^F(q_F)^*$, and rearranging the inequality yields

$$\left(1 - \frac{\Delta_S^*(r) + \Delta^*}{2}\right)\pi_E^S(r) \geq f. \tag{3}$$

We have $\partial \pi_E^S(r)/\partial r \leq 0$, hence $\partial \Delta_S(r)/\partial r \geq 0$ and the left-hand side of the inequality (3) decreases with r. Besides, inequality (3) holds for $r = 0$ by assumption, and it is violated for $r = v$, as $\pi_E^S(v) = 0$. Therefore, there exists a rental price $\overline{r}$ such that for all $r > \overline{r}$, inequality (3) is violated; hence, the entrant does not lease the loop. ■

As the adoption date of the new technology differs when the entrant leases loops and when it does not, a relevant question is whether unbundling accelerates or retards adoption.

Lemma 6 *Whenever the entrant leases loops, i.e., for any given r such that $r \leq \overline{r}$, technology adoption when there is unbundling is later than when there is no unbundling.*

Proof. Straightforward from comparison of adoption dates determined with equations (1) and (2). ■

The delay of adoption introduced by unbundling is

$$\Delta^* - \Delta_S^* (r) = \pi_E^S(r)/a,$$

and it is decreasing with the rental rate, r. This is because the opportunity cost of adopting technology is decreasing with r. The delay of technology adoption with unbundling reflects a "*replacement effect*"; it takes more time for the entrant to replace its own technology than to adopt a technology without having been operating in the relevant market (the higher the profits obtained by service-based competition, the later the new technology is adopted).

Lemma 5 and Lemma 6 represent the trade-off the incumbent faces for its decision on the rental price. Lemma 5 implies that the incumbent might charge a high rental price to increase its profits up to the monopoly level, prior to adoption. In contrast, Lemma 6 implies that it may charge a low rental price to delay competition from the new technology.

In the following subsection, we extend our analysis to multiple new technologies and show that unbundling may not only retard technology adoption, but may also distort technology choice.

Multiple new technologies In this section, we introduce another new technology that is available for adoption, one that brings a lower quality, q_L, compared to q_F. Let us re-label q_F as q_H so H stands for technology *High* and L stands for technology *Low,*with $q_H > q_L > 0$. We assume that the adoption cost of technology L has similar properties to H, but at any time t it is cheaper to adopt technology L. Formally,

$$a_H > a_L \Leftrightarrow A_H(\Delta) > A_L(\Delta).$$

As an alternative to the copper local loop, fiber-optic loops may exemplify a technology H. It provides a very high bandwidth, but is currently very costly to build (which is why entrants use this technology to bypass the incumbent's loop where penetration is sufficiently high - in particular, in business areas). Satellite or wireless local loop technologies can be examples of technology L, as they are relatively cheaper to build, but their quality of service is inferior to fiber-optic loops.[19] Introducing a choice in technology to be adopted better reflects the flexibility of the entrant for market targeting.

For $q_L \in \left(0, \underline{q}_H\right)$, firms may obtain maximum or minimum horizontal differentiation. For all possible equilibrium horizontal locations, profit flows have the same properties as stated in Lemma 3 and Lemma 4. Therefore, we have $\partial\pi_E^F(q_L)/\partial q_L > 0$, $\pi_E^S(r) < \pi_E^F(q_L)$, and $\pi_I^S(r) < \pi_I^F(q_L)$ (see Appendix C3-4, and D2).

[19] Although we consider two technologies, the analysis can be extended to n technologies as long as the order $q_1 > q_2 > ... > q_n$, and $a_1 > a_2 > ... > a_n$ hold for all new technologies that are defined by a pair (a_τ, q_τ), with $\tau = 1, 2, ..., n$.

Contrary to the previous analysis, the discounted profits of the firms depend not only on the timing of the adoption, but also on the type of the technology adopted. If the local loop is not unbundled (or is priced sufficiently high) the adoption date of technology τ, with $\tau = L, H$, is

$$\Delta_\tau^* = \pi_E^F\left(q_\tau\right)/a_\tau.$$

The discounted net profit of the entrant is

$$\left(\Pi_E^F\right)^* = \max_{\tau=L,H} \Pi_E(\Delta_\tau^*, \pi_E^F(q_\tau), a_\tau).$$

If the entrant leases loops prior to adopting technology τ, the optimal adoption date is

$$\left(\Delta_{S\tau}\left(r\right)\right)^* = \frac{\pi_E^F\left(q_\tau\right) - \pi_E^S\left(r\right)}{a_\tau}.$$

The discounted profit of the entrant is

$$\left(\Pi_E^{S+F}\left(r\right)\right)^* = \max_{\tau=L,H} \Pi_E(\left(\Delta_{S\tau}\left(r\right)\right)^*, \pi_E^F(q_\tau), a_\tau).$$

With the following lemma we show that the type of technology adopted by the entrant is not necessarily the same when the entrant leases loops and when it does not lease loops prior to technology adoption. Hence, unbundling may distort the technology choice of the entrant.

Lemma 7 *The entrant may adopt a different technology when it leases loops prior to technology adoption and when it does not: given that the entrant adopts* L *when it does not lease loops, for* a_H *sufficiently small, there exists* $\widetilde{r}$ *such that, if* $r < \widetilde{r}$*; the entrant adopts technology* H *instead of* L *if it leases loops.*

Proof. See Appendix E. ■

Unbundling may distort the technology choice if the rental price is set sufficiently low. This is because the cost of adopting both technologies approaches zero as time approaches infinity. We know that technology H yields a higher profit flow to the entrant compared to technology L. Hence, if unbundling sufficiently retards technology adoption, it makes technology H more attractive for adoption. In the remaining sections we focus on the cases in which the entrant adopts the same technology whether or not it leases loops prior to technology adoption. Concentrating on those cases simplifies the analysis when we study the incumbent's strategy and social welfare. The results we obtain hold with technology distortion, with different conditions.

5 Decision for Unbundling and the Rental Price of the Local Loop

We have analyzed the entrant's strategy for technology adoption given the decision for unbundling and the rental price r for the local loop. Moving backwards, we now study the incentives of the incumbent to unbundle the local loop, and the choice of r if it decides to unbundle.

Lemma 8 *The incumbent prefers to lease its loops at $r = v - 5/4$ rather than not to unbundle.*

Proof. The proof is composed of two parts. First we show that when $r = v - 5/4$, the entrant leases loops (i.e., $\overline{r} \geq v - 5/4$); second we show that the incumbent prefers to lease loops at $r = v - 5/4$ rather than not to unbundle.

First, leasing loops at $r = 0$, alone, yields positive profits to the entrant as $f < \overline{f}$. Then, the threshold $\overline{r}$ is characterized by $\overline{r} \geq v - 5/4$. To see that, assume that $\overline{r} < v - 5/4$. Then, for any r such that $r \geq v - 5/4$, the entrant gets negative profits from service-based competition, i.e.,

$$(1 - \Delta_{S\tau}(r))\, \pi_E^S(r) < f.$$

Since $\Delta_{S\tau}(x)$ and $\pi_E^S(x)$ are constant for all $x \leq v - 5/4$, the above equation is true for all $r \leq v - 5/4$, (hence for $r = 0$), which establishes a contradiction. Hence, $\overline{r} \geq v - 5/4$ and the entrant leases loops when $r = v - 5/4$.

Second, the incumbent prefers to lease its loops at $r = v - 5/4$, rather than not lease at all, if and only if $\Pi_I^{S+F}(r, q_\tau) > \Pi_I^F(q_\tau)$, for $r = v - 5/4$, which implies

$$(\Delta_\tau - \Delta_{S\tau}(v - 5/4))\left(\pi_I^S(v - 5/4) - \pi_I^F(q_\tau)\right) \geq (1 - \Delta_\tau)\left(\pi_I^M - \pi_I^S(v - 5/4)\right). \tag{4}$$

The above inequality can be interpreted as follows. The left-hand side represents the additional profit that the incumbent makes when it leases loops. Because of retarded technology adoption and high service-based profits, the incumbent makes $\pi_I^S(v - 5/4) - \pi_I^F(q_\tau) > 0$ during $\Delta - \Delta_{S\tau}(v - 5/4)$. The right-hand side represents the additional profit the incumbent makes when it does not lease loops. Because of higher profits (monopoly profits), the incumbent gets $\pi_I^M - \pi_I^S(v - 5/4)$ during $(1 - \Delta_\tau)$. Now, note that $\pi_I^S(v - 5/4) - \pi_I^F(q_\tau)$ increases with v, as $\pi_I^S(v - 5/4) = v - 3/4$, while $\pi_I^M - \pi_I^S(v - 5/4)$ does not depend on v. The adoption dates Δ_τ and $\Delta_{S\tau}(v - 5/4)$ do not depend on v either. Therefore, for a high v, the incumbent finds it more profitable to lease loops, as it increases its profit until the time that the entrant adopts the new technology $(\Delta - \Delta_{S\tau}(v - 5/4))$. Replacing the relevant values for $\pi_I^S(v - 5/4)$ and π_I^M, and rearranging inequality (4) yields the following condition on a_τ

$$a_\tau \leq v - 3/4 - \pi_I^F(q_\tau) + \pi_E^F(q_\tau),$$

which is satisfied for $a_\tau \leq \overline{a}_\tau$. ■

It remains to be determined whether this rental price yields the global maximum of the incumbent's profit function.

Proposition 1 *If $a_\tau < v - 5/4 - \pi_I^F(q_\tau) + \pi_E^F(q_\tau)$, with $\tau = L, H$, at the equilibrium the incumbent leases its loops at $r^* = v - 5/4$, and the entrant leases loops prior to its technology adoption.*

Proof. First, note that the incumbent's discounted profit function increases with r when $r < v - 5/4$. Indeed, the entrant's optimal adoption date when it leases loops prior to adoption is constant over that range, while the incumbent's profit flow under service-based competition increases with r.

Second, the incumbent's discounted profit function decreases with r when $r \in [v - 5/4, \overline{r})$ if

$$a_\tau < v - 5/4 - \pi_I^F(q_\tau) + \pi_E^F(q_\tau).$$

Third, remember that the entrant never leases loops when $r > \overline{r}$; hence, the incumbent's discounted profit is constant when $r > \overline{r}$. From Lemma 8, we know that the incumbent leases loops at $r^* = v - 5/4$. Therefore, $r^* = v - 5/4$ is the global maximum of the incumbent's discounted profit function. Furthermore, the entrant leases loops at r^*, as $r^* \leq \overline{r}$. ■

When the incumbent leases its local loops, it faces a trade-off between charging a low rental rate which delays the entrant's technology adoption, and a high rental rate, which increases its revenues. Since the entrant's adoption date is constant when $r < v - 5/4$, the incumbent has an incentive to increase its rental rate up to $v - 5/4$. For $r \geq v - 5/4$, increasing the rental rate r accelerates the entrant's technology adoption.

When a_τ is sufficiently low, the entrant is likely to adopt the new technology relatively early; hence, the incumbent is willing to lease its loops to delay facility-based competition, as implied by Proposition 1. Intuitively, when a_τ is sufficiently high, so that the incumbent does not expect any facility-based entry to the market in the near future, it chooses not to unbundle -or sets too high a price- and enjoys monopoly profits.

Finally, remember that we have normalized the discount rate to 1. It is clear that whenever the incumbent discounts the future at a very low rate, the threat to its future profits driven by facility-based competition becomes less severe. Hence, it may prefer not to unbundle and to remain a monopolist until the entrant shows up with a new technology. Furthermore, a lower discount rate may delay technology adoption, due to the lag between the adoption date in which the adoption cost is borne and the profit flows in the phase of facility-based competition.

6 The Social Optimum and Regulatory Tools

To compare unregulated and socially efficient outcomes, in this section we introduce a regulator that maximizes social welfare, defined as the sum of consumers's surplus and industry profits. In the following, we consider regulation of the rental price as the only regulatory tool. Hence, we assume that the regulator does not control final prices.[20] We also investigate the sunset clauses as a regulatory tool to achieve socially desirable outcomes.

[20] In our setting, regulating final prices would not improve the social welfare as final prices transform consumer surplus to industry profits (vice versa). However, it is true that a regulator which assigns different weights to consumer surplus and industry profits, may choose to regulate final prices. In practice, prices for high bandwidth services are not subject to heavy regulation.

6.1 The Social Optimum

In this section we determine the socially optimum rental price. Let W denote the social welfare

$$W = \begin{cases} W^{S+F}(q_\tau, r) & \text{if } r \leq \overline{r} \\ W^F(q_\tau) & \text{if } r > \overline{r} \end{cases},$$

with

$$W^{S+F}(q_\tau, r) = (1 - \Delta_{S\tau}(r))\, w_S(r) + \Delta_{S\tau}(r)\, w_F(q_\tau) - \frac{a_\tau}{2}(\Delta_{S\tau}(r))^2 - f, \quad (5)$$

and

$$W^F(q_\tau) = (1 - \Delta_\tau)\, w_M + \Delta_\tau w_F(q_\tau) - \frac{a_\tau}{2}(\Delta_\tau)^2, \quad (6)$$

where w_M, $w_S(r)$, and $w_F(q_\tau)$ denote social welfare under monopoly, service-based competition and facility-based competition with technology τ, respectively. Values of w_M, $w_S(r)$, and $w_F(q_\tau)$ can be found in Appendix F.

Proposition 2 *Assume that unbundling is socially desirable. Then, the socially optimum rental price r^w is higher than the price charged by the incumbent.*
Proof. *See Appendix F1.* ■

To understand this result, consider the following. When $r \geq v - 5/4$, consumer surplus and industry profits under service-based competition do not depend on r; two firms act as two local monopolies and extract all surplus from marginal consumers.[21] This is because when $\overline{r} \in (v - 5/4, v - 3/4)$ we have a corner equilibrium in which the two firms act as if they were maximizing joint profits. Each firm charges the monopoly price, $v - 1/4$, and they share the market equally. Therefore, the equilibrium prices do not depend on r; the lease of loops leads to a transfer from the entrant to the incumbent, which does not affect the industry profits. Furthermore, when r sufficiently high, i.e., $r > \overline{r}$, the entrant does not lease loops, hence, the profit functions of the firms do not depend on r. Therefore, the social welfare function depends only on the adoption date of the new technology. Recall that $\Delta^*_{S\tau}(r)$ increases with r, since the greater r, the lower the replacement effect. Proposition 2 implies that the entrant tends to adopt the new technology *too late* from a welfare point of view, and that it is socially efficient to increase the rental price of loops to accelerate facility-based competition.

Now, it remains to determine whether unbundling is desirable or not. To that end, we have to compare social welfare with and without unbundling.

Proposition 3 *Unbundling the local loop is not desirable when the entrant plans to adopt technology H, but it may be desirable when the entrant plans to adopt technology L.*

[21] There is no welfare loss because demand is (relatively) inelastic. Indeed, remember that consumers buy zero or one access line.

Proof. We begin by showing that $W^F(q_\tau) > W^{S+F}(q_\tau, r_\tau^w)$ for $\tau = H$, where $r_\tau^w = \overline{r} - \epsilon$ for $\tau = H$. In the proof of Lemma 8, we showed that the threshold for rental price, above which the entrant does not lease loops $(\overline{r})$, is such that $\overline{r} \geq v - 5/4$. Furthermore for all $r \geq v - 3/4$, the entrant finds it unprofitable to lease loops, as $f > \underline{f}$. Hence, $\overline{r} \in (v - 5/4, v - 3/4)$, which implies that $r_H^w \in (v - 5/4, v - 3/4)$. Hence, it suffices to show that $W^F(q_\tau) > W^{S+F}(q_\tau, r)$ is true for $r \in (v - 5/4, v - 3/4)$. We know that $\partial \left(W^{S+F}(q_H, r)\right)/\partial r > 0$ for all $r \in (v - 5/4, v - 3/4)$ (see the proof of Proposition 2). Therefore, if $W^F(q_H) > W^{S+F}(q_H, r)$ is true for $r = v - 3/4$, then it is true for all $r \in (v - 5/4, v - 3/4)$. Replacing the relevant values for $W^F(q_H)$ and $W^{S+F}(q_H, r)$, we verify that this is true if and only if $f > -1/(32a_H)$, which is always satisfied as $f > 0$. Therefore, it is never socially desirable to unbundle the local loop when the entrant envisions to adopt technology H. Now we show that there exist some $\{a_L, q_L, f\}$ such that $W^{S+F}(q_\tau, r_\tau^w) > W^F(q_\tau)$ for $\tau = L$. It suffices to show that this is true for $W^{S+F}(q_L, \widehat{r})$ (see the proof of Proposition 2 for $\widehat{r}$). Replacing for the relevant values, we find that $W^{S+F}(q_L, \widehat{r}) > W^F(q_L)$ is true if and only if

$$f < \left(q_L^4 + 4q_L^3 - 20q_L^2 - 48q_L + 144\right)/(1152a_L) \equiv k. \tag{7}$$

It remains to show that there exists some f such that $f > \underline{f}$ and $f < k$, i.e., that $\underline{f} < k$. To begin with, note that $\partial k/\partial q_L < 0$ and that $0 < k < 144/(1152a_L)$ for all q_L and a_L. Furthermore, $144/(1152a_L)$ decreases with a_L. We can show that inequality (7) holds for a_L and q_L very low (near zero), since one can verify that for any v, if q_L is sufficiently low, then $144/(1152\underline{a}_L) > \underline{f}$. Therefore, for q_L sufficiently low, there exists some values of a_L and f such that unbundling is desirable. ■

This result shows that the incumbent has stronger incentives than a social welfare maximizing regulator to unbundle its local loop. Indeed, the incumbent is willing to lease loops at a relatively low price, while a welfare maximizing regulator might choose not to unbundle the local loop. The intuition is that while a quality-improving innovation threatens the incumbent's position, it increases social welfare. The incumbent is willing to delay adoption by charging a lower rental price, while the regulator is willing to hasten adoption by setting a high rental price. The same reasoning explains why the regulator never unbundles when the entrant plans to adopt technology H, but might choose to unbundle when the entrant plans to adopt technology L. Note that technology H provides higher social welfare flows than technology L.

Our welfare analysis ignores some aspects of unbundling. For instance, it may be socially desirable to unbundle the local loop to prevent incumbent operators from preempting the market for high bandwidth services. Furthermore, we have ignored the possibility of the distortion that unbundling may have on the technology choice. This distortion occurs in one direction, from lower to higher quality technology, which stimulates a higher social welfare flows. This distortional replacement effect may further increase the social desirability of unbundling when the entrant envisions adopting technology L.

6.2 A Regulatory Tool: Sunset Clauses

The previous subsection dealt with the determination of the socially optimal rental price. Another important supply condition is the timing of introduction of local loops for leasing. *Sunset clauses* specify ex ante a period of time after which the incumbent's facilities are no longer regulated. Sunset clauses have been specified in the unbundling regulations in Canada and the Netherlands. For example, Opta, the Dutch regulatory authority, has specified a five-year period after which the incumbent operator, KPN Telecom, would be "in principle, free to set a tariff on a commercial basis".[22] Similarly, the Canadian Radio-Television and Telecommunications Commission issued a decision (CRTC-97-8), which stated that following a five-year mandatory unbundling, the incumbent's services and components that are deemed to be essential facilities (including local loops in certain areas) would not be subject to mandatory unbundling and the rental rate would not be regulated any longer. In March 2001, CRTC extended this sunset period without specifying a termination date.[23] The motivation behind these sunset clauses is to provide the entrants with incentives to build their own facilities. In this respect, deregulating the rental rate is assumed to render leasing loops an unattractive option to the entrant.

However, in our setting, sunset clauses do not enhance the incentives of the entrant to build up its own infrastructure. To validate this assertion, we start by computing the socially optimum adoption date. Since unbundling is never desirable when the entrant adopts technology H after leasing loops, we consider technology L only. Furthermore, we assume that f, a_L and q_L are such that condition (7) is satisfied, i.e., unbundling is socially desirable when the entrant adopts technology L after leasing loops. When the entrant leases loops, and then adopts technology L at date Δ_L, the total discounted welfare is

$$W^{S+F}(q_L, r) = (1 - \Delta_L(r))\, w_S(r) + \Delta_L(r)\, w_F(q_L) - \frac{a_L}{2}(\Delta_L(r))^2 - f,$$

hence the socially optimal adoption date is

$$\Delta_L^w(r) = \frac{w(q_L) - w_S(r)}{a_L}.$$

Proposition 4 *Assume that unbundling is socially desirable and that the entrant adopts technology L after leasing loops. Then, if the rental price is set at the socially optimum level, the adoption date is either socially optimal or too late.*

Proof. *See Appendix F2.* ■

This proposition implies that, when it is socially desirable to unbundle the local loop, regulating the rental price is sufficient to maximize welfare if the entrant leases loops at the social welfare maximizing rental price, which is defined by

$$r_L^w = \min\{\widehat{r}, \overline{r}\},$$

[22] See Guidelines on Access to the Unbundled Loop, March 1999.

[23] See Order CRTC 2001-184.

with $\widehat{r} = v - 5/4 + q_L/6 + q_L^2/12$ for technology L (computations can be found in Appendix F1). When $r_L^w = \widehat{r}$, and the loops are regulated at that price, introducing a sunset clause does not improve social welfare. When $r_L^w = \overline{r}$, adoption occurs too late from a social point of view, and so introducing a sunset clause does not improve welfare in this case either. To see why, let $\underline{\Delta}$ be the sunset clause, i.e., the date from which the local loop will be no longer regulated, which is determined -and commited to- by the regulator at the initial stage ($t = 0$). Let $\underline{\Delta} > \Delta_{SL}(r^*)$, and let r_L^w be the regulated rental price. As the sunset clause ends earlier than the unregulated adoption date,[24] discounted welfare is given by

$$(1 - \underline{\Delta})\, w_S(r_L^w) + (\underline{\Delta} - \Delta_{SL})\, w_S(r^u) + \Delta_{SL} w_F(q_L) - \frac{a_L}{2}\Delta_L^2 - f,$$

where r^u is the unregulated rental price. Now we define the entrant's problem. During $(1 - \underline{\Delta})$, the entrant leases loops at the regulated price r^w. Once the sunset clause applies, the entrant leases loops at the unregulated rental price, r^u. Finally, once it adopts technology L, it obtains $\pi_E^F(q_L)$. Therefore, its discounted profit is

$$(1 - \underline{\Delta})\, \pi_E^S(r_L^w) + (\underline{\Delta} - \Delta_{SL})\, \pi_E^S(r^u) + \Delta_{SL}\pi_E^F(q_L) - \frac{a_L}{2}(\Delta_{SL})^2 - f. \quad (8)$$

The incumbent's discounted profit is

$$(1 - \underline{\Delta})\, \pi_I^S(r_L^w) + (\underline{\Delta} - \Delta_{SL})\, \pi_I^S(r^u) + \Delta_L \pi_I^F(q_L).$$

An analysis similar to that used in Proposition 1 shows that $r^u = r^* = v - 5/4$. Hence, the incumbent sets the same rental price in the presence of a sunset clause. The entrant chooses the date of adoption, for given r^w, r^u, and $\underline{\Delta}$. The maximization of (8) yields the following adoption date

$$(\Delta_{SL})^* = \frac{\pi_E^F(q_L) - \pi_E^S(r^u)}{a_L}.$$

Note that the adoption date of the entrant depends neither on the regulated price, r^w, nor on the sunset clause, $\underline{\Delta}$. It depends solely on the unregulated rental rate, r^u. As $r^u = r^*$, the entrant adopts at the same time as in the unregulated case. Therefore, the regulator sets r^w and $\underline{\Delta}$, but it cannot influence $(\Delta_{SL})^*$ whenever $\underline{\Delta} > (\Delta_{SL})^*$. Since we know that the entrant adopts the new technology too late from a social point of view when the rental price is not regulated, the sunset clause does not improve welfare.

7 Extensions

Our analysis may be extended in several directions. In this section we discuss how our analysis would change with i) the incumbent having an opportunity

[24] Redundancy of a sunset clause which ends after the unregulated adoption date ($\underline{\Delta} < \Delta_{SL}(r^*)$) is straightforward.

to upgrade the quality of its local loop, ii) the incumbent determining a time-dependent rental path.

Quality upgrade investment in the local loop We have normalized the quality of service provided with the local loops to zero, and assumed that it can not be improved. However, in reality, incumbent operators may upgrade the quality of service provided with the loops. Our main results would hold with any upgrade investment which leads to profit flows that satisfy Lemmas 3 and 4. In other words, whenever i) the incumbent has higher profit flows with service-based competition than with facility-based competition, and ii) the entrant obtains higher profit flows with facility-based competition than with service-based competition, the incumbent sets a rental price such that technology adoption is delayed.

An important question is whether the incumbent can achieve a quality of service which is superior to new technologies, by upgrading its loops. Our observation is that, this is not the case. Today, the maximum bandwidth available with the DSL copper-based technology is around 50 Mbps,[25] while digital signals can be transmitted over a single wavelength of fibre at 40 Gbps. With the following, we assume that the incumbent has an option to upgrade its loops, which would bring a quality of service $q_I \in [0, q_F)$. Since we have assumed that $q_E \in (0, q_F)$, the upgrade can achieve, *at most*, the same quality of service which can be obtained with the new technology. We further assume that the incumbent makes the upgrade investment at the initial stage, i.e., before it leases its loops. This implies that the quality of service provided by the incumbent and the entrant is the same when they compete on the basis of services.[26] We assume that the upgrade investment costs $C(q_I)$, with $C(q_I) = cq_I^2/2$, where $c > 0$.

Finally, for tractability reasons, we assume that consumers have the same valuation for quality, θ_f, with $\theta_f \in [0, 1]$.[27] In this simplified setting, the incumbent's and the entrant's profits under infrastructure-based competition are,

$$\pi_I^F(q_D) = (3 - \theta_f q_D)^2 / 18,$$

and

$$\pi_E^F(q_D) = (3 + \theta_f q_D)^2 / 18,$$

respectively, with $q_D = q_E - q_I$. This is a classical result in the differentiation literature (see, for example, Tirole (1988)).

First, assume that the incumbent does not upgrade its network. Hence, when firms compete on the basis of facilities $q_D = q_E = q_F$. Proposition 1

[25] Note also that the VDSL technology, which provides this bandwidth, works only for very short access lines.

[26] This setting corresponds to a "bitstream access" unbundling scheme, rather than to raw copper unbundling. In bitstream access, the incumbent upgrades the loops prior to the lease.

[27] It proves very complicated to derive the equilibrium for service-based competition outside the competitive range of rental price with heterogenous consumers with respect to θ.

applies and shows that the incumbent leases its loops at $r^* = v - 5/4$, and that the entrant leases loops prior to technology adoption, if

$$a < v - 5/4 + 2\theta_f q_F/3. \tag{9}$$

When the incumbent makes no upgrade investment, its discounted profit is

$$\Pi_I^{NU} = \left(1 - \Delta_S^*\left(r^*, q_F\right)\right)\pi_I^S\left(r^*\right) + \Delta_S^*\left(r^*, q_F\right)\pi_I^F\left(q_F\right).$$

Second, assume that the incumbent upgrades its network. The quality of service of traditional local loops is now q_I. Lemma 8 and Proposition 1 apply, except that we replace v by $v' = v + \theta_f q_I$. We find that the incumbent leases its loops at $r_u^* = v' - 5/4 = v + \theta_f q_I - 5/4$, and that the entrant leases loops prior to technology adoption, if

$$a < v - 5/4 + \theta_f\left(2q_F + q_I\right)/3. \tag{10}$$

Hence, when the incumbent upgrades its network it finds it profitable to lease loops at a higher price. In particular, note that condition (9) implies condition (10), which in turn implies that the incumbent has even stronger incentives to unbundle when it upgrades its loops. This is because the incumbent bears the cost of upgrade investment once, whereas it obtains a higher revenue flows from the lease of its loops, than when it does not upgrade. The incumbent's discounted profit when it upgrades its loops to quality of service q_I is

$$\Pi_I^U(q) = \left(1 - \Delta_S^*\left(r_u^*, q_D\right)\right)\pi_I^S\left(r_u^*\right) + \Delta_S^*\left(r_u^*, q_D\right)\pi_I^F\left(q_D\right) - C\left(q_I\right),$$

which shows two main implications of an upgrade investment. First, profit flow of the incumbent during service-based competition increases, as it can extract more of the consumer surplus by charging a higher rental price to the entrant. Second, the adoption of the new technology is delayed compared to the case in which there is no upgrade investments, since the facility-based competition with a smaller -or no- quality advantage yields lower profits to the entrant. Naturally, when q_I goes to 0, then $\Pi_I^U(q_I)$ approaches to Π_I^{NU}.

Now we study the optimal level of upgrade investment. The upgrade problem of the incumbent is to maximize $\Pi_I^U(q_I)$ with respect to $q_I \in [0, q_F)$. One can prove that there exist $\underline{c}$ such that for all $c > \underline{c}$, we have $\partial^2\Pi_I^U(q_I)/\partial q_I^2\left(q_I = 0\right) < 0$. Since $\partial^3\Pi_I^U(q_I)/\partial q_I^3 < 0$ is also true, it follows that $\partial\Pi_I^U(q)/\partial q_I$ decreases with q_I.[28] We then have three possible cases:

Case 1. The incumbent does not upgrade, i.e., $q_I^* = 0$.

This is true if $\partial\Pi_I^U(q)/\partial q_I\left(q_I = 0\right) < 0$, which implies that $\partial\Pi_I^U(q)/\partial q_I < 0$ is true for all $q_I \in [0, q_F)$.

[28] $c > \underline{c}$ is a sufficient condition for $\partial^2\Pi_I^U(q_I)/\partial q_I^2 < 0$ which treats every possible cases for the level of upgrade investment. Hence, we do not consider $c \leq \underline{c}$.

Case 2. The incumbent upgrades to the maximum quality, i.e., $q_I^* = q_F - \epsilon$, with ϵ very small.

This is true if $\partial\Pi_I^U(q)/\partial q_I(q_I = q_F) > 0$, which implies that $\partial\Pi_I^U(q)/\partial q_I > 0$ is true for all $q_I \in [0, q_F)$.

Case 3. The incumbent upgrades to $q_I^* \in (0, q_F)$.

This is true when $\partial\Pi_I^U(q_I)/\partial q_I(q_I = 0) > 0$ and $\partial\Pi_I^U(q_I)/\partial q_I(q_I = q_F) < 0$. Then, one can show that there exists q_I^* such that $\partial\Pi_I^U(q_I)/\partial q_I(q_I = q_I^*) = 0$. In this case the entrant has a quality advantage of $q_F - q_I^*$.

We have showed that the incumbent not always finds it profitable to upgrade its network. Furthermore, if it upgrades, it does not necessarily choose the same quality of service as the entrant. We have also showed that the incumbent has stronger incentives to unbundle its network when it upgrades its loops.

Time-dependent rental path Throughout the analysis we have assumed that the incumbent (or the regulator) commits to a fixed rental price. Although this assumption provides a framework for studying the effect of unbundling on the timing and the type of technology adopted, in reality the rental price is rarely set "once and for all". Intuitively, a time-dependent rental path resolves the trade-off for the incumbent given in Section 4. Suppose that the order for the incumbent's profit flows stated in Lemma 4 holds. Then, with an incentive to protect its monopoly profits, the incumbent can begin charging an unattractive rental price (or may deny unbundling), $\overline{r}(\Delta)$, during the time when there is no effective threat of entry because of the high adoption cost. Then, from the date Δ^* on, at which the entrant is willing to adopt the new technology (when there is no unbundling, or when the price is set too high), the incumbent would change its pricing strategy. It would charge a rental path, $r(\Delta)$, such that at each time t the entrant prefers (or keeps preferring) leasing loops to adopting the new technology. Therefore, the rental price set by the incumbent tends to decrease over time, as the new technology becomes cheaper to adopt. The rental price would continue to decrease until the time when the entrant finds it optimal to adopt the new technology, no matter how low the rental price is. After that date on, the rental price is irrelevant, as the entrant adopts the new technology. By following such a strategy, the incumbent can delay technology adoption and at the same time can extract as much rent as possible from the entrant. Similar to our analysis with fixed rental price, unbundling with a time-dependent unregulated rental path may sub-optimally delay technology adoption. Again, this would call for a higher regulated rental price, at least after the date in which adoption of the new technology is socially optimal.

8 Conclusion

This paper provides a formal analysis of the effects of unbundling on the investment decisions for technologies that are alternatives to traditional loops. Our analysis suggests that the incumbent, as the owner of the loops, has an incentive to provide attractive terms for lease, and hence sets a low rental price. By doing so, it delays the entrant's adoption of a new and better technology. Although we did not consider the possibility of entry deterrence, a slight modification in the adoption cost function can extend the analysis in that direction. Adding a fixed component to the adoption cost would give rise to a deterred entry of a new technology if the rental price is set sufficiently low.

The incumbent faces the following trade-off regarding its pricing decision: if it sets the price too high, which is tantamount to not unbundling, it can maintain its monopoly profits, at least in the short run. However, in this case the entrant will face no replacement effects and will adopt a new technology at an earlier date. The incumbent will face fiercer competition than it would had it leased its loops to the entrant. In contrast, if the consumer valuation for the high bandwidth services is sufficiently high, the incumbent has no incentives to give away its loops at a very low price as its rental revenues and the benefits from retarding fierce competition should balance the loss from foregone high monopoly profits. It is important to note that, along with the standard replacement effect on the entrant decision for the date of adoption, there may also be a distortion on the type (quality) of technology to be adopted.

From a social welfare point of view the main trade-off is clear; service-based competition through unbundling is good since it promotes immediate competition and increases the variety of services. However, facility-based entry brings forth a better quality of service and a greater flexibility for the entrant for customer targeting. The regulator who is concerned with promoting facility-based competition should regulate the rental price of the loops. It may also choose to determine the duration of the lease contract if the rental price is unregulated.

In our setting, a sunset clause, another regulatory tool that has been claimed to improve socially desirable outcomes, does not improve social welfare. Sunset clauses are expected to give entrants an incentive to invest in alternative technologies as the regulators commit not to regulate the rental price after the clause. As we have shown that the incumbent sets a lower price than is socially efficient, rather than a higher price, a sunset clause does not put a pressure on the entrant for technology adoption.

Finally, an interesting extension to our analysis is to introduce 'learning ', from which the entrant benefits when it leases loops. Entrants may prefer to have some experience in the industry before building their own infrastructures. Learning would in particular be important when the entrant is asymmetrically uninformed about the demand, and/or when experience in the industry improves efficiency (for example, leasing loops prior to adoption may decrease the adoption cost by reducing a). The latter is prominent when adopting new technologies are very expensive (a very high) without a prior experience. We have showed that when a is sufficiently high, the incumbent may not unbundle its loops; a learning effect of this type would give even stronger incentives to the incumbent to deny unbundled access to its loops.

References

[1] Arrow, K. (1962), Economic Welfare and the Allocation of Resources for Invention, in NBER Conference, "The Rate and Direction of Inventive Activity: Economic and Social Factors", Princeton University Press, Princeton.

[2] Bourreau, M., and Doğan, P., (2001), Regulation and Innovation in the Telecommunications Industry, Telecommunications Policy, Vol. 25, 167-184.

[3] CRTC 97-8 Decision , http://www.crtc.gc.ac/archive/eng/Decisions/1997/DT97-8.htm, May 1997.

[4] CRTC 2001-184 Order, "Local Competition: Sunset clause for non-essential facilities".

[5] Dumont, B., (1999), Reasonable Access to Essential Facilities: An Empty Label of Competition in Information Technologies, Communications & Strategies, No. 34, 137-163.

[6] Gallini, N., (1984), Deterrence through Market Sharing: A Strategic Incentive for Licensing, American Economic Review, Vol. 74, 931-941.

[7] Guidelines on Access to the Unbundled Local Loop, OPTA, March 1999.

[8] Harris, R. and Kraft, J. (1997), Meddling Through: Regulating Local Telephone Competition in the United States, Journal of Economic Perspectives, Vol. 11(4), 93-112.

[9] Kahn, A.E., Tardiff, T.J., and Weisman, D.L., (1999), The Telecommunications Act at three years: an economic evaluation of its implementation by the Federal Communications Commission, Information Economics and Policy, Vol. 11, 319-365.

[10] Katz, M.L., and Shapiro, C.(1987), R&D Rivaly with Licensing or Imitation, American Economic Review, Vol. 77(3), 402-420.

[11] Kim, J-Y, Kim S. T., and Kim, D-J, (2000), Local Loop Unbundling and Antitrust Policy, Information Economics and Policy, Vol. 12, 393-412.

[12] Neven, D. and Thisse, J-F., (1989), Choix des Produits: Concurrence en Qualité et en Variété, Annales D'Economie et Statistique, No. 15/16, 85-112.

[13] Oftel, 19 December 2001, "Delivering a competitive broadband market - Oftel's regulatory strategy for broadband".

[14] Prieger, J. E. (2001), Regulation, Innovation, and the Introduction of New Telecommunications Services, mimeo.

[15] Reinganum, J.(1983), Uncertain Innovation and the Persistence of Monopoly, American Economic Review, Vol. 73(4), 741-748.

[16] Riordan, M. H., (1992), Regulation and Preemptive Technology Adoption, RAND Journal of Economics, Vol. 23(3), 334-349.

[17] Sidak, J.G. and Spulber, D.F., (1998), Deregulatory Takings and the Regulatory Contract, Cambridge University Press, Cambridge.

A Appendix

In this Appendix, we determine lower and upper bounds for both a and f, in order to rule out the uninteresting cases for our analysis. To that end, we have to use some results obtained in the paper.

A1 - Determination of the bounds of f We assume that the fixed cost of unbundling is bounded below, so that if the rental price is set too high, i.e., $r \geq v - 3/4$, the entrant obtains a negative discounted profit from service-based competition. Therefore, we exclude quasi-monopolistic equilibrium in the phase of service-based competition (see the next section of the Appendix).We define $\underline{f}$ such that for all $f > \underline{f}$ and all $r \geq v - 3/4$,

$$(1 - \Delta_{SH}(r))\, \pi_E^S(r) - f < 0$$

with

$$\Delta_{SH}(r) = \frac{\pi_E^F(q_H) - \pi_E^S(r)}{a_H}.$$

Let $\Psi_H(r) = (1 - \Delta_{SH}(r))\, \pi_E^S(r)$. Note that $\partial \Psi_H(r) / \partial \pi_E^S(r) > 0$. Furthermore, $\partial \pi_E^S(r) / \partial r < 0$ implies that $\partial \Psi_H(r) / \partial r < 0$. Therefore, if $\Psi_H(r) - f < 0$ is true for $r = v - 3/4$, then it is true for all $r > v - 3/4$. Replacing for r in the inequality (see the next section where we compute profits for service-based competition) and re-arranging it yields $f > 1/4 + (9 - 16q_H) / 144a_H$. The right-hand side of this inequality is increasing in a_H, since $(9 - 16q_H) < 0$ for all $q_H \in \left(\underline{q}_H, \overline{q}_H\right)$. Furthermore, as $a_H \in (\underline{a}_H, \overline{a}_H)$, if the inequality holds for $\overline{a}_H$, where $\overline{a}_H = v - 3/4 + q_H/3$, it holds for all a_H. Replacing for a_H, we find $f > (18v - 9 - 2q_H) / 6\,(12v - 9 + 4q_H)$. Observe that the right-hand side of this inequality decreases with q_H. Hence, if the inequality is satisfied for $\underline{q}_F$, with $\underline{q}_F = 2$, then it is satisfied for all q_H. Finally, replacing for q_H, we derive the condition $f > (18v - 13) / (72v - 6)$. The same reasoning for technology L yields the condition $f > (v - 1) / (4v - 3)$. Since we have assumed that $v > 3$, it is easy to verify that the condition for technology L is binding. Hence, the sufficient condition on f to exclude quasi-monopolistic equilibrium in service-based competition is

$$f > (v - 1) / (4v - 3) \equiv \underline{f}.$$

Now, we determine $\overline{f}$. The entrant chooses to rent loops before building its own infrastructure, if and only if it gets higher profit when it leases loops than when it does not:

$$\frac{\left(\pi_E^F(q_H) - \pi_E^S(r)\right)^2}{2a_H} + \pi_E^S(r) - f > \frac{\left(\pi_E^F\right)^2}{2a_H},$$

or

$$f < \frac{\pi_E^S(r)}{2a_H}\left(\pi_E^S(r) - 2\pi_E^H + 2a_H\right).$$

The entrant leases loops at $r = 0$ if the condition above holds for $r = 0$, i.e., if

$$f < \frac{1}{2} + \frac{1}{8a_H} - \frac{\pi_E^H}{2a_H},$$

or

$$f < \frac{1}{2} + \frac{1}{8a_H} - \frac{2q_H}{9a_H}.$$

The same reasoning for technology L yields that the entrant leases loops at $r = 0$ if and only if

$$f < \frac{1}{2} + \frac{1}{8a_L} - \frac{(6 + q_L)^2}{144a_L}.$$

Hence,

$$\overline{f} = \min\left\{\frac{1}{2} + \frac{1}{8a_H} - \frac{2q_H}{9a_H}; \frac{1}{2} + \frac{1}{8a_L} - \frac{(6 + q_L)^2}{144a_L}\right\}.$$

Having determined $\underline{f}$ and $\overline{f}$, it remains to check whether $\overline{f} > \underline{f}$. Note that $\underline{f}$ increases with v and that $\underline{f} < 1/4$ for all v. Furthermore, we have $\overline{f} > \underline{f}$ if and only if

$$\overline{f} > (v - 1) / (4v - 3).$$

Since $\underline{f}$ increases with v and approaches to $1/4$ when v goes to the infinite, it is sufficient to check that $\overline{f} > 1/4$. When $\overline{f} = 1/2 + 1/(8a_L) - (6 + q_L)^2 / (144a_L)$, this is equivalent to

$$a_L > (6 + q_L)^2 /36 - 1/2 \equiv \underline{a}_L.$$

The same analysis applies when $\overline{f} = 1/2 + 1/(8a_H) - 2q_H/(9a_H)$. We find that $\overline{f} > 1/4$ if and only if

$$a_H > 8q_H/9 - 1/2 \equiv \underline{a}_H.$$

A2 - Determination of the bounds of a We assume that $a \in (\underline{a}, \overline{a})$, with

$$\underline{a} = 8q_F/9 - 1/2,$$

and

$$\overline{a} = v - 3/4 + q_F/3,$$

for $q_F \in \left(\underline{q}_F, \overline{q}_F\right)$. The lower bound on a is determined in Appendix A1 above. It also ensures that the technology is not adopted immediately (i.e., $\Delta^* < 1$). Indeed, the earliest adoption occurs when the entrant does not lease loops, at $\Delta^* = \pi_E^F(q_F)/a = 4q_F/(9a)$. Hence, $\Delta^* < 1$ if and only if $a > 4q/9$. It is easy to check that $q_F > 2$ implies that $4q_F/9 < \underline{a}$. The upper bound on a excludes the case in which the incumbent never unbundles its loops; it is determined in Lemma 8.

Similarly, upper and lower bounds for technology L (which is introduced in Section 4) can be derived: $a_F \in ((6 + q_F)^2 /36 - 1/2, v - 3/4 + q_F/3)$, with $q_F \in \left(0, \underline{q}_F\right)$. As for technology H, the lower bound on a ensures that technology L is not adopted immediately.

B Appendix

B1 - Computations for Service-Based Competition

$$p_I^M = \pi_I^M = v - \frac{1}{4}.$$

Profit flows of the incumbent and the entrant are

$$\pi_I^S(r) = p_I^S x + (1 - \overline{x}) r$$

and

$$\pi_E^S(r) = \left(p_E^S - r\right)(1 - \overline{x}),$$

where $\overline{x}$ is the marginal customer who is indifferent between purchasing access from the incumbent or the entrant. Equilibrium prices and profits depend on the rental rate r. We proceed in three steps. We first derive the profit functions, then we determine the reaction functions. Finally, we solve for the Nash equilibrium of the game.

Step One: We start by deriving the profit function of firm $i \in \{I, E\}$ for any price charged by firm $j \neq i$, $\pi_i(p_i \mid p_j)$. Notice that the demands for the two firms overlap only when $p_i \in (p_j - 1, p_j + 1)$. First, assume that $p_j \geq v$; then $\pi_i(p_i \mid p_j)$ is independent of p_j, as firm j serves no consumer. Second, assume that $p_j < v$; then the marginal consumer is defined by $\overline{x} = (p_E - p_I + 1)/2$. The marginal consumer obtains a positive surplus if and only if

$$p_i \leq \overline{p}_i(p_j) \equiv p_j - 1 + 2\sqrt{v - p_j}.$$

If $p_i > \overline{p}_i(p_j)$, firm i and j get the following local monopoly profits

$$\pi_I^M(p_I, p_E) = p_I\sqrt{v - p_I} + r\sqrt{v - p_E},$$

and

$$\pi_E^M(p_I, p_E) = (p_E - r)\sqrt{v - p_E}.$$

If $p_i < \overline{p}_i(p_j)$, firm i and j get the following duopoly profits

$$\pi_I^D(p_I, p_E) = p_I D_I + r D_E,$$

and

$$\pi_E^D(p_I, p_E) = (p_E - r) D_E,$$

where

$$D_I = \begin{cases} 0 & \text{if} \quad \overline{x} \leq 0 \\ (p_E - p_I + 1)/2 & \text{if} \quad \overline{x} \in (0,1) \\ 1 & \text{if} \quad \overline{x} \geq 1 \end{cases},$$

and $D_E = 1 - D_I$.

Step Two: Now we can determine the reaction functions of the firms. The reaction function of firm i is defined as the optimal choice of p_i given p_j. Let p_i^M and p_i^D denote the prices that maximize π_i^M and π_i^D, respectively. We find $p_i^D(p_j) = (p_j + 1 + r)/2$, $p_I^M = v - 1$, and

$$p_E^M = \begin{cases} (2v + r)/3 & \text{if} \quad r \geq v - 3 \\ v - 1 & \text{if} \quad r < v - 3 \end{cases}.$$

We start by deriving the reaction function of firm I. We have four possible cases. The optimal price for firm I is

1. p_I^M if $\overline{p}_I(p_E) \leq p_I^M$,
2. $p_I^D(p_E)$ if $\overline{p}_I(p_E) > p_I^M$, $p_I^D(p_E) < \overline{p}_I(p_E)$ and $p_E - 1 < p_I^D(p_E) \leq p_E + 1$,
3. $p_E - 1$ if $\overline{p}_I(p_E) > p_I^M$, $p_I^D(p_E) < \overline{p}_I(p_E)$ and $p_I^D(p_E) \leq p_E - 1$,
4. $\overline{p}_I(p_E)$ if $p_I^M < \overline{p}_I(p_E) < p_I^D(p_E)$.

To begin with, consider case 1. We find that $\overline{p}_I(p_E) \leq p_I^M$ if $p_E > v$. Now, consider cases 2-4. First, we look for the conditions for case 2. We find that $p_I^D(p_E) < \overline{p}_I(p_E)$ if and only if $p_E < r - 5 + 4\sqrt{v - r + 1}$ and that $p_I^D(p_E) > p_E - 1$ if and only if $p_E < r + 3$. We have to compare these two conditions. The comparison yields $r - 5 + 4\sqrt{v - r + 1} \geq r + 3$ if and only if $r \leq v - 3$. Firm I gets positive demand when it charges $p_I^D(p_E)$ if and only if $p_I^D(p_E) \leq p_E + 1$, which is satisfied if $p_E \geq r - 1$. When $p_E < r - 1$, firm I prefers that firm E serve all customers and pay r for leasing loops rather than charge a retail price lower than r.

This analysis shows that when $r \leq v - 3$, the optimal price for firm I is $p_I^D(p_E)$ if $p_E \in [r - 1, r + 3]$ and $p_E - 1$ if $p_E > r + 3$. When $r > v - 3$, the optimal price for firm I is $p_I^D(p_E)$ if $p_E \in \left[r - 1, r - 5 + 4\sqrt{v - r + 1}\right]$ and $\overline{p}_I(p_E)$ if $p_E > r - 5 + 4\sqrt{v - r + 1}$. To summarize, we have two cases. If $r \in (0, v - 3)$, then

$$R_I(p_E) = \begin{cases} r & \text{if} \quad p_E \in [0, r - 1) \\ (p_E + 1 + r)/2 & \text{if} \quad p_E \in [r - 1, r + 3) \\ p_E - 1 & \text{if} \quad p_E \in [r + 3, v) \\ v - 1 & \text{if} \quad p_E \in [v, \infty) \end{cases}$$

If $r \geq v - 3$, then

$$R_I(p_E) = \begin{cases} r & \text{if} \quad p_E \in [0, r - 1) \\ (p_E + 1 + r)/2 & \text{if} \quad p_E \in \left[r - 1, r - 5 + 4\sqrt{v - r + 1}\right) \\ \overline{p}_I(p_E) & \text{if} \quad p_E \in \left[r - 5 + 4\sqrt{v - r + 1}, v\right) \\ v - 1 & \text{if} \quad p_E \in [v, \infty) \end{cases}$$

We proceed the same way to derive the reaction function of firm E. The only difference is that when $r > v - 3$, firm E does not serve all customers when it charges its monopoly price, $p_E^M = (2v + r)/3$. When $r > v - 3$, firm E can charge its monopoly price if $p_E^M > \overline{p}_E(p_I)$, which is satisfied if and only if $p_I > (2v+r)/3 - 1 + 2\sqrt{v-r}/\sqrt{3}$. To summarize, we have two cases. If $r \in (0, v-3)$, then

$$R_E(p_I) = \begin{cases} r & \text{if} \quad p_I \in [0, r-1) \\ (p_I + 1 + r)/2 & \text{if} \quad p_I \in [r-1, r+3) \\ p_I - 1 & \text{if} \quad p_I \in [r+3, v) \\ v - 1 & \text{if} \quad p_I \in [v, \infty) \end{cases}$$

If $r \in [v-3, \infty)$, then

$$R_E(p_I) = \begin{cases} r & \text{if} \quad p_I \in [0, r-1) \\ (p_I + 1 + r)/2 & \text{if} \quad p_I \in \left[r-1, r-5+4\sqrt{v-r+1}\right) \\ \overline{p}_E(p_I) & \text{if} \quad p_I \in \left[r-5+4\sqrt{v-r+1}, (2v+r)/3 - 1 + 2\sqrt{v-r}/\sqrt{3}\right) \\ (2v+r)/3 & \text{if} \quad p_I \in \left[(2v+r)/3 - 1 + 2\sqrt{v-r}/\sqrt{3}, \infty\right) \end{cases}.$$

Step Three: Now, we can determine the equilibrium of the game. First, for all $r \in (0, v-3)$, $p_I^S = p_E^S = 1 + r$ is an equilibrium and is the unique equilibrium. Second, let us assume that $r \geq v - 3$. The competitive equilibrium $(1+r, 1+r)$ exists if and only if $1 + r \in \left[r-1, r-5+4\sqrt{v-r+1}\right]$, which is satisfied if $r < v - 5/4$. There is an equilibrium such that firm I charges its monopoly price, $v-1$, only if $v - 1 < r - 1$, i.e., $r > v$.

When $r \in (v-5/4, v-3/4)$, there is a corner equilibrium such that the marginal consumer gets zero surplus, i.e., $p_I^S = p_E^S = v - (1/2)^2 = v - 1/4$. Indeed, we find that $v - 1/4 > r - 5 + 4\sqrt{v-r+1}$ if and only if $r > v - 5/4$. Besides, we find that $v - 1/4 < (2v+r)/3 - 1 + 2\sqrt{v-r}/\sqrt{3}$ if $v - 27/4 < r < v - 3/4$.

Finally, when $r \in (v-3/4, v)$, there is an equilibrium such that firm E charges its monopoly price, $p_E^M = (2v+r)/3$ and firm I charges $\overline{p}_I\left(p_E^M\right)$. Indeed, when $r > v - 3/4$ and firm I charges $p_I^S = v - 1/4$, the optimal price for firm E is $p_E^M = (2v+r)/3$. The best response of firm I is then to charge $\overline{p}_I\left(p_E^M\right) = (2v+r)/3 - 1 + 2\sqrt{v-r}/\sqrt{3}$. We check that $R_I\left(p_E^M\right) = \overline{p}_I\left(p_E^M\right)$, as $(2v+r)/3 > r - 5 + 4\sqrt{v-r+1}$ when $r > v - 21/2 + 3\sqrt{10} \approx v - 1.01 < v - 3/4$. We also check that $R_E\left(\overline{p}_I\left(p_E^M\right)\right) = p_E^M$, as $\overline{p}_I\left(p_E^M\right) = (2v+r)/3 - 1 + 2\sqrt{v-r}/\sqrt{3}$.

To summarize, for $r \leq v - 5/4$, we have a competitive equilibrium; for $r \in (v-5/4, v-3/4)$, we have a corner equilibrium; for $r \in (v-3/4, v)$, we have a quasi-monopolistic equilibrium. Equilibrium prices and profits are

$$p_I^S = \begin{cases} 1 + r & \text{if} \quad r \in [0, v-5/4) \\ v - 1/4 & \text{if} \quad r \in [v-5/4, v-3/4) \\ (2v+r)/3 - 1 + 2\sqrt{v-r}/\sqrt{3} & \text{if} \quad r \in [v-3/4, v) \end{cases}$$

$$p_E^S = \begin{cases} 1 + r & \text{if} \quad r \in [0, v-5/4) \\ v - 1/4 & \text{if} \quad r \in [v-5/4, v-3/4) \\ (2v+r)/3 & \text{if} \quad r \in [v-3/4, v) \end{cases}$$

$$\pi_E^S(r) = \begin{cases} 1/2 & \text{if} \quad r \in [0, v - 5/4) \\ (v - 1/4 - r)/2 & \text{if} \quad r \in [v - 5/4, v - 3/4) \\ 2\sqrt{3}\,(v - r)^{3/2}/9 & \text{if} \quad r \in [v - 3/4, v) \end{cases}$$

and

$$\pi_I^S(r) = \begin{cases} 1/2 + r & \text{if} \quad r \in [0, v - 5/4) \\ (v - 1/4 + r)/2 & \text{if} \quad r \in [v - 5/4, v - 3/4) \\ r - 1 + \sqrt{3}\sqrt{v - r} - 2\sqrt{3}\,(v - r)^{3/2}/9 & \text{if} \quad r \in [v - 3/4, v) \end{cases}.$$

B2 - Proof of Lemma 1. Since for all $r \geq v - 3/4$, the entrant finds it unprofitable to lease loops, it suffice to determine whether $\partial\pi_I^S(r)/\partial r \geq 0$ and $\partial\pi_E^S(r)/\partial r \leq 0$ for $r \in [0, v - 3/4)$. As $\pi_E^S(r) = 1/2$ and $\pi_I^S(r) = 1/2 + r$ for all $r \in [0, v - 5/4)$, and as $\pi_E^S(r) = (v - 1/4 - r)/2$ and $\pi_I^S(r) = (v - 1/4 + r)/2$ for all $r \in [v - 5/4, v - 3/4)$, it is straightforward to conclude that $\partial\pi_I^S(r)/\partial r \geq 0$ and $\partial\pi_E^S(r)/\partial r \leq 0$. ■

C Appendix

C1 - Proof of Lemma 2. While computing the payoffs in this section, we assume that $y_I \geq y_E$ without any loss of generality. We first start by deriving the demand function. Marginal consumers are defined by

$$\overline{\theta}(x) = \left((\overline{p}_E - p_I) + \left(y_E^2 - y_I^2\right) - 2\,(y_E - y_I)\,x\right)/q_H.$$

Let $p_I^{(0,0)}$ such that $\overline{\theta}(x = 0) = 0$ for a given $\overline{p}_E$ ($\overline{\theta}(x)$ passes through the southwest corner of the unit square, so superscript $(0, 0)$ stands for $(x = 0, \theta = 0)$).

$$p_I^{(0,0)} = \overline{p}_E + (y_E^2 - y_I^2).$$

Then, whenever $p_I \geq p_I^{(0,0)}$, demand for the incumbent is zero. Similarly, let $p_I^{(1,0)}$ such that $\overline{\theta}(x = 1) = 0$; hence,

$$p^{(1,0)} = \overline{p}_E + (y_E^2 - y_I^2) - 2(y_E - y_I).$$

Following Neven and Thisse (1989), the demand for the incumbent is formed by three segments. We focus on the linear part of the demand curve for computing equilibrium profit flows. Considering non-linear parts would complicate the exposition without substantively enhancing our analysis. Assume that $q_F > 2$. For all $q_F > 2$, (as $\left|\partial\overline{\theta}(x)/\partial x\right| < 1$) The linear segment of the demand for facility-based competition is determined by

$$D_I^F = \int_0^1 \overline{\theta}(x)dx,$$

for $p_I \in [p_I^{(0,1)}, p_I^{(1,0)})$. Therefore, the demand for the incumbent is

$$D_I^F = \left((p_E - p_I) + (y_E^2 - y_I^2) - (y_E - y_I)\right)/q_F, \tag{11}$$

and the entrant's demand can be found by $D_E^F = \left(1 - D_I^F\right)$. Now we solve for the equilibrium and show that it exists. Let

$$y = (y_E^2 - y_I^2) - (y_E - y_I),$$

and we have $D_I^F = (p_E - p_I + y)/q_F$ and $D_E^F = 1 - ((p_E - p_I) + y)/q_F$. The incumbent and the entrant maximize their profit flows, which are

$$\pi_I^F = ((p_E - p_I + y)/q_F)\, p_I,$$

and

$$\pi_E^F = (1 - (p_E - p_I + y)/q_F)\, p_E,$$

respectively. If it exists, the Nash equilibrium of this price game yields $p_I^F = (q_F + y)/3$, and $p_E^F = (2q_F - y)/3$. Corresponding profits are $\pi_I^F = (q_F + y)^2/9q_F$, and $\pi_E^F = (2q_F - y)^2/9q_F$. It remains to check whether price equilibrium exists, i.e., if p_I^F and p_E^F are valid in the linear part of the demand. It suffices to check whether $p_I^F \in [p_I^{(0,1)}, p_I^{(1,0)})$. We know that $p_I^{(0,1)} = p_E^F - 1$, and $p_I^{(1,0)} = p_E^F + 1$. Furthermore, $p_E^F = (2q_F - y)/3$. Thus we have

$$p_I^{(0,1)} = (2q_F - y)/3 - 1$$

$$p_I^{(1,0)} = (2q_F - y)/3 + 1.$$

We have $p_I^F \in [p_I^{(0,1)}, p_I^{(1,0)})$ if $2y + 3 > q_H$ and $2y/3 < q_F$ holds. The former inequality holds if $q_F < 3$ and the latter holds if $q_F > 2/3$.

As we have assumed that $q_F > 2$, both inequalities hold if $q_F < 3$. We find the same conditions for $p_E^F \in [p_I^{(0,1)}, p_I^{(1,0)})$. Hence, for $q_F \in (2,3)$, the price equilibrium exists, and it is easy to verify that the equilibrium horizontal locations are $y_E = y_I = 1/2$.

We determine $\underline{q}_F = 2$ (so that we have $\left|\partial\overline{\theta}(x)/\partial x\right| < 1$) and $\overline{q}_F = 3$ (to ensure the existence of price equilibrium). Note that for $q_F < 2$, depending on the horizontal locations, we can have either $\left|\partial\overline{\theta}(x)/\partial x\right| < 1$ or $\left|\partial\overline{\theta}(x)/\partial x\right| > 1$, and the demand function is derived differently when $\left|\partial\overline{\theta}(x)/\partial x\right| > 1$.

Finally, for $q_F \in (2,3)$, prices and profit flows in the phase of facility-based competition are $p_I^F = q_F/3$, $p_E^F = 2q_F/3$, $\pi_I^F = q_F/9$, and $\pi_E^F = 4q_F/9$. ■

C2 - Proof of Lemma 3. $\partial\pi_E^F(q_F)/\partial q_F > 0$ is straightforward since $\pi_E^F(q_F) = 4q_F/9$. To demonstrate that $\pi_E^F(q_F) > \pi_E^S(r)$ is true for all q_F and r, it suffices to show that this is true for $q_F = \underline{q}_F = 2$ and for $r = 0$, since $\partial\pi_E^F(q_F)/\partial q_F > 0$ and $\partial\pi_E^S(r)/\partial r \leq 0$. Replacing for r, and q_F, we find that $\pi_E^S(0) = 1/2 < 8/9 = \pi_E^F(2)$. ■

C3- Computations for Technology L Similar to technology H, while computing the payoffs in this section, we assume that $y_I \geq y_E$ without any loss of generality. We first start by deriving the demand function. For all $q_F < 2$, we may have either $\left|\partial\overline{\theta}(x)/\partial x\right| > 1$ (then the analysis are the same as subsection C1), or $\left|\partial\overline{\theta}(x)/\partial x\right| < 1$. If $\left|\partial\overline{\theta}(x)/\partial x\right| < 1$, the linear segment of the demand curve during the facility-based competition is determined by

$$D_I^L = x + \int_{\overline{x}}^{\overline{\overline{x}}} \theta(x)dx,$$

where $\overline{x}$ and $\overline{\overline{x}}$ are defined such that $\overline{\theta}(\overline{x}) = 0$ and $\overline{\theta}(\overline{\overline{x}}) = 1$, respectively. Replacing for $\overline{x} = \left(p_E - p_I + y_E^2 - y_I^2\right)/2y$ and $\overline{\overline{x}} = \left(p_E - p_I + y_E^2 - y_I^2 - q\right)/2y$, we find

$$D_I^L = \left(p_E - p_I + \left(y_E^2 - y_I^2\right)\right)/2y - q_L/4\left(y_E - y_I\right). \tag{12}$$

The price interval for which the linear segment of the demand curve is valid is defined by $p_I \in \left(p_I^{(1,0)}, p_I^{(0,1)}\right)$, with

$$p_I^{(0,1)} = \overline{p}_E + \left(y_E^2 - y_I^2\right) - q_L$$

$$p_I^{(1,0)} = \overline{p}_E + \left(y_E^2 - y_I^2\right) - 2\left(y_E - y_I\right)$$

Similar computations to subsection C-1 show that if price equilibrium exists, the equilibrium prices are

$$p_E^L = \left(8\left(y_E - y_I\right) - 2\left(y_E^2 - y_I^2\right) + q_L\right)/6,$$

and

$$p_I^L = \left(4\left(y_E - y_I\right) + 2\left(y_E^2 - y_I^2\right) - q_L\right)/6.$$

One can verify whether if the equilibrium prices are within the range for which the linear segment of the demand is defined, i.e., whether if $p_I \in \left(p_I^{(1,0)}, p_I^{(0,1)}\right)$.We have $p_I \geqslant p_I^{(1,0)}$ if

$$4\left(y_E - y_I\right) - \left(y_E^2 - y_I^2\right) \geqslant q_L.$$

Furthermore, $p_I \leqslant p_I^{(0,1)}$ is true if

$$q_L \leqslant \frac{\left(y_E^2 - y_I^2\right) + 2\left(y_E - y_I\right)}{2}.$$

One can verify that if $(y_E - y_I) > q_L/2$ the demand is determined by equation (12), and if $(y_E - y_I) < q_L/2$ it is determined by equation (11). Assume that $(y_E - y_I) > q_L/2$. Then, equilibrium profit flows are

$$\pi_I^F\left(q_L\right) = \frac{\left(4\left(y_E - y_I\right) + 2\left(y_E^2 - y_I^2\right) - q_L\right)^2}{72\left(y_E - y_I\right)},$$

and

$$\pi_E^F\left(q_L\right) = \frac{\left(8\left(y_E - y_I\right) - 2\left(y_E^2 - y_I^2\right) + q_L\right)^2}{72\left(y_E - y_I\right)}.$$

One can show that if $(y_E - y_I) > q_L/2$, then the equilibrium locations are $y_I = 0$, and $y_E = 1$. Hence, $\pi_I^F(q_L) = (6-q_L)^2/72$, and $\pi_E^F(q_L) = (6+q_L)^2/72$. This case is referred as 'horizontal dominance' by Neven and Thisse (1998) , as horizontal differentiation dominates vertical differentiation. If $(y_E - y_I) < q_L/2$, equilibrium locations are $y_I = y_E = 1/2$, hence the profit flows are $\pi_I^F(q_L) = q_L/9$, and $\pi_E^F(q_L) = 4q_L/9$ (vertical dominance). For a given q_L ,horizontal locations of the firms determine whether there is vertical or horizontal dominance, hence the shape of the demand curve. For sufficiently small q_L ($q_L < 0.6$), firms' dominant strategy is to obtain maximum horizontal differentiation. Furthermore, whenever both maximum and minimum differentiation is an equilibrium, the equilibrium profit flows with maximum differentiation payoff-dominates the profit flows with minimum differentiation, for all $q_L \in (0,2)$. Therefore, when the entrant adopts technology L, we define the profit flows in the phase of facility-based competition with $\pi_I^F(q_L) = (6-q_L)^2/72$, and $\pi_E^F(q_L) = (6+q_L)^2/72$.

C4 - Lemma 3 applies to $q_F \in \left(0, \underline{q}_F\right)$**.** First, $\partial\pi_E^F(q_L)/\partial q_L > 0$, as $\pi_E^F(q_L) = (6+q_L)^2/72$. Second, one can verify that $\pi_E^S(r) < \pi_E^F(q_L)$ is true for $r = 0$, and $q_L = \epsilon$ (with ϵ very small); hence, $\pi_E^S(r) < \pi_E^F(q_L)$ is true for all $q_L \in (0,2)$. ■

D Appendix

D1 - Proof of Lemma 4. We show that $\pi_I^M > \pi_I^S(r) > \pi_I^F(q_F)$ is true for all r, with the following. We begin by showing that $\pi_I^S(r) > \pi_I^F(q_F)$. If we show that this is true for $r = 0$ and $q_F = 0$, then it holds for all r and q_H, since $\partial\pi_I^S(r)/\partial r \geq 0$, and $\partial\pi_I^F(q_F)/\partial q_F \geq 0$. Indeed, we have $(v - 1/4 + r)/2 = 1/2 > 0 = \pi_I^F(0)$. Now we show that $\pi_I^M > \pi_I^S(r)$ for all r. Similarly, it suffices to show that this is true for $r = v - 3/4$. We know that $\pi_I^M = v - 1/4$, and hence we can verify that $\pi_I^S(v - 3/4) = v - 1/2 < v - 1/4 = \pi_I^M$. ■

D2 - Lemma 4 applies to $q_F \in \left(0, \underline{q}_F\right)$**.** We know that $\pi_I^S(r) = 1/2 + r$ and $\pi_I^F(q_L) = (6-q_L)^2/72$ for $r \in [0, v - 5/4)$. As $(6-q_L)^2/72 < 1/2$, $\pi_I^F(q_L) < \pi_I^S(r)$ holds for all $r \geq 0$. Note that $\pi_I^S(r)$ is increasing with r for $r \in [v - 5/4, v - 3/4)$. Then, if $\pi_I^S(r) > \pi_I^F(q_L)$ is true for this range, $r = v - 5/4$; i.e., if

$$(v - 1/4 + r)/2 > (6 - q_L)/72$$

it is also true for all $r \in [v - 5/4, v - 3/4)$. Furthermore, observe that the right-hand side of the inequality is decreasing with q_L. We have $q_L \in (0,2)$; therefore, if this inequality is satisfied for $q_L = 0$, it is satisfied for all q_L. Replacing for $r = v - 5/4$ and $q_L = 0$, the inequality becomes $72v - 60 > 0$, which is always satisfied as we have assumed $v > 3$. ■

E Appendix

Proof of Lemma 7. We begin by showing that if the entrant adopts technology H when there is no unbundling, it also does so when there is unbundling. First, assume that the entrant prefers technology H when there is no unbundling

$$\frac{\left(\pi_E^H\right)^2}{a_H} > \frac{\left(\pi_E^L\right)^2}{a_L} \Rightarrow \frac{\pi_E^H}{\sqrt{a_H}} > \frac{\pi_E^L}{\sqrt{a_L}}.$$

And assume that, when there is unbundling, it prefers technology L instead of H, which is true if

$$\left(\pi_E^H - \pi_E^S(r)\right)^2 / a_H < \left(\pi_E^L - \pi_E^S(r)\right)^2 / a_L$$

or

$$\pi_E^H / \sqrt{a_H} - \pi_E^L / \sqrt{a_L} < \left(1/\sqrt{a_H} - 1/\sqrt{a_L}\right) \pi_E^S(r)$$

holds. Since $a_H > a_L$, we have $1/\sqrt{a_H} < 1/\sqrt{a_L}$. Therefore, the right-hand side of the above expression is negative while the left-hand side is positive. Therefore, if the entrant prefers technology H when there is no unbundling, it also prefers technology H when there is unbundling. Now we show that when the entrant prefers technology L with no unbundling, it may prefer technology H when there is unbundling. Observe that the entrant chooses technology L when there is unbundling if

$$\pi_E^L / \sqrt{a_L} > \pi_E^H / \sqrt{a_H}$$

and prefers technology H when there is unbundling if and only if

$$\left(\pi_E^H - \pi_E^S(r)\right) / \sqrt{a_H} > \left(\pi_E^L - \pi_E^S(r)\right) / \sqrt{a_L} \Leftrightarrow$$

$$\pi_E^L / \sqrt{a_L} - \pi_E^H / \sqrt{a_H} < \left(1/\sqrt{a_L} - 1/\sqrt{a_H}\right) \pi_E^S(r).$$

Note that both sides of the inequality are positive. Therefore, the entrant prefers technology H if and only if

$$\pi_E^S(r) > \frac{\pi_E^L / \sqrt{a_L} - \pi_E^H / \sqrt{a_H}}{1/\sqrt{a_L} - 1/\sqrt{a_H}} \equiv \widetilde{\pi}_E^S > 0.$$

If $\pi_E^S(r) < \widetilde{\pi}_E^S$, the entrant prefers technology L. We know that $\pi_E^S(r)$ decreases with r when $r \in [v - 5/4, v]$, and is constant otherwise. Therefore, if $\pi_E^S(r) > \widetilde{\pi}_E^S$ is true for some r, there exists $\widetilde{r} \in (v - 5/4, v]$ such that $\pi_E^S(r) > \widetilde{\pi}_E^S$ for $r < \widetilde{r}$ and $\pi_E^S(r) < \widetilde{\pi}_E^S$ for $r > \widetilde{r}$. We find that $\widetilde{r} = v - 1/4 - 2\widetilde{\pi}_E^S$ when $\widetilde{\pi}_E^S \in (1/4, 1/2)$ and that $\widetilde{r} = v - \sqrt[3]{18}\left(\sqrt{3}\widetilde{\pi}_E^S\right)^{2/3}/2$ when $\widetilde{\pi}_E^S \in (0, 1/4)$. It remains to show that $\pi_E^S(r) > \widetilde{\pi}_E^S$ is true for some r. Indeed, $\widetilde{\pi}_E^S < 1/2$ is true if and only if

$$a_H < a_L K_S(0),$$

with

$$K_S(0) = \left(\frac{\pi_E^H - \pi_E^S(0)}{\pi_E^L - \pi_E^S(0)}\right)^2,$$

in other words, if a_H is sufficiently small. ■

F Appendix

F1 - Proof of Proposition 2. Social welfare is defined as the sum of consumer surplus and industry profits. Let $s(r)$, $s_F(q_\tau)$,and s_M denote consumer surplus under service-based competition, facility-based competition with technology τ, and monopoly, respectively, with

$$s(r) = \begin{cases} v - 13/12 - r & \text{if} \quad r \in [0, v - 5/4) \\ 1/6 & \text{if} \quad r \in [v - 5/4, \overline{r}) \end{cases},$$

$$s_F(q_\tau) = \begin{cases} v - 13/12 + q_L/4 + (q_L)^2/36 & \text{if} \quad \tau = L \\ v - 1/12 - q_H/9 & \text{if} \quad \tau = H \end{cases},$$

and $s_M = 1/6$. When the incumbent is a monopolist, the social welfare flow is

$$w_M = s_M + \pi_I^M = v - 1/12.$$

When the firms compete on the basis of services $w_S(r) = s(r) + \pi_I^S(r) + \pi_E^S(r) = v - 1/12$ for all $r \in [0, \overline{r})$, and when firms compete on the basis of facilities, social welfare flow is

$$w_F(q_\tau) = \begin{cases} v - 1/12 + q_L/4 + q_L^2/18 & \text{if} \quad \tau = L \\ v - 1/12 + 4q_H/9 & \text{if} \quad \tau = H \end{cases}.$$

Discounted social welfare functions with and without unbundling ($W^{S+F}(q_\tau, r)$ and $W^F(q_\tau)$) are determined in equations (5) and (6). First, note that, since $\Delta_E^S(r)$ is constant when $r \leq v - 5/4$, the implication is that $W^{S+F}(q_\tau, r)$ is also constant. Second, if $r > \overline{r}$, $W^{S+F}(q_\tau, r) = W^F(q_\tau)$, as the entrant does not lease loops. Third, assume that $r \in [v - 5/4, v - 3/4)$ and that $\overline{r}$ is near $v - 3/4$. Also assume that the entrant adopts technology L. Let $W_L'(r) = \partial\left(W^{S+F}(q_L, r)\right)/\partial r$. We find that $W_L'(r) < 0$, as $W_L''(r) = -1/(4a_L) < 0$. We also have $W_L'(r = v - 5/4) > 0$ and $W_L'(r = v - 3/4) < 0$, as $q_L < 2$. We find that

$$W_L'(\widehat{r}) = 0 \Longleftrightarrow \widehat{r} = v - 5/4 + q_L/6 + q_L^2/12.$$

Therefore, $\widehat{r}$ maximizes welfare if $\widehat{r} < \overline{r}$; otherwise, $\overline{r}$ maximizes welfare. Now assume that the the entrant adopts technology H. Letting $W_H'(r) = \partial\left(W^{S+F}(q_H, r)\right)/\partial r$, we find that $W_H'(r) = -(1 - 4v + 4r)/16a_H$, and it is decreasing with r . Furthermore, $W_H'(r = v - 3/4) > 0$. Therefore, $W^{S+F}(q_H, r)$ increases with r up to $r = \overline{r} - \epsilon$ (with ϵ very small), and social welfare is maximized with $r = \overline{r} - \epsilon$. In summary, if unbundling is socially desirable, the social welfare maximizing rental price is

$$r_\tau^w = \begin{cases} \min\{\widehat{r}, \overline{r}\} & \text{if } \tau = L \\ \overline{r} - \epsilon & \text{if } \tau = H \end{cases},$$

with $\widehat{r} = v - 5/4 + q_L/6 + q_L^2/12$. We conclude that $r_\tau^w > r^*$ is always true, as $\min\{\widehat{r}, \overline{r}\} \in (v - 5/4, v - 3/4)$ (as $q_L \in (0, 2)$); hence, the rental price that maximizes social welfare is greater than the unregulated rental price. ■

F2 - Proof of Proposition 4. Socially optimal adoption date is defined by

$$\Delta_L^w(r) = \frac{(w_F(q_L) - w_S(r))}{a_L}.$$

Replacing for $w_F(q_L)$ and $w_S(r)$, we find

$$\Delta_L^w(r) = \left(q_L/4 + q_L^2/18\right)/a_L < \Delta_{SL}^*(r).$$

It is then easy to check that $\Delta_L^w = \Delta_{SL}(r) \Longleftrightarrow r = r_L^*$. Therefore, when the rental price is set at the socially optimal level, r_L^*, the entrant adopts technology L at the socially optimal date. When $\overline{r} < r_L^*$, the welfare-maximizing rental price, $\overline{r}$, leads to late adoption. ■