J Regul Econ (2017) 52:189–210
DOI 10.1007/s11149-017-9337-7

ORIGINAL ARTICLE

Strategic bypass deterrence

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Published online: 29 July 2017

Abstract In liberalized network industries, competitors can either compete for service using the existing infrastructure (access) or deploy their own capacity (bypass). We revisit this make-or-buy problem making two contributions to the literature. First we analyze both the profit maximizing behavior of an incumbent and the welfare maximizing behavior when the entrant chooses between access and bypass. Second, we extend the baseline model studied in the literature by allowing for fixed costs of network installation. By analogy to the literature on strategic entry deterrence, we distinguish three régimes of blockaded bypass, deterred bypass and accommodated bypass depending on the entrant's unit cost. We show that the make-or-buy decision of the entrant is not necessarily technologically efficient: when bypass is chosen, it is always the cheapest option but access may be chosen when it is not cost effective.

Keywords Make-or-buy · Access price · Bypass

We are grateful to the editor, two anonymous referees, M. Armstrong, P. Belleflamme, C. Cambini, F. Etro, B. Lyons, K. Mizuno and conference participants at the IIOC (Washington) and EARIE (Roma) for helpful comments. This research was funded through the ARC Grant for Concerted Research Actions, financed by the French-speaking Community of Belgium.

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JEL Classification L13 · L51

1 Introduction

In liberalized network industries, competitors can choose between service-based and facility-based competition. In the former case, competing firms offer retail products and services using the incumbent's installed infrastructure for which they pay an access fee (the "buy"or "access"option). In the latter case, firms develop their own infrastructure to compete on the retail market (the "make"or "bypass"option). This choice between access and bypass is illustrated by the broadband service market where the two modes of competition currently coexist. In countries where access to the incumbent's DSL network is mandatory rival firms either supply services on the incumbent's network or develop their own platform (cable TV network, fiber network, wireless) to provide broadband services to consumers.[1]

When the cost of building an alternative network is large, incumbents have an incentive to deny access in order to block entry of competitors.[2] Faced with this risk of market foreclosure, regulators have taken steps to mandate access to the network of the historical operator and guarantee access at a reasonable price. This regulatory policy which originated in the 1990s—and is still prevalent in Europe—has evolved in the face of increasing competition among network operators, due to a convergence between technologies and a the development of new generation access networks. In the United States, the FCC has lifted in 2003 most of the regulations imposed by the Telecommunications Act of 1996, maintaining access obligations for the legacy copper networks but lifting them for new infrastructures. In Europe, mandatory access and regulated access prices continue to be imposed but only if the incumbent operator holds significant market power on the wholesale broadband market.[3] In 2006, virtually all countries found the incumbent operator to hold significant market power on the wholesale broadband market and imposed some form of regulation (Schwarz 2007) but more recently, with the development of competition, regulations have started to be lightened or even removed.[4] In the future, it is expected that regulation of network infrastructures will be partially removed both in the EU and in the US (Vogelsang 2013) though there are exceptions.[5]

Our objective in this paper is to shed light on the use of (and the necessity to use) regulatory instruments in network industries. We revisit the literature on access in network industries by comparing technological and economic efficiency in regulated

[1] While we cast our analysis in the framework of network industries, it covers more generally any situation where a vertically integrated incumbent faces an entrant who can choose to make an input or buy it from the incumbent.

[2] See Laffont and Tirole (1994).

[3] See Marcus (2005) and Vogelsang (2013) for a discussion of the evolution of regulatory policy in the US and Europe.

[4] For example, in the UK, the regulator OFCOM has decided that some local broadband markets are sufficiently competitive for access regulations to be lifted.

[5] The Belgian regulators impose mandatory third-party access to the cable-TV network, the Canadian regulators have recently imposed regulated access for optical fibre networks.

and unregulated markets. Our contribution to the literature is twofold. First we analyze both the profit maximizing behavior of an incumbent and the welfare maximizing behavior when the entrant chooses between access and bypass. Second, we extend the baseline model studied in the literature by allowing for fixed costs of network installation.

We study how an unregulated incumbent manipulates access prices in order to deter bypass by the incoming firm. By analogy with the literature on entry deterrence (Tirole 1988) we identify three régimes: accommodated bypass, deterred bypass and blockaded bypass and we characterize the threshold cost levels that separate the three régimes.[6]

Our analysis revolves around the limit access charge—the maximal access charge under which the entrant prefers to access the incumbent's network than to bypass. If the limit access charge is too low and induces large losses on the access market, the incumbent prefers to let the entrant construct an alternative network (régime of accommodated bypass). If the limit access charge is higher than the profit maximizing level, the incumbent blocks bypass without distorting the access charge (régime of blockaded bypass). For intermediate values of the limit access charge, the incumbent sets access charges at the limit access charge level in order to deter bypass (régime of deterred bypass). The limit access charge may be lower than the incumbent's marginal cost so that the incumbent sometimes optimally chooses to sell access at a loss.

We next draw a comparison between regulated and unregulated markets using two different efficiency criteria: social welfare measured by total surplus and technological efficiency. We consider a regulator setting access charges but leaving the retail market and the entrant's option between access and bypass unregulated. If access is chosen, the regulator wants to decrease the access charge with respect to the unregulated incumbent's choice in order to lower the retail prices paid by consumers. In addition, the regulator wants to induce more access than in an unregulated market. There is thus *excessive bypass* from a welfare point of view when the access charge is unregulated. The analysis of technological efficiency leads to a different conclusion. Reproducing Mandy's (2009) analysis—but with a positive fixed cost of bypass—we show that the make or buy decision depends on the level of the access charge and may be inefficient. When bypass is chosen, it is always efficient, but access may be chosen even when bypass is cheaper. There is thus *excessive access* from a technological point of view.[7]

The choice between service-based and facility-based competition has already been studied in previous papers. In a static setting, Sappington (2005) demonstrates the irrelevance of the access charge for the choice between service- and facility-based competition and shows that the most efficient mode of competition always emerges in an unregulated market. The entrant develops its own infrastructure only if he can provide the network input more efficiently than the incumbent. Sappington's argument is obtained assuming a Hotelling model with a fully-covered market. Gayle and

[6] The analogy between bypass and entry deterrence, while useful, is not complete. The model of competition with access is more complex than a simple model of competition because of the interactions between the access and retail markets. Existing results on entry deterrence cannot be directly applied to bypass deterrence.

[7] Mandy (2009) shows that in the absence of fixed cost the make or buy decision of the entrant is technologically efficient for a broad range of access charges.

Weisman (2007) demonstrate that, in more general settings, the access price matters for the choice of a mode of competition. Mandy (2009) identifies a set of access prices that induce productive efficiency which includes pricing access at the incumbent's or at the entrant's marginal cost. In dynamic models, facility-based competition is often considered as a long-term objective. The question then is to know whether allowing for service-based competition accelerates the development of facility based competition (the so-called stepping-stone effect identified by Cave and Vogelsang 2003) or delays the installation of new infrastructure (Bourreau and Doğan 2005).[8]

The rest of the paper is organized as follows. We present the model of competition with access in the next Section and the retail price game in Sect. 3. We characterize the profit maximizing behavior of the unregulated incumbent in Sect. 4. In Sect. 5, we discuss efficiency and regulation, analyzing the optimal behavior of a regulator maximizing social welfare. In Sect. 6, we analyze the technological efficiency of the entrant's make or buy decision. We conclude and discuss possible extensions in Sect. 7. Proofs of the results which are not given in the text are collected in "Appendix A".

2 The model

We analyze price competition between two firms: a vertically integrated incumbent, firm 1, and an entrant, firm 2. To produce for the retail market, firms need a network input. The incumbent has already installed the network at cost f_1 and can produce one unit of network input at a constant marginal cost c_1. Firm 2 has no installed network. To produce, it has two options: *access* or *bypass*. The entrant either buys access to firm 1's network at unit price w or it installs its own network infrastructure at a fixed cost f_2 and produces the network input at a constant marginal cost c_2.

On the retail market, the demand for product supplied by firm $i = 1, 2$ at prices (p_i, p_j) is given by $q_i(p_i, p_j)$. Products are imperfect substitutes and we represent the demand by the following system of linear demand functions:

$$q_i(p_i, p_j) = 1 - p_i + \delta p_j, \ \ i, j = 1, 2, \ i \neq j, \ \ \delta < 1. \tag{1}$$

The parameter $\delta \in (0, 1)$ is the *displacement ratio* which indicates how an increase in the price of good j raises the demand of good i. The linear demand function can be derived from the maximizing behavior of a representative consumer with net surplus function

[8] For Cave and Vogelsang (2003), service-based competition allows newcomers in the industry to invest progressively in their own infrastructure, first in replicable assets (e.g., long-distance conveyance facility) then in less replicable ones (e.g., local loop). When there are ladders of investment, leasing part of the existing infrastructure is then essential for the development of facility-based competition. Accordingly, a low access charge accelerates the deployment of alternative infrastructures. For Bourreau and Doğan (2005), allowing for access delays investment in competing infrastructures because the cost of a new infrastructure includes an opportunity cost equal to the profit realized under service-based competition (an effect that is similar to the replacement effect in innovation races). Following that, a lower access price increases the opportunity cost of bypass and should delay further infrastructure building. In an international study using a sample of OECD countries, Bouckaert et al. (2010) found that mandatory access to the incumbent DSL networks negatively affects the incentives to invest in alternative broadband networks.

$$V \equiv U(q_1, q_2) - p_1 q_1 - p_2 q_2,$$

where U is the quadratic function[9]

$$U = \frac{(1+\delta)}{(1-\delta^2)}(q_1 + q_2) - \frac{q_1^2 + q_2^2}{2(1-\delta^2)} - \delta \frac{q_1 q_2}{(1-\delta^2)}.$$

In order to guarantee that a monopolist makes positive profits if markets are independent, we restrict the set of admissible cost parameters to $c_1 \in [0, 1]$. We also suppose for simplicity that the two firms have identical retail costs that we normalize to zero.[10] Hence a market in our model is characterized by the five parameters c_1, f_1, c_2, f_2 and δ. We now compute the profits of the incumbent and the entrant and the welfare.

When firm 2 chooses the access option, the incumbent sells two products: the retail good 1 at price p_1 and access to its network at price w. Both goods are produced at unit cost c_1 and the firms' profits are given by:

$$\pi_1^a(p_1, p_2) = (p_1 - c_1)q_1 + (w - c_1)q_2 - f_1, \quad (2)$$

$$\pi_2^a(p_2, p_1) = (p_2 - w)q_2. \quad (3)$$

Welfare is measured by total surplus, with equal weights on consumer and producer surplus:

$$W^a = U(q_1, q_2) - c_1 q_1 - c_1 q_2 - f_1.$$

When firm 2 chooses the bypass option, each firm sells a single product and the profits are given by:

$$\pi_1^b(p_1, p_2) = (p_1 - c_1)q_1 - f_1, \quad (4)$$

$$\pi_2^b(p_2, p_1) = (p_2 - c_2)q_2 - f_2. \quad (5)$$

and welfare under bypass is given by:

$$W^b = U(q_1, q_2) - c_1 q_1 - c_2 q_2 - (f_1 + f_2).$$

The timing of the model is as follows. In the first stage, the access price w is chosen—either by the incumbent firm in an unregulated market or by a regulator maximizing welfare. In the second stage, after observing the access price w, the entrant chooses between infrastructure-based competition (bypass) and service-based competition (access). In the third stage, both firms simultaneously choose the retail prices p_1 and p_2.

[9] Notice that δ cannot be strictly interpreted as a parameter of product differentiation in the utility function, as utility explodes to $+\infty$ or $-\infty$ when δ goes to 1.

[10] Allowing for different retail costs would introduce an additional dimension of heterogeneity of the model, greatly complicating the computations with little additional insight.

Our model is similar to the standard model analyzed by Sappington (2005), Gayle and Weisman (2007) and Mandy (2009), except for two important differences. First, we allow for fixed network costs $f_i \geq 0$, $i = 1, 2$. In our analysis, fixed costs play an asymmetric role. For the incumbent, the fixed cost is sunk at the time decisions are made while the entrant must incur the fixed cost only if he chooses bypass. Second, we endogenize the choice of the access charge w by an unregulated firm or by the regulator.

3 Retail price competition

We solve the game by backward induction, starting with the optimal retail prices under access and bypass. We will denote the equilibrium prices charged by firm $i = 1, 2$ under access ($k = a$) and bypass ($k = b$) by $\tilde{p}_i^k$, the equilibrium quantities by $\tilde{q}_i^k = q_i(\tilde{p}_i^k, \tilde{p}_j^k)$ and the equilibrium profits by $\tilde{\pi}_i^k = \pi_i^k(\tilde{p}_i^k, \tilde{p}_j^k)$. Equilibrium profits are a function of the input cost of the entrant. Let us denote this input cost by x, with x equal to the access charge w under access and the marginal cost c_2 under bypass. Abusing notations, we let $\tilde{p}_i^k(x)$ and $\tilde{\pi}_i^k(x)$ denote equilibrium prices and profits as a function of the entrant's input cost.

3.1 Competition under access

Suppose that the entrant has chosen to buy access at price w. At the price competition stage, firms' equilibrium prices are characterized by the first order conditions:

$$q_1(p_1, p_2) + \frac{\partial q_1}{\partial p_1}(p_1 - c_1) + \frac{\partial q_2}{\partial p_1}(w - c_1) = 0, \tag{6}$$

$$q_2(p_2, p_1) + \frac{\partial q_2}{\partial p_2}(p_2 - w) = 0. \tag{7}$$

In the linear model, best response functions are linear, and equilibrium prices are uniquely determined by the solution to a system of two linear equations.[11] Equilibrium prices $\tilde{p}_1^a$ and $\tilde{p}_2^a$ are increasing in the access charge w. In addition to the classical positive effect of an increase in the marginal cost of the entrant on equilibrium prices, an increase in w increases the margin on the access market, prompting the incumbent firm to increase its price in order to increase the demand of the entrant on the access market (Chen 2001 refers to this effect as the "collusive effect"in the context of vertical mergers). As both prices increase simultaneously, the effect of an increase in the access price on equilibrium quantities is unclear. On the one hand, an increase in the access charge increases the own price, reducing quantities (the direct effect) ; on the other hand, an increase in the access charge increases the entrant's price, increasing quantities (the indirect effect). We observe that in the linear model, the direct effect

11 The exact computations for the linear model involve tedious expressions and are deferred to the Appendix which contains all explicit formulae.

dominates the indirect effect so that an increase in w lowers both equilibrium quantities $\tilde{q}_1^a$ and $\tilde{q}_2^a$.

From of the point of view of the entrant, an increase in w is similar to an increase in marginal cost, resulting in a decrease on equilibrium profit. From the point of view of the incumbent, the effect of an increase in w on equilibrium profit is ambiguous. On the one hand, an increase in the access charge amounts to an increase in the rival firm's cost, increasing the incumbent's profit on the product market. On the other hand, an increase in w reduces quantities sold in the access market, possibly reducing revenues in the access market. In the linear model, we observe that the incumbent's profit is quadratic, and hence strictly concave, in the access charge w. It reaches a maximum at the value

$$w^* = \underset{w}{\operatorname{argmax}}\ \tilde{\pi}_1^a(w).$$

We note that the optimal access charge for the incumbent, w^*, is always larger than the incumbent's marginal cost c_1. The intuition is that, for $w < c_1$, as the incumbent makes losses on the access market, raising the access charge only has positive effects—it softens competition on the retail market and reduces losses on the access market. Hence the incumbent's profit is always increasing in the access charge when $w < c_1$.

3.2 Competition under bypass

We now turn to retail price competition under bypass. Suppose that the entrant has chosen to build its own infrastructure. The equilibrium prices are now characterized by the first order conditions:

$$q_1(p_1, p_2) + \frac{\partial q_1}{\partial p_1}(p_1 - c_1) = 0, \tag{8}$$

$$q_2(p_2, p_1) + \frac{\partial q_2}{\partial p_2}(p_2 - c_2) = 0. \tag{9}$$

In the linear model, the equilibrium prices are unique and given by the solution to a system of linear equations. The comparative statics effects of changes in costs are standard: an increase in the marginal cost c_i results in an increase in both equilibrium prices, a reduction in the equilibrium quantity $\tilde{q}_i^b$ sold by firm i but an increase in the quantity sold by its competitor $\tilde{q}_j^b$, a reduction in the profit of firm i $\tilde{\pi}_i^b$ but an increase in the profit of its competitor $\tilde{\pi}_j^b$.

4 Strategic bypass deterrence

We now consider the second stage of the game in which the entrant chooses between bypass and access. The entrant's "make-or-buy"decision depends on the comparison between the access and bypass profits $\tilde{\pi}_2^a(w)$ and $\tilde{\pi}_2^b(c_2)$. We will start our analysis by defining an access charge $\omega^l(x)$ such that an entrant with a marginal cost $x = c_2$ is indifferent between buying access at $\omega^l(x)$ and bypass at cost x. By analogy with the literature on entry deterrence, we call $\omega^l(x)$ the *limit access charge*. This limit access charge is defined as:

$$\tilde{\pi}_2^a(\omega^l(x)) = \tilde{\pi}_2^b(x). \tag{10}$$

Because the profit π_2^b is decreasing in the costs c_2 and f_2, the limit access charge is increasing in the entrant's marginal and fixed costs c_2 and f_2. As $\tilde{\pi}_2^a(w)$ is increasing in w, the entrant will choose access if the access charge is below the limit access charge and bypass if it is above. The discussion in this section is organized around this question: is the optimal access charge selected by the incumbent above or below the limit access charge? To conduct our analysis of the optimal access charge, we will assume the following: First, the entrant prefers access to bypass if access is free: $\tilde{\pi}_2^a(0) > \tilde{\pi}_2^b(c_2)$. This assumption guarantees that the limit access charge is uniquely defined. Second, the entrant prefers bypass to access when both options have a zero marginal cost: $\tilde{\pi}_2^a(0) < \tilde{\pi}_2^b(0)$. That is, the entrant's fixed cost under bypass is not so large that it offsets the tendency for the incumbent to charge a lower price under access because of losses from the sales of access. Third, the entrant's bypass option constraints the incumbent's access pricing when the firms' marginal costs are equal: $\omega^l(c_1) < w^*$.

We start by comparing the equilibrium prices and profits under access and bypass for a fixed input cost x.

Lemma 1 *If $x < c_1$, equilibrium prices and gross profits are higher under bypass than under access: $\tilde{p}_i^b(x) > \tilde{p}_i^a(x)$, $i = 1, 2$, $\tilde{\pi}_1^b(x) > \tilde{\pi}_1^a(x)$ and $\tilde{\pi}_2^b(x) + f_2 > \tilde{\pi}_2^a(x)$. If $w^* \geq x > c_1$, equilibrium prices and gross profits are higher under access than under bypass and if $x = c_1$, equilibrium prices and gross profits are equal under access and bypass.*

Lemma 1 is a fundamental result which will be used repeatedly in the analysis. Lemma 1 shows that the ranking of the two régimes of access and bypass is the same for the incumbent and for the entrant, up to the fixed cost f_2 (at this stage, the fixed cost f_1 is sunk and plays no role in the comparisons). If the input cost x is lower than the incumbent's marginal cost c_1, equilibrium prices and profits are higher under bypass than under access. If the input cost x is higher than the incumbent's marginal cost, equilibrium prices and profits are higher under access than under bypass. The intuition underlying Lemma 1 is easily understood. For a given input cost x, the best response function of the entrant is identical under access and bypass, but not the incumbent's. Under access, an increase in the price p_1 generates an additional effect due to the presence of the access market, $\frac{dq_2}{dp_1}(x - c_1)$.[12] If $x < c_1$, this effect is negative: the incumbent has an incentive to lower prices in order to reduce the quantity of the entrant, so that equilibrium prices are reduced, and the two firms price more aggressively, leading to lower gross profits. If $x > c_1$, this effect is positive: the incumbent raises his price to increase the quantity of its entrant, equilibrium prices are increased and softer competition results in higher gross profits.

12 Sappington (2005) labels this effect the opportunity cost of access.

4.1 Equivalent access charges

We now compute the value of the access price which makes the incumbent indifferent between access and bypass and we call it the equivalent access charge ω^e. Recall that $\tilde{\pi}_1^a(w)$ is strictly increasing when $w \leq w^*$. By Lemma 1, because $0 < c_1$, $\tilde{\pi}_1^a(0) < \tilde{\pi}_1^b(0)$. Furthermore because the incumbent's equilibrium profit under bypass is increasing in the entrant's marginal cost, $\tilde{\pi}_1^b(0) < \tilde{\pi}_1^b(c_2)$ so that $\tilde{\pi}_1^a(0) < \tilde{\pi}_1^b(c_2)$. Now by optimality of the access charge w^*, $\tilde{\pi}_1^a(w^*) \geq \max\{\tilde{\pi}_1^a(c_1), \tilde{\pi}_1^a(c_2)\}$. If $c_2 > c_1$, by Lemma 1, $\tilde{\pi}_1^a(c_2) > \tilde{\pi}_1^b(c_2)$ so that $\tilde{\pi}_1^a(w^*) > \tilde{\pi}_1^b(c_2)$. If $c_1 > c_2$, by Lemma 1, $\tilde{\pi}_1^a(c_1) = \tilde{\pi}_1^b(c_1)$ and because the equilibrium profit of the incumbent is increasing in the marginal cost of the entrant, $\tilde{\pi}_1^b(c_1) > \tilde{\pi}_1^b(c_2)$ so that again $\tilde{\pi}_1^a(w^*) > \tilde{\pi}_1^b(c_2)$. We conclude that there is a unique access charge $\omega^e(x)$ in $(0, w^*)$ such that:

$$\tilde{\pi}_1^a(\omega^e(x)) = \tilde{\pi}_1^b(x). \tag{11}$$

We call ω^e the *equivalent access charge*. As both $\tilde{\pi}_1^a(x)$ and $\tilde{\pi}_1^b(x)$ are increasing in x for $x \leq w^*$, the equivalent access charge ω^e is increasing in c_2.

Figure 1 displays the profit of the incumbent as a function of the entrant's unit cost x. It displays the optimal access charge w^* and shows the construction of the equivalent access charge ω^e for a fixed value of the entrant's cost c_2. In the figure, we have placed c_2 below c_1 in which case, the equivalent access charge belongs to $w^e \in [c_2, c_1]$. If $c_2 > c_1$, then we would have $w^e \in [c_1, c_2]$ as it can be seen on the figure.

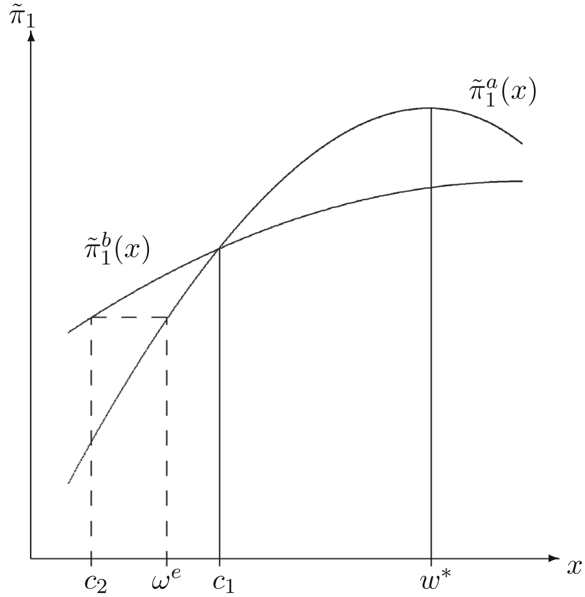

Fig. 1 Incumbent's profit under bypass and access

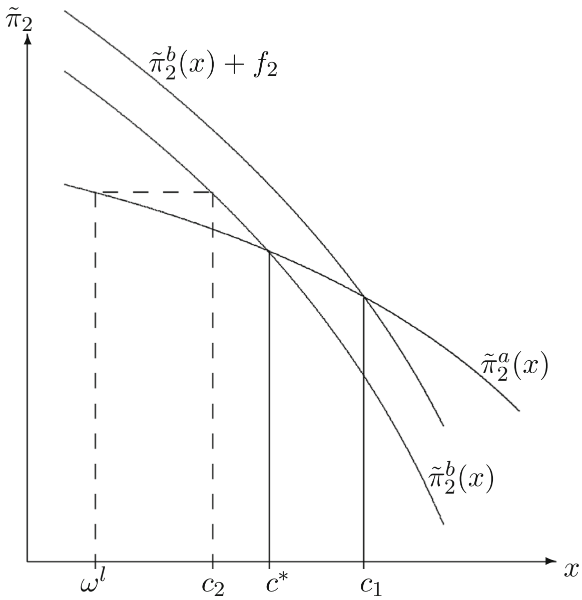

Fig. 2 Entrant's profit under bypass and access

4.2 Limit access charges

The entrant's equilibrium profits under access and bypass satisfy an important regulatory property stated in the following lemma.

Lemma 2 *The difference between the entrant's profit under access and bypass, $\tilde{\pi}_2^a(x) - \tilde{\pi}_2^b(x)$, is increasing in the entrant's input cost x.*

By Lemma 1, $\tilde{\pi}_2^a(c_1) - \tilde{\pi}_2^b(c_1) = f_2 > 0$. By assumption, $\tilde{\pi}_2^a(0) - \tilde{\pi}_2^b(0) < 0$, Lemma 2 guarantees that there exists a unique value of the entrant's input cost $c^* \in (0, c_1)$ such that

$$\tilde{\pi}_2^a(c^*) = \tilde{\pi}_2^b(c^*). \tag{12}$$

Figure 2 displays the gross and net profit of the entrant under bypass and access as a function of the entrant's cost x. It highlights the role of c_1 and c^* and shows the construction of the limit access price ω^l for any value of the incumbent's marginal cost c_2. On the figure, we have represented the case of $c_2 < c^* < c_1$. Notice that the limit access price ω^l is smaller than c_2 if and only if c_2 is smaller that c^*.

Finally, we can establish a lemma on the regularity of the incumbent's profit, this lemma will be useful to characterize the optimal access charge.

Lemma 3 *The difference between the incumbent's profit under access at the limit access charge ω^l and under bypass, $\tilde{\pi}_1^a(\omega^l(x)) - \tilde{\pi}_1^b(x)$, is increasing in the entrant's input cost x as long as $\omega^l(x) < c_1$.*

4.3 Optimal access charge

We now make use of the limit and equivalent access charges, ω^l and ω^e to characterize the profit maximizing behavior of the incumbent in the first stage of the game. If $\omega^l \geq w^*$, the incumbent blocks bypass by selecting his profit-maximizing access charge w^*: this is the régime of *blockaded bypass*. If $w^* \geq \omega^l \geq \omega^e$, by selecting the limit access charge ω^l, the incumbent obtains a higher profit than under bypass: this is the régime of *deterred bypass*.[13] Finally, if $\omega^e \geq \omega^l$, the incumbent prefers to accept bypass: this is the régime of *accommodated bypass*.

The preceding discussion describes the emergence of the three possible régimes of accommodated bypass, deterred bypass and blockaded bypass as a function of the endogenous *variables* w^*, ω^e and ω^l. In the next step of the analysis, we delineate the regions of *parameters* under which the three régimes arise. Our discussion focuses on the marginal cost c_2 of the entrant. We identify two thresholds value for c_2 –called c^D and c^B– that separate the three régimes.

Notice that as $c^* < c_1$, by Lemma 1, the incumbent prefers bypass to access at c^*: $\tilde{\pi}_1^a(c^*) < \tilde{\pi}_1^b(c^*)$ and recall that $\omega^l(c^*) = c^*$ so that $\tilde{\pi}_1^a(\omega^l(c^*)) < \tilde{\pi}_1^b(c^*)$. Next note that by Lemma 1, at c_1, $\tilde{\pi}_1^a(c_1) = \tilde{\pi}_1^b(c_1)$. Furthermore $\omega^l(c_1) > c_1$ as $c_1 > c^*$. As the profit of the incumbent is increasing in the access charge when $x < w^*$, and we assume that the limit access charge $\omega^l(c_1)$ is smaller than w^*, $\tilde{\pi}_1^a(c_1) < \tilde{\pi}_1^a(\omega^l(c_1))$ and hence $\tilde{\pi}_1^a(\omega^l(c_1)) > \tilde{\pi}_1^b(c_1)$. Lemma 3 implies that there is a unique threshold value $c^D \in (c^*, c_1)$ of the entrant's cost such that

$$\tilde{\pi}_1^a(\omega^l(c^D)) = \tilde{\pi}_1^b(c^D). \tag{13}$$

The incumbent chooses to accommodate bypass when $c < c^D$ and to deter bypass when $c \geq c^D$. Blockaded bypass occurs whenever the optimal access charge w^* is lower than the limit access charge, namely whenever $\omega^l(c_2) \geq w^*$. As ω^l is strictly increasing in c_2, we can invert this expression to define

$$c^B = \omega^{l^{-1}}(w^*). \tag{14}$$

We summarize our findings in the following Proposition:

Proposition 1 *There exists c^D and c^B, with $c^* \leq c^D \leq c_1 \leq c^B$, such that the incumbent sets the access charge ω as follows. If $c_2 \leq c^D$, bypass occurs. If $c^D \leq c_2 \leq c^B$, the incumbent sets the limit access charge ω^l to deter bypass. If $c_2 \geq c^B$, the incumbent sets the access charge w^* and bypass is blocked.*

Proposition 1 characterizes the profit maximizing behavior of the incumbent as a function of the entrant's unit cost. When $c_2 > c_1$, both firms prefer access to bypass. When $c_2 \leq c^* < c_1$, the limit access charge is lower than the entrant's marginal

[13] In our model, there is a commitment to the access charge which is set prior to the decision of the entrant on whether to bypass the incumbent's network. Absent this commitment, the incumbent would have incentives to raise the access price (to w^*) *after* access has been chosen by the entrant. Commitment to the access price is thus essential for the existence of the bypass deterrence régime.

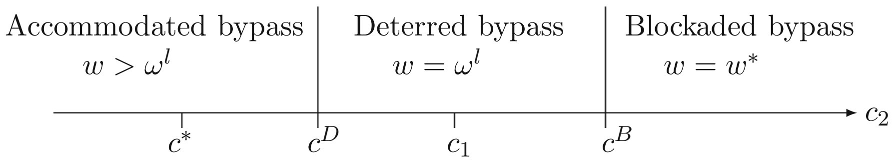

Fig. 3 Optimal access charge and the three regimes

Table 1 Boundaries of the three regions

f_2	c^D	c^B
0	0.5	1.13
0.05	0.37	0.92
0.10	0.27	0.76
0.15	0.17	0.63

cost, so that the incumbent prefers to allow bypass at c_2 than access at ω^l. When the entrant's unit cost lies in the intermediate region (c^*, c_1), the choice between access and bypass is ambiguous because, on the one hand, as $\omega^l > c_2$ access makes the entrant softer in the retail pricing game, but on the other hand, when $\omega^l < c_1$ access makes the incumbent more aggressive in the retail pricing game. There is then a unique threshold value of the cost, c^D, which separates the access and bypass regions. Notice that, in the region of unit costs $[c^D, c_1]$, when the cost is close to c^D, the incumbent may prefer to sell access at a price $\omega^l < c_1$ There is a region of costs where the incumbent prefers to encourage access at a loss rather than face competition by a rival who installs his own network.[14] We illustrate the three regions of Proposition 1 in Fig. 3.

The fixed costs f_1 and f_2 play an asymmetric role in the analysis. At the pricing stage, the fixed cost of the incumbent is sunk and does not affect the equilibrium analysis. On the other hand, the fixed cost of the entrant affects the limit access price ω^l. As f_2 increases, ω^l increases, reducing c^D and hence the region of parameters for which bypass is chosen by the incumbent.

The exact expressions of the thresholds c^D and c^B are complex and we only provide a numerical illustration. We compute the thresholds using the following parameters: $c_1 = 0.5$ and $\delta = \frac{1}{2}$. Table 1 reports the threshold values c^D and c^B for different values of the fixed cost f_2.[15]

In the special case where $f_2 = 0$, Lemma 1 immediately establishes that $c^* = c^D = c_1$. This is the situation analyzed by Mandy (2009) who observes that, for any exogenous access charge $w \in [\min\{c_1, c_2\}, \max\{c_1, c_2\}]$, the make-or-buy decision of the entrant is technologically efficient. This result is a direct consequence of the equality $c^* = c_1$. If $c_2 < c^* = c_1$, the entrant efficiently chooses bypass at c_2 and for any access charge $c_2 \leq w$. If $c^* = c_1 < c_2$, the entrant efficiently chooses access at

14 Vickers (1995) was the first to identify that an access price below the induced cost might be optimal, in his case to curb the entrant's market power.

15 These values guarantee a positive profit for firm 1 if we assume that $f_1 = f_2$.

c_2 and for any $w \leq c_2$. Proposition 1 shows that, similarly, an unregulated incumbent will always encourage access when $c_1 < c_2$ and bypass when $c_2 < c_1$, leading to a technically efficient choice. In Sect. 6, we show that this conclusion only holds for the special case where $f_2 = 0$.

5 Welfare and regulation

We next consider the optimal access charge chosen by a regulator maximizing social welfare. We assume that the social planner can select the access charge w but cannot choose retail prices nor decide on the make-or-buy choice of the entrant.

5.1 Optimal access charge regulation

Under access, the problem of the regulator is:

$$[R1] = \max_{w} W^a \text{ subject to:}$$
$$\tilde{\pi}_1^a(w) \geq 0,$$
$$w \leq \omega^l.$$

The welfare maximizing access charge must satisfy two constraints. First, the access provider should cover its fixed cost and make a non-negative profit. Second, the access charge must be such that the entrant effectively chooses to buy access. The first constraint is equivalent to $w \geq \omega_0$, where ω_0 is the smaller root of the quadratic equation:

$$\tilde{\pi}_1^a(\omega_0) = 0.$$

So the welfare maximization problem [R1] has a solution only if the parameters of the model satisfy: $\omega_0 \leq \omega^l$.

In the linear model, it is easy to check that welfare is a quadratic, strictly concave function of the access charge w, so that we can define the socially optimal access charge as:

$$\hat{w} = \underset{w}{\text{argmax}}\ W^a.$$

Contrary to the profit maximizing access charge w^*, the socially optimal access charge $\hat{w}$ is always smaller than the incumbent's unit cost c_1 because such an access charge is an artificially low marginal cost in the retail pricing subgame and therefore induces the firms to price closer to true marginal cost in equilibrium.[16]

In the linear model, the socially optimal access charge $\hat{w}$ is too low to guarantee positive profit to the incumbent even when the incumbent has a zero fixed cost. Therefore the solution to [R1] is to set the access charge at the lowest possible level

[16] However, with a negative margin on access, the incumbent may resist the imposition of the access charge $\hat{w}$ and resort to sabotage in order to protect its profit on the downstream market.

compatible compatible with a positive profit for the incumbent, ω_0, and the problem admits a solution only if $\omega^l \geq \omega_0$. Given that $\omega^l(\cdot)$ is increasing in c_2 and ω_0 is independent of c_2, as long as $\tilde{\pi}_1^a(\omega^l(0)) < 0$, there exists a unique threshold value of the marginal cost of the entrant, c^W such that

$$\omega^l(c^W) = \omega_0 \tag{15}$$

Access is only possible if $c_2 \geq c^W$. Notice that, as ω_0 is increasing in f_1, the threshold value c^W is increasing in f_1. For higher values of the incumbent's fixed cost, the region of marginal costs of the entrant for which access can be chosen is reduced.

5.2 Regulated access or bypass

We next compare the welfare under access at ω_0 and under bypass. We first note that welfare under bypass $W^b(c_2)$ is decreasing in c_2. An increase in the marginal cost of the entrant results in three effects: it increases consumer prices leading to a decrease in consumer surplus, reduces the entrant's profit and increases the incumbent's profit. In the linear model, the first two effects dominate the last, so that welfare under bypass is decreasing in c_2. Hence, as long as $W^a(\omega_0) < W^b(0)$, there exists a unique value of the entrant's marginal cost, c^I, for which welfare under access and bypass are equal,

$$W^a(\omega_0) = W^b(c^I). \tag{16}$$

Notice that $W^b(\cdot)$ and $W^a(\cdot)$ are decreasing functions for $x > \hat{w}$. Hence an increase in f_1, resulting in an increase in ω_0 will raise the value of the threshold level c^I. We now characterize the optimal behavior of the regulator. Two cases need to be distinguished: if $c^W \leq c^I$, the threshold value separating access and bypass is c^I . The regulator prefers to encourage bypass whenever $c_2 < c^I$. If $c_2 > c^I \geq c^W$, the regulator prefers to induce access and sets an access charge at $\omega_0 < \omega^l(c_2)$ If on the other hand $c^I < c^W$, the regulator cannot induce access when $c^I < c_2 < c^W$, so he chooses to allow bypass whenever $c_2 < c^W$ and to promote access when $c_2 \geq c^W$. We summarize this finding in the following Proposition.

Proposition 2 *The regulator sets the access charge w as follows. For $c_2 < Max[c^W, c^I]$, the regulator chooses bypass. For $c_2 \geq Max[c^W, c^I]$, the regulator chooses to induce access and sets the access charge at ω_0.*

As opposed to the case of the unregulated incumbent, the incumbent's fixed cost plays a role in the choice between access and bypass under regulation. A higher fixed cost f_1 results in an increase in c^W and c^I and hence reduces the region of parameters for which the regulator chooses access.

We finally compare the make-or-buy decisions under regulation and for an unregulated incumbent by comparing the threshold values c^D, c^I and c^W. This requires a comparison of the values of consumer surplus under access and bypass. Contrary to the firms' profits, the difference in consumer surplus under access and bypass is not

Table 2 Access and bypass in the regulated régime

f_2, f_1	c^W	c^I	
0	0.22	0.40	Excessive bypass: $c^I < c^D$
0.05	0.19	0.35	Excessive bypass
0.10	0.15	0.30	Excessive access: $c^D < c^I$
0.15	0.12	0.25	Excessive access

easy to sign. We obtain a clear ranking of consumer surplus only when the fixed cost f_2 is sufficiently small.

To establish this result, we suppose that access at $\omega = c_1$ is profitable for the incumbent. Because $\tilde{\pi}_1^a(\omega_0) = 0 < \tilde{\pi}_1^a(c_1)$ and $\omega_0 < w^*$, we necessarily have $\hat{w} < \omega_0 < c_1$. The access price at which the profit of the incumbent vanishes must be smaller than the incumbent's marginal cost but is larger than the welfare maximizing access charge. But as $W^a(x)$ is strictly concave, this implies that $W^a(\omega_0) > W^a(c_1)$. Now when f_2 is small, c^D converges to c_1, and prices and profit at c_1 are equal under access and bypass, so that $W^b(c^D) = W^b(c_1) = W^a(c_1) < W^a(\omega_0) = W^b(c^I)$, establishing that $c^I < c^D$. Furthermore, as $\omega_0 < c_1$ and $\omega^l(c^D)$ converges to $\omega^e(c_1)$ and c_1, we also have $c^W < c^D$. Hence, we obtain:

Proposition 3 *For all $c_2 < c_1$, there exists $\overline{f} > 0$ such that, whenever $f_2 \leq \overline{f}$, $c^W < c^D$ and $c^I < c^D$.*

Propositions 2 and 3 suggest that an unregulated incumbent sets an excessive access charge inducing the entrant to bypass too often with respect to the social optimum. The regulator sets an optimal access charge below the unregulated access charge and encourages access for a broader range of the entrant's unit cost. In the absence of regulation, there is excessive bypass by the entrant.[17]

Proposition 1 shows that the incumbent may decrease its access charge below the optimal level to deter bypass. Proposition 2 shows that the social planner finds it optimal to decrease the access charge even further, sometimes selling access at a loss to stimulate retail competition. However, notice that our analysis ignores the explicit and implicit costs of regulation. Regulating the access price may be costly in terms of regulatory resources, and also result in uncertainty when the firms' regulatory environment changes over time. Introducing costs of regulation would make the regulatory régime less likely and hence increase the probability of excessive bypass.

Table 2 reports the results of a numerical simulation using the parameter values: $c_1 = 0.5$ and $\delta = \frac{1}{2}$ and considering equal fixed costs $f_1 = f_2$. It illustrates Proposition 3 and shows that for low values of the fixed cost, there is excessive bypass when the market is not regulated. However, this effect is only obtained for low values of the fixed cost, and the result is reversed and excessive access arises when the fixed cost becomes large.

[17] Bloch and Gautier (2008) found the same result in a different model where the regulator has the ability to set both the access and retail prices.

6 Technological efficiency

Mandy (2009) demonstrates that in the absence of fixed costs, for any access charge w in the interval $[\min\{c_1, c_2\}, \max\{c_1, c_2\}]$, the entrant chooses the technologically efficient option. We revisit this question for positive values of the fixed cost.[18] In the presence of a fixed cost, technological efficiency does not only depend on the unit production costs but also on the total production level: access may be technologically efficient for low production levels and bypass technologically efficient for high production levels. As the incumbent's technology does not change under bypass, his production does not directly enter the computations. We define technical efficiency as follows.

Definition 1 Fix c_1, c_2 and w. We say that *bypass is technologically efficient* if the cost of producing $\tilde{q}_2^b(c_2)$ is lower under bypass than access:

$$c_2\tilde{q}_2^b(c_2) + f_2 < c_1\tilde{q}_2^b(c_2).$$

We say that *access is technologically efficient* if the cost of producing $\tilde{q}_2^a(w)$ is lower under access than bypass:

$$c_1\tilde{q}_2^a(w) < c_2\tilde{q}_2^a(w) + f_2.$$

Given this definition, we cannot partition the set of costs into two exclusive regions—one where bypass is efficient and one where access is efficient. There may exist unit costs and access charges for which both access and bypass (or neither) are technologically efficient.

Consider the entrant's optimal make-or-buy decision under a fixed access charge $w \in [\min\{c_1, c_2\}, \max\{c_1, c_2\}]$. If $c_1 < c_2$, then $c_1 \leq w \leq c_2$ and $\tilde{\pi}_2^b(c_2) < \tilde{\pi}_2^b(w) < \tilde{\pi}_2^a(w)$, so that the entrant always chooses access which is clearly the best technological option.

If, on the other hand, $c_2 < c_1$, the discussion becomes more complex. For any access charge w, let $\kappa(w)$ be the unique solution to

$$\tilde{\pi}_2^b(\kappa) = \tilde{\pi}_2^a(w).$$

The function $\kappa(w)$ assigns to each access charge w the value of the marginal cost c_2 which makes the entrant indifferent between access and bypass. (The function $\kappa(w)$ is the inverse of the strictly increasing mapping $\omega^l(c_2)$.) By definition, $\kappa(c^*) = c^*$. Let c^A denote the entrant's unit cost which makes him indifferent between buying access at c_1 or building his own network, $c^A = \kappa(c_1)$. For any $w \in [c^*, c_1]$, because $\kappa(w)$ is a strictly increasing function, $c^* = \kappa(c^*) \leq \kappa(w) \leq c^A = \kappa(c_1)$.

[18] For simplicity, we consider the same range of access charges as Mandy (2009). However our analysis also extends to the optimal access charges set by the incumbent and the regulator even if they fall outside this interval.

We now observe that the threshold value c^D is smaller than c^A. First note that $\tilde{\pi}_1^a(\omega^l(\kappa(c_1)) \equiv \tilde{\pi}_1^a(c_1) = \tilde{\pi}_1^b(c_1)$. Furthermore, as $\kappa(c_1) \le c_1, \tilde{\pi}_1^b(c_1) \ge \tilde{\pi}_1^b(\kappa(c_1))$. Hence,

$$\tilde{\pi}_1^a(\omega^l(\kappa(c_1)) - \tilde{\pi}_1^b(\kappa(c_1)) \ge 0,$$

which under Lemma 2 shows that $c^D \le \kappa(c_1) = c^A$.

In the next step, we argue that when $c_2 = c^A$, *bypass is technologically efficient*. To check this, recall that $\tilde{\pi}_2^a(c_1) = \tilde{\pi}_2^b(c_1) + f_2$ so that

$$\tilde{\pi}_2^b(c^A) - \tilde{\pi}_2^a(c_1) = \tilde{\pi}_2^b(c^A) - \tilde{\pi}_2^b(c_1) - f_2 \le \tilde{\pi}_2^b(c^A) - \tilde{\pi}_2^b(c_1).$$

We now compute the difference in the profit of the entrant at bypass under c^A and c_1:

$$\begin{aligned}\tilde{\pi}_2^b(c^A) - \tilde{\pi}_2^b(c_1) &= -\int_{c^A}^{c_1} \frac{\partial \pi_2^b}{\partial c} dc,\\ &= -\int_{c^A}^{c_1} \left[-q_2^b(c) + (p_2^b - c)\frac{\partial q_2^b}{\partial p_1}\frac{\partial p_1}{\partial p_2}\frac{\partial p_2}{\partial c} \right] dc,\\ &< (c_1 - c^A)q_2^b(c^A),\end{aligned}$$

where the last inequality is due to the fact that, as prices are strategic complements, $\frac{\partial p_1}{\partial p_2} > 0$ and as $\tilde{q}_2^b$ is decreasing in c, $\tilde{q}_2^b(c^A) \ge \tilde{q}_2^b(c)$ for all $c > c^A$. Hence

$$(c_1 - c^A)\tilde{q}_2^b(c^A) > \tilde{\pi}_2^b(c^A) - \tilde{\pi}_2^a(c_1) = 0,$$

so that bypass is technologically efficient at c^A. Furthermore, as $\tilde{q}_2^b$ is decreasing in c_2, bypass will remain technologically efficient for any $c_2 < c^A$. The following Proposition summarizes our discussion.

Proposition 4 *Consider any access charge* $w \in [\min\{c_1, c_2\}, \max\{c_1, c_2\}]$. *For any* $c_2 > c_1$, *access is chosen by the entrant and is technologically efficient. For any* $c_2 < c_1$, *whenever bypass is chosen by the entrant, it is technologically efficient.*

Proposition 4 shows that when the unit cost of the entrant is greater than the unit cost of the incumbent, access is always chosen by the incumbent and is technologically efficient. When the unit cost of the entrant is lower than the unit cost of the incumbent and the entrant chooses bypass, bypass is technologically efficient. This result does not rule out the possibility that, when $c_2 < c_1$, the entrant chooses access when bypass would have been technologically efficient. In fact, the following example shows that this possibility can occur. Let δ approach 1 and assume that the access charge is equal to the unit cost of the entrant, $w = c_2$. We know from Sect. 4.3 that $c^* = c_1 - 3(\sqrt{1 + f_2} - 1) < c_1$ where we assume $f_2 < 3$ to obtain a positive value for c^*. We compute $q_2^a = 1$. Hence access is technologically efficient at c^* if and only if $c_1 < c_1 - 3(\sqrt{1 + f_2} - 1) + f_2$ which can only be true if $f_2 > 3$ in contradiction with our assumption on the fixed cost. We conclude that there exists $\epsilon > 0$ such that for values $c_2 = c_1 - 3(\sqrt{1 + f_2} - 1) + \epsilon$, access occurs at equilibrium but is technologically inefficient. This example shows that an unregulated market does not necessarily lead to a technologically efficient outcome in a model with positive fixed costs.

7 Conclusion

In liberalized network industries, the wholesale price paid by a new competitor for using the existing infrastructure is a key determinant of the choice between access and bypass as it determines both the entrant's input cost and the intensity of retail price competition. This paper characterizes the profit maximizing behavior of an unregulated incumbent and compares regulated and unregulated régimes.

By analogy to the literature on strategic entry deterrence, we distinguish three régimes of blockaded bypass, deterred bypass and accommodated bypass depending on the entrant's unit cost. The unregulated incumbent chooses excessive access charges inducing excessive bypass by the entrant. The make-or-buy decision of the entrant is not necessarily technologically efficient: when bypass is chosen, it is always the cheapest option but access may be chosen when it is not cost effective.

Our analysis provides an exhaustive picture of the behavior of an unregulated incumbent in a network industry, showing the tension between allocative and productive efficiency when alternative infrastructures are viable but not necessarily more efficient. These tensions originate in the softening of competition effect under access when the incumbent manages to realize a positive margin on access. In conclusion, we would like to point out three restrictions of the model that deserve attention for future research.

As noted by Nardotto et al. (2015), the creation of a new network is often associated with an increase in the quality of the service. In this case, the characterization of the profit-maximizing access charge chosen by the incumbent is more complicated because two opposite effects are at play. On the one hand, because bypass is more attractive for the entrant, the limit access charge decreases, making access more costly to the incumbent. On the other hand by allowing bypass, the incumbent is harmed by the difference in qualities between the two services, making bypass less attractive. An increase in the quality of service under bypass thus produces ambiguous effects on the incumbent's incentive to accept or deter bypass. It would also be of interest to check whether the welfare comparisons between regulated and unregulated markets continue to hold if we consider next generation networks.[19] Likewise, we considered that the construction of the entrant's network has no effect on how the incumbent builds out or replaces its network. It would be interesting to depart from this assumption and consider that the incumbent might cut back on network upgrades or expansion if part of the capacity in the market was provided by the entrant. In some cases, this takes the form of the incumbent no longer having a duty to serve - hence, it may not require the same network capacity it did previously. In the limit, the incumbent's fixed cost

[19] Avenali et al. (2009), Bourreau et al. (2010).

f_1 might simply represent capacity that need no longer be required of the incumbent, particularly in a two-way access framework, which is not modeled here.

The model considered a single competitor. An alternative view would be to consider multiple competitors, possibly with different costs. In this case, suppose that the competitors massively buy access to develop service-based competition. Competition then would erode retail margins and give the incumbent an incentive to focus on the access market. A complete analysis of this model with competition among competitors remains to be undertaken.

Last, we could also consider multiple incumbents competing to provide access to competitors. Indeed, wholesale broadband access markets are becoming more and more competitive with alternative providers that could possibly sell access to competitors. It would be interesting to extend the analysis to take into account competition at both the access and the retail level between incumbents and competitors.

A The linear model

In this Appendix, we use the linear demand functions defined in Eq. (1) to derive the explicit functional forms for the equilibrium prices, quantities and profits and to check our comparative static results. Lemmas are proven using these explicit formulae. The linear model allows us to derive the thresholds for the access charge ω^e and ω^l and for the cost c^D, c^B, c^W and c^I as they are the solution to second degree equations. These expressions are used for our numerical simulations reproduced in Tables 1 and 2.

Equilibrium prices and quantities under access Profits under access are defined as:

$$\pi_1^a(p_1, p_2, w) = (p_1 - c_1)(1 - p_1 + \delta p_2) + (w - c_1)(1 - p_2 + \delta p_1) - f_1,$$
$$\pi_2^a(p_1, p_2, w) = (p_2 - w)(1 - p_2 + \delta p_1).$$

From the profit functions, we can derive the unique equilibrium prices and the corresponding quantities for any given w:

$$\tilde{p}_1^a = \frac{2+\delta}{4-\delta^2} + \frac{2(1-\delta)}{4-\delta^2}c_1 + \frac{3\delta}{4-\delta^2}w,$$
$$\tilde{p}_2^a = \frac{2+\delta}{4-\delta^2} + \frac{\delta(1-\delta)}{4-\delta^2}c_1 + \frac{(2+\delta^2)}{4-\delta^2}w,$$
$$\tilde{q}_1^a = \frac{2+\delta}{4-\delta^2} - \frac{(1-\delta)(2-\delta^2)}{4-\delta^2}c_1 - \frac{\delta(1-\delta^2)}{4-\delta^2}w,$$
$$\tilde{q}_2^a = \frac{2+\delta}{4-\delta^2} + \frac{\delta(1-\delta)}{4-\delta^2}c_1 - \frac{2(1-\delta^2))}{4-\delta^2}w.$$

It is straightforward to check that equilibrium prices are increasing in w and the corresponding equilibrium quantities are decreasing. The equilibrium profits are given by:

$$\tilde{\pi}_1^a = \frac{[2 - c_1(2 + 2\delta - \delta^2) + \delta + 3w\delta][2 + \delta - \delta w(1 - \delta^2) - c_1(1 - \delta)(2 - \delta^2)]}{(4 - \delta^2)^2}$$
$$+ \frac{[(w - c_1)(4 - \delta^2)][2 + \delta + c_1\delta(1 - \delta) - 2w(1 - \delta^2)]}{(4 - \delta^2)^2},$$
$$\tilde{\pi}_2^a = \frac{(2 + \delta + \delta(1 - \delta)c_1 - 2(1 - \delta^2)w)^2}{(4 - \delta^2)^2}.$$

The profit functions are quadratic in w, $\tilde{\pi}_1^a$ is concave in w and $\frac{\partial \tilde{\pi}_2^a}{\partial w} < 0$. The profit maximizing access charge w^* is defined as:

$$w^* = \frac{8 + \delta^3}{2(1 - \delta)(8 + \delta^2)} + \frac{(1 - \delta)(8 + 2\delta^2 - \delta^3)}{2(1 - \delta)(8 + \delta^2)} c_1 > c_1.$$

Equilibrium prices and quantities under bypass Profits under bypass are defined as:

$$\pi_1^b(p_1, p_2) = (p_1 - c_1)(1 - p_1 + \delta p_2) - f_1,$$
$$\pi_2^b(p_1, p_2) = (p_2 - c_2)(1 - p_2 + \delta p_1) - f_2.$$

Solving for the linear demand model, equilibrium prices, quantities and profits are given by:

$$\tilde{p}_1^b = \frac{2 + \delta}{4 - \delta^2} + \frac{2}{4 - \delta^2} c_1 + \frac{\delta}{4 - \delta^2} c_2,$$
$$\tilde{p}_2^b = \frac{2 + \delta}{4 - \delta^2} + \frac{\delta}{4 - \delta^2} c_1 + \frac{2}{4 - \delta^2} c_2,$$
$$\tilde{q}_1^b = \frac{2 + \delta}{4 - \delta^2} - \frac{(2 - \delta^2)}{4 - \delta^2} c_1 + \frac{\delta}{4 - \delta^2} c_2,$$
$$\tilde{q}_2^b = \frac{2 + \delta}{4 - \delta^2} + \frac{\delta}{4 - \delta^2} c_1 - \frac{(2 - \delta^2)}{4 - \delta^2} c_2.$$
$$\tilde{\pi}_1^b = \frac{(2 + \delta - (2 - \delta^2)c_1 + \delta c_2)^2}{(4 - \delta^2)^2} - f_1,$$
$$\tilde{\pi}_2^b = \frac{(2 + \delta - (2 - \delta^2)c_2 + \delta c_1)^2}{(4 - \delta^2)^2} - f_2.$$

And the standard comparative static results apply: $\frac{\partial \tilde{p}_i^b}{\partial c_i} > \frac{\partial \tilde{p}_i^b}{\partial c_j} > 0$, $\frac{\partial \tilde{\pi}_i^b}{\partial c_i} < 0$ and $\frac{\partial \tilde{\pi}_i^b}{\partial c_j} > 0$.

Proof of Lemma 1 The proof of Lemma 1 can be easily done by replacing w and c_2 by x in $\tilde{p}_i^a$ and $\tilde{p}_i^b$. Then, we have that:

$$\tilde{p}_1^a - \tilde{p}_1^b = \frac{2\delta}{4 - \delta^2}(c_1 - x), \;\; \tilde{p}_2^a - \tilde{p}_2^b = \frac{\delta^2}{4 - \delta^2}(c_1 - x).$$

And the lemma is proven. □

Limit and equivalent access charges Solving Eq. (10), we find the *limit access charge* ω^l:

$$\omega^l = \frac{2+\delta+c_1\delta(1-\delta)-\sqrt{(2+\delta-(2-\delta^2)c_2+\delta c_1)^2-f_2(4-\delta^2)^2}}{2(1-\delta^2)}.$$

And ω^l is increasing in both c_2 and f_2. When the entrant has no fixed cost ($f_2=0$), then $\omega^l = \frac{c_2(2-\delta^2)-c_1\delta^2}{2(1-\delta^2)}$ and it is easy to check that $\omega^l > c_2$ if $c_2 > c_1$ and $\omega^l < c_2$ if $c_2 < c_1$. The *equivalent access charge* is the solution to Eq. (11) but it is not reproduced here as the expression is complicated and has no value-added.

Proof of Lemma 2 To check that Lemma 2 is satisfied, note that:

$$\begin{aligned}\frac{\partial\tilde{\pi}_2^a(x)}{\partial x}-\frac{\partial\tilde{\pi}_2^b(x)}{\partial x} &= \tilde{q}_2^b-\tilde{q}_2^a+\delta\left[\frac{\partial\tilde{p}_1^a}{\partial x}-\frac{\partial\tilde{p}_1^b}{\partial x}\right]\\ &= \frac{\delta}{4-\delta^2}\left[(2-\delta)c_1-\delta x+2\delta\right]\\ &> 0.\end{aligned}$$

□

Proof of Lemma 3 We check that Lemma 3 is satisfied by noting that $\frac{\partial\tilde{\pi}_1^a(w)}{\partial w}\frac{\partial w^l(x)}{\partial x}-\frac{\partial\tilde{\pi}_1^b(x)}{\partial x}$ is a decreasing function of x. Hence, $\frac{\partial\tilde{\pi}_1^a(w)}{\partial w}\frac{\partial w^l(x)}{\partial x}-\frac{\partial\tilde{\pi}_1^b(x)}{\partial x}>0$ if and only if the function is positive when $x=c_1$ and $\tilde{w}_2(x)=c_1$. Computations show that, at this point,

$$\begin{aligned}\frac{\partial\tilde{\pi}_1^a(w)}{\partial w}\frac{\partial w^l(x)}{\partial x}-\frac{\partial\tilde{\pi}_1^b(x)}{\partial x} &= -4\delta(1-\delta^2)(2+\delta)+(2-\delta^2)(2+\delta)(2\delta+\delta^3+1)\\ &\quad+c_1\left[1-\frac{2(1-\delta^2)(1+\delta^2)}{(2-\delta^2)}\right.\\ &\quad\left.+(2-\delta^2)(1-\delta)(2+3\delta-4\delta^2-4\delta^3+\delta^4)\right]\end{aligned}$$

□

which is a linear function of c_1 and is positive for all $0<\delta<1$ both at $c_1=0$ and at $c_1=1$, showing that the lemma is satisfied.

Welfare and regulation

It is easy to check that the welfare under access is concave in the access charge:

$$\frac{\partial W^a}{\partial w}=\frac{1-\delta^2}{(4-\delta^2)^2}\left[-(2+\delta)^2-w(4+5\delta^2)+(8+2\delta^2-\delta^3)c_1\right].$$

We can thus identify an access charge $\hat{w}$ that maximizes the welfare function W^a:

$$\hat{w} = \frac{(8 + 2\delta^2 - \delta^3)c_1 - (2 + \delta)^2}{(4 + 5\delta^2)} < c_1. \tag{17}$$

However, the incumbent's profit $\pi_1^a(\hat{w})$ is negative and the access charge $\hat{w}$ does not satisfy the constraint $\hat{w} \geq \omega_0$ even for $f_1 = 0$:

$$\tilde{\pi}_1^a(\omega_0) = -\frac{(1 - c_1(1 - \delta))^2(12 + \delta(28 + \delta(20 + \delta(17 + 4\delta))))}{(4 + 5\delta^2)^2} < 0.$$

The welfare under bypass is decreasing in the entrant's cost c_2:

$$\frac{\partial W^b}{\partial c_2} = \frac{1}{(4 - \delta^2)^2}\left[-(2 + \delta)(2 - \delta - \delta^2) - 2c_1\delta(2 - \delta^2) + c_2(\delta^2 + (2 - \delta)^2\right] < 0.$$

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