Cahiers du LASER

n°22-02-07

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April 5, 2008

Abstract

A regulator imposes a universal service obligation (USO) to a vertically integrated firm that owns an essential network. It has imperfect information on the network fixed cost. Network access is supplied to licensed competitors at a regulated fixed and/or unit charges. The USO consists in a constraint on market coverage and is compensated through a mix of public funds, access charges and/or restrictive licensing. Because of information rents, a sufficiently high shadow cost of public funds can lead to a lower coverage with the USO than without it. The compensation mix reflects a trade-off between allocative efficiency and the cost of public funds.

Keywords: universal service obligations, coverage constraints, asymmetric information, regulation

JEL: D82, K23, L43, L51

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1 Introduction

In recent years, regulatory reforms of public utility sectors, such as telecommunications, electricity and postal services, have been implemented worldwide. In general, these reforms imply a move from franchised monopolies towards more open markets. With free entry and exit in markets, however, unprofitable markets are at risk of loosing service. As a result, the reforms often include a Universal Service Obligation (USO), i.e. an obligation to provide all consumers access to the public utility services. In most cases, the USO design is very simple: one firm has to serve some non-profitable segments of the market but receives a financial compensation for this obligation.[1]

The USO and its funding, however, interfere directly with the competitive market that regulatory reforms are meant to promote. The literature on USOs has thus focused on the distortions they entail. Valletti *et al.* [24], Anton *et al.* [1], Bourguignon and Ferrando [2] and Hoernig [14] have singled out the strategic linkages that USOs create among markets when pricing and/or coverage constraints are imposed. Distortions then come from the fact that, because of such linkages, the universal service provider can become more or less aggressive on a specific market than it would be without the USO. Mirabel and Poudou [20] and Illie and Losada [15] analyse the distortions created by the tax instruments imposed on taxpayers or industry competitors to fund compensations. As distortions are dependent on the specificities of the USO, some authors study in more details different aspects of implementations: the allocation method of the USO (auctions in Anton et al. [1], restricted entry and "pay-or-play"[2] in Chone et al. [5], [6] and Mirabel and Poudou [20]) or industry-specific implementations (postal service in Crew and Kleindorfer [8] and Fabra et al. [9], broadband in Foros and Kind [10]).

Although asymmetry of information is as pervasive in universal service implementations as in any form of regulation, none of these papers has considered its impact on the efficiency of universal service. Because the cost of providing services is better known by the universal service provider than the regulator, an adverse selection problem is likely to arise when designing the USO. In this paper, we derive optimal incentive contracts between a universal service provider and the regulator. We consider a network industry where the network is an essential input, in the sense that it cannot be bypassed by suppliers.[3] The network is owned by the incumbent and covers a continuum of markets that

[1] A USO can also bring benefits to its provider. For instance, in UK, the telecommunications regulator has identified "brand enhancement and corporate reputation" as one benefit of the USO (see Cremer et al. [7]). For this reason, the compensation can in principle be non-positive if benefits are greater than or equal to the costs.

[2] "Pay-or-play" allocation allows the entrant to choose between paying the taxes that fund the USO or entering unprofitable markets. This is contrasted to "restricted entry" where the USO is allocated to the incumbent in exclusivity.

[3] Electricity and natural gas are prime examples of such industries.

differ in terms of their fixed costs. The incumbent must provide access to the network to competitors at a regulated fixed and/or unit charges. Firms, including the incumbent, compete *à la Cournot* on the final market. The USO is modelled as a coverage constraint imposed on the incumbent. We develop fully the model for a welfare-maximizing coverage constraint when firms have no outside opportunities. We also discuss two adaptations that reflect real implementations of USOs but that do not modify basic results. First, we consider a full coverage constraint instead of the welfare-maximizing one. Full coverage is known as the "ubiquity constraint" in the USO literature and it represents what is usually meant by universal service. Second, we take the unregulated coverage profits as the outside opportunities of firms. This follows the practice of compensating firms for the profit loss due to the USO.

Because implementations of the USO vary widely among sectors and countries, we endow the regulator with four potential instruments for the financing of the USO and study different constraints imposed on these instruments. These instruments are (*i*) a lump-sum access charge, (*ii*) a unit access charge, (*iii*) the control of market structure through licensing and (*iv*) public funding.[4] The first three instruments serve to finance the USO from the industry proceeds and we refer to them as internal funding instruments. As internal funding is limited by the industry profit, it involves an opportunity cost in terms of allocative efficiency whenever marginal cost pricing does not allow to cover the cost of the USO constraint. Public funding is provided at an exogenous shadow cost of public funds, which represents the economy-wide marginal cost of taxation in terms of deadweight loss. The optimal mix of funding instruments thus involves a trade-off between allocative efficiency and the cost of public funds.

Since licenses are generally granted for a longer period than the length of time between regulatory reviews of access charges and public transfers, we first determine welfare-maximizing charges and public funding for a given number of licensed firms.[5] If the regulator is able to fix both unit and fixed access charges, the unit charge is used to control market power while the fixed charge serves to transfer profit from the entrants to the

[4] All these instruments are found in practice, either in combination or in isolation. Here are examples for each of them. (*i*) A lump-sum access charge is used in the Spanish telecommunications sector for interconnection circuits (Calzada [4]). (*ii*) Netherlands and Italy have a fixed component on electricity transmission access pricing along with variable components based on power and energy, while other European countries have only the variable components (Glachant [12]). (*iii*) Although market liberalization of network industries is generally thought to mean that licenses for network access are granted to any firm meeting basic technical standards, licensing is sometimes used in railways and telecommunications as an instrument to finance networks through the moderation of competition (Caillaud and Tirole [3]). (*iv*) Public funding is practiced in Canada to make telecommunications firms extend broadband services to isolated communities (IUT [16]). It is deemed "particularly suited to countries where the USO burden is high compared with the funds that could be raised, for example, from taxes imposed on operators or their customers." (Oxera [22]).

[5] This is equivalent to considering that licensing is not an available instrument to the regulator, i.e. that licensing is granted provided technical standards are met.

incumbent for the USO compensation. In order to stimulate entrants' output, it is then possible for the regulator to set the unit charge below the incumbent's marginal cost of supplying access. In the case where the regulator cannot impose a fixed access charge, entrants' profit cannot be directly transferred to the incumbent anymore. This profit thus carries an opportunity cost whenever it entails an increase in public funding. The unit access charge, which is now the unique instrument for both funding and allocation purposes, must then be set with the additional consideration of repartition of output between the incumbent and entrants. Finally, in the case where the use of a unit access charge is not available to the regulator or is constrained to be equal to the marginal cost of access, the regulator cannot control market power and simply uses the fixed access charge to avoid public funding as much as possible.

We then consider that the regulator has the power to issue licenses to control for market power (or moderate competition). This power proves to be useless if the regulator can use unit and fixed access charges, since both licensing and the unit access charge control market power. In other words, licensing is a perfect substitute to unit access charge in the presence of the fixed charge. In the absence of a fixed access charge, unit charge will deal both with allocative efficiency and internal funding, while licensing will be used to control entrants' profit.

The main contribution of the paper is to compare the socially optimal coverage under asymmetry of information to the unregulated coverage, where the incumbent chooses freely the extent of the network. As the incumbent does not take into account consumers' surplus when it chooses coverage, the socially optimal coverage under complete information is always greater than the unregulated one. Under asymmetry of information, however, the USO automatically raises a new cost in the form of information rents. As usual, controlling this cost entails a reduction of coverage, which is the more important the less efficient the firm is. The choice of coverage thus involves a trade-off between surplus and information rents and the terms of this trade-off is set by the shadow cost of public funds. We show that, if the shadow cost of public funds is relatively high, coverage under the USO can be lower than the unregulated coverage when the firm turns out to be relatively inefficient. In other words, the regulation aimed at extending service can have the perverse effect of reducing it.

Because of the essential input assumption, this paper can be related to the literature on the regulation of infrastructure. Caillaud and Tirole [3] analyse the funding of an infrastructure project when an incumbent operator has private information about market profitability. An open access policy raises welfare, but can make the project non-viable since funding must be provided by operators' capital contributions. In Gautier and Mitra [11], a vertically integrated firm owns an essential input and faces a potential entrant in the downstream market. When the regulator's objectives are to ensure financing of the essential input and to foster competition in the downstream market, the optimal regulatory mechanism generates inefficient entry: it is possible that a cost efficient entrant stays out of the market or that a cost inefficient entrant gets in. Both papers thus feature the trade-off between efficiency and financing in the context of infrastructure funding that we capture in our model of universal service funding.

The following section presents the basic elements of the model as well as the benchmark cases that serve to assess a USO under imperfect information. Section 3 derives and analyses optimal access charges and coverage under imperfect information. Section 4 discusses the two extensions to the model, i.e. the imposition of an ubiquity constraint rather than welfare maximizing coverage and the introduction of unregulated coverage profit opportunities in the firms' participation constraints. Section 5 concludes.

2 Model

A network industry supplies a homogeneous good on a continuum of locations $\mu \in [0,1]$. At each location, there is a mass 1 of identical consumers that are represented by their inverse demand $P(Q)$, where P is a twice differentiable function, Q is quantity and $P(Q) = 0$ for all $Q \geq Q_{\max}$. We denote by $\eta(Q) \equiv -\frac{P(Q)}{QP'(Q)}$, the elasticity of demand, by $R(Q) \equiv P(Q)Q$, the consumers' expenditure for the good and by $S(Q) \equiv \int_0^Q P(x)dx - R(Q)$, the consumers' surplus.

Reaching consumers at location μ requires the connection to an essential network. The network is owned and operated by a vertically integrated incumbent firm. Locations are ordered by increasing fixed connection costs $K(\mu,\theta) = \theta\mu$, where $\theta \in [\underline{\theta}, \bar{\theta}]$ represents an efficiency parameter that is privately known by the incumbent. Ordered locations are distributed according to density and distribution functions g and G respectively. We say that location μ is covered if the incumbent has incurred its fixed connection cost.

The industry is composed of the incumbent and n competitors, called entrants. The latter cannot bypass the incumbent's network and one unit of output requires one unit of access. A regulated two-part access charge is paid to the incumbent: a fixed fee A and a variable fee a per unit of output. We also consider the case where the regulator is constrained to use only a variable fee ($A = 0$) and the case where it is constrained to set the variable fee at marginal access cost.

All firms produce under the same constant variable cost, normalized to zero. Entrants and the incumbent compete *à la Cournot* at each location where the incumbent incurs the connection cost.[6] Industry's, incumbent's and each entrant's equilibrium quantities

[6] As shown by Kreps and Scheinkman [13], this can be seen as a reduced form of a capacity-constrained

are denoted $Q(a), q^I(a)$ and $q^E(a)$, respectively,[7] and the price at the Cournot equilibrium is $p(a) \equiv P(Q(a))$. The entrant's equilibrium profit at a covered location is $\pi^E(a, A) \equiv m(a)q^E(a) - A$, where $m(a) \equiv p(a) - a$ is the margin between the equilibrium price and the access charge. The incumbent's equilibrium revenue and profit are $r_n(a, A) \equiv R(Q(a)) - n\pi^E(a, A)$ and $\pi^I(\mu, a, A) \equiv r_n(a, A) - \theta\mu$, respectively. The following Lemma[8] presents properties of the Cournot equilibrium.[9]

Lemma 1 *At the Cournot equilibrium of a covered location* μ,

a. $p(a)$ *is such that* $\frac{m(a)}{p(a)} = \frac{1}{n}\left(\frac{1}{\eta(Q(a))} - 1\right)$.

b. $Q' < 0$, $q^{I\prime} > 0$, $q^{E\prime} < 0$, $0 < p' \leq 1$, $\frac{\partial r_n}{\partial a} > 0$ *and* $\frac{\partial \pi^E}{\partial a} < 0$.

c. $\dot{Q} > 0$, $\dot{q}^I < 0$ *and* $\dot{Q} - \dot{q}^I > 0$, *where a dot denotes the first partial derivative with respect to* n.

By a slight abuse of language, we say that the coverage is μ whenever the firms serve all locations of the interval $[0, \mu]$. Aggregate profits are then $\Pi^E(\mu, a, A) = G(\mu)\pi^E(a, A)$ for an entrant and $\Pi^I(\mu, a, A, \theta) \equiv G(\mu)(r_n(a) + nA) - \theta H(\mu)$, where $H(\mu) \equiv \int_0^\mu zg(z)dz$, for the incumbent.

We define the USO as a coverage constraint imposed by the regulator on the incumbent.[10] Whenever this constraint leads the incumbent to make a negative profit, a compensation is given to the incumbent. This compensation is financed through a transfer T from public funds, which is raised at a unit shadow cost of $\lambda > 0$.[11] The regulator sets coverage, access charges and public funding with the aim of maximizing welfare. As it

price game. For instance, entrants may have to reserve capacity on the incumbent's network prior to the downstream production stage as mentioned by Foros and Kind [10]: "The suppliers of access to Internet typically have long term contracts with suppliers of connectivity to the global backbone".

[7] We omit the argument n in functions whenever this does not create confusion. It must be remembered, however, that equilibrium quantities and other functions defined below are dependent on n.

[8] Proofs of Lemmas and Propositions are found in Appendix.

[9] This Lemma formally takes into account an oligopoly situation where $0 < n < \infty$. Polar cases can however be considered by taking limits. In the case of a monopoly ($n = 0$), the access charges become irrelevant and we get $\eta(Q) = 1$, i.e. the usual profit maximizing output for a monopoly with zero marginal cost. Derivatives with respect to a become 0. In the case of perfect competition ($n \to \infty$), entrants' profit tends to zero as $p(a) \to a$. The regulator then controls the price through the access charge. The incumbent then gets the industry's revenue.

[10] In practice, USOs also include the "uniform pricing constraint", which forces the incumbent to supply its service at the same price across locations. The Cournot equilibrium satisfies *de facto* this constraint.

[11] For simplicity, we allow the transfer to be negative if the incumbent makes a positive profit, i.e. any profit is taxed away by the regulator. In Section 4, we consider the more realistic case where the regulator can take only profit that exceeds the one obtained under unregulated coverage. Note that negative transfers are sometimes encountered in cases where the incumbent is a publicly-owned enterprise. For instance, the province of Quebec (Canada) annually sets a dividend target for its publicly-owned electric utility and this dividend is integrated in the general provincial budget. Cases where no negative transfers

does not have knowledge of parameter θ, it must then design a type contingent contract. This can be viewed as a regulatory game that has the following timing:

1. Nature chooses $\theta \in [\underline{\theta}, \bar{\theta}]$.
2. The incumbent learns its type.
3. The regulator offers a USO contract $\mathcal{C}(\theta) = \langle \mu(\theta), a(\theta), A(\theta), T(\theta) \rangle$.
4. The incumbent accepts or refuses.
5. All markets $\mu \in [0, \mu(\theta)]$ clear *à la Cournot.*

The regulator has *a priori* distribution and density functions F and f, respectively, which display an increasing inverse hazard rate $\varphi(\theta) \equiv \frac{F(\theta)}{f(\theta)}$. We also assume that $\varphi(\theta)$ is convex in θ: as θ increases, the regulator becomes more and more concerned about the rents left below θ at the margin.[12]

Three benchmarks will serve to assess the USO.

- *Direct Industry Regulation*

  This is the case where a welfare-maximizing regulator has perfect information on costs and controls itself the industry. It then decides output $Q(\theta)$ and coverage $\mu(\theta)$ under the constraint that the incumbent makes a non-negative profit.[13] This constraint is met through the payment of a transfer $T(\theta)$ paid out of public funds. For any θ, the regulator then solves:

$$\max_{\mu(\theta), Q(\theta), T(\theta)} \quad G(\mu(\theta))\left[S(Q(\theta)) + R(Q(\theta))\right] - \theta H(\mu(\theta)) - \lambda T(\theta)$$
$$\text{s.t. } T(\theta) \geq \theta H(\mu(\theta)) - G(\mu(\theta)) R(Q(\theta))$$

  As the constraint is necessarily binding at optimum, this can be rewritten as:

$$\max_{\mu(\theta), Q(\theta)} G(\mu(\theta)) S(Q(\theta)) + (1+\lambda)[G(\mu(\theta)) R(Q(\theta)) - \theta H(\mu(\theta))]$$

are allowed are easily dealt with by adding the constraint $T(\theta) \geq 0$. This would imply that internal funding is "used" first, so that public funds are raised only when internal transfers are insufficient to cover the USO cost.

[12] Rochet and Stole [23] use this assumption in a nonlinear pricing model. For instance, it is satisfied with uniform, exponential, Pareto and normal distributions. It mainly implies that $\frac{d(\varphi(\theta)/\theta)}{d\theta} \geq 0$, i.e. the mean inverse hazard rate is also increasing. Under this assumption our solution is uniquely characterized.

[13] We assume that this output is allocated to the incumbent : since the firms operate under the same variable cost function, this is an optimal allocation whether the regulator has the capacity to make monetary transfers among firms or not.

The first-order condition (FOC) with respect to output is independent of θ. Letting Q^D satisfy this FOC, we obtain:

$$P(Q^D) + \lambda R'(Q^D) = 0 \tag{1}$$

Output Q^D is thus increased until the marginal social value of output P equals the shadow cost of financing the lost incumbent's profit $-R'$ from increased output. Condition (1) can be rewritten as $\eta(Q^D) = \alpha$, where $\alpha \equiv \frac{\lambda}{1+\lambda}$. This amounts to the inverse elasticity rule with a zero marginal cost.

Optimal coverage $\mu^D(\theta)$ then balances marginal coverage benefit $g(\mu^D(\theta))[S\left(Q^D\right) + (1+\lambda)R(Q^D)]$ to marginal coverage cost $\theta\mu^D(\theta)g(\mu^D(\theta))$, so that:

$$\mu^D(\theta) \equiv \frac{S\left(Q^D\right) + (1+\lambda)R(Q^D)}{\theta}$$

- *USO under complete information*

  This is the Cournot equilibrium described in Lemma 1 when the regulator does not control output but rather offers contract $C(\theta)$ with full knowledge of θ. The regulator's problem is to maximize welfare under the participation constraints of the firms:

$$\max_{\mu(\theta),a(\theta),A(\theta),T(\theta)} \quad G\left(\mu(\theta)\right)\left[S\left(Q(a(\theta))\right) + R(Q(a(\theta)))\right] - \theta H(\mu(\theta)) - \lambda T(\theta)$$
$$\text{s.t. } \Pi^I(\mu(\theta), a(\theta), A(\theta), \theta) + T(\theta) \geq 0,\ \Pi^E(\mu(\theta), a(\theta), A(\theta)) \geq 0$$

The entrants' participation constraint guarantees that the n firms are active whenever the contract is accepted by the incumbent, so that the market equilibrium is given by Lemma 1. As constraints are necessarily binding at optimum, the problem can be rewritten as:

$$\max_{\mu(\theta),a(\theta),A(\theta),T(\theta)} \quad G\left(\mu(\theta)\right)S\left(Q(a(\theta))\right) + (1+\lambda)[G\left(\mu(\theta)\right)R(Q(a(\theta))) - \theta H(\mu(\theta))]$$
$$-\lambda n \Pi^E(\mu(\theta), a(\theta), A(\theta))$$

Note that entrants' profit is a market power rent that is costly to society because such a rent is not available to fund the universal service: whenever access pricing of the network leaves one dollar to each entrant, it has to be replaced by n dollars from public funding at the opportunity cost of λ per dollar. Letting $\mu^C(\theta)$ represent the welfare-maximizing coverage under complete information, we obtain from the FOC on coverage:[14]

$$\mu^C(\theta) = \begin{cases} 1 & \text{if } \theta \leq \theta_n^\lambda \\ \frac{S(Q(a)) + (1+\lambda)R(Q(a)) - \lambda n \pi^E(a,A)}{(1+\lambda)\theta} & \text{if } \theta > \theta_n^\lambda \end{cases} \tag{2}$$

[14] One can check that FOCs on a and A are independent of θ. As a consequence, they will not be modified by asymmetry of information. We report the derivation of these conditions when we introduce asymmetry of information because we will at the same time consider constraints on a and A.

where $\theta_n^\lambda \equiv \frac{S(Q(a))+(1+\lambda)R(Q(a))-\lambda n\pi^E(a,A)}{(1+\lambda)}$. To interpret this solution, note that increasing market coverage by $d\mu$ increases the sum of consumers and producers surplus by $(S+R)g(\mu)d\mu$ and the fixed cost by $\theta\mu g(\mu)d\mu$. It also allows an increase of internal funding of the marginal profit of $(R-n\pi^E-\theta\mu)g(\mu)d\mu$, inducing a saving of $\lambda(R-n\pi^E-\theta\mu)g(\mu)d\mu$ in terms of the cost of public funds. Marginal welfare is thus $[S+(1+\lambda)(R-\theta\mu)-\lambda n\pi^E]g(\mu)$. If $\theta \leq \theta_n^\lambda$, marginal welfare is positive at all locations and there is full coverage. If $\theta > \theta_n^\lambda$, $\mu^*(\theta)$ is the value that makes marginal welfare equal to zero.

- *Unregulated coverage*

  This is the Cournot equilibrium described in Lemma 1 when the regulator sets the access charges, but does not impose a USO, so that coverage is chosen by the profit-maximizing incumbent. Unregulated coverage with n entrants is then:

$$\mu^I(\theta) \equiv \frac{r_n(a,A)}{\theta} > 0$$

  In order to ensure that the USO will become a constraint to the incumbent, we assume that it is never profitable for the incumbent to serve the costliest location $\mu = 1$, even when it is the most efficient monopoly:[15]

$$r_0 < \underline{\theta}$$

  This assumption implies that, without USO, there is never full coverage.

3 Optimal Policy

Given a contract $\mathcal{C}(\theta)$, the incumbent's utility when it announces to be of type τ is:

$$U(\theta,\tau) \equiv \Pi^I(\mu(\tau), a(\tau), A(\tau), \theta) + T(\tau) \quad (3)$$

For any entrant, the profit is:

$$u(\tau) \equiv \Pi^E(\mu(\tau), a(\tau), A(\tau))$$

Contract $\mathcal{C}(\theta)$ must then satisfy the following participation and incentive compatibility constraints:

$$\forall\theta \in [\underline{\theta},\bar{\theta}] : U(\theta) \equiv U(\theta,\theta) \geq 0 \text{ and } u(\theta) \geq 0 \quad (4)$$

$$\forall\theta,\tau \in [\underline{\theta},\bar{\theta}] : U(\theta,\theta) \geq U(\theta,\tau) \quad (5)$$

[15]Note that r_0 is independent of (a,A) in a monopoly case, since the incumbent pays the access charge to itself. Note also that it is always profitable to serve location $\mu = 0$ even for $\theta = \bar{\theta}$ as there is no cost to serve this location.

The incumbent's participation constraint now includes an information rent. The incentive constraint ensures truth-telling by the incumbent. The regulator's problem is then to maximize expected welfare $\mathcal{E}W$ under constraints (4) and (5), where:

$$\mathcal{E}W = \int_{\underline{\theta}}^{\bar{\theta}} \{G(\mu(\theta)) S(Q(a(\theta))) + U(\theta) + nu(\theta) - (1+\lambda) T(\theta)\} dF \tag{6}$$

As shown in the Appendix, incentive compatibility is obtained if and only if $\mu'(\theta) \leq 0$ and $U(\theta) = \int_{\theta}^{\bar{\theta}} H(\mu(z)) dz$. The regulator's problem then becomes:

$$\max_{\mu(\theta)\leq 1, a(\theta), A(\theta)} \mathcal{E}W \text{ s.t. } u(\theta) \geq 0 \text{ and } \mu'(\theta) \leq 0 \tag{7}$$

where expected welfare (6) is rewritten as:

$$\begin{aligned} \mathcal{E}W &= \int_{\underline{\theta}}^{\bar{\theta}} \{G(\mu(\theta)) S(Q(a)) + (1+\lambda)[G(\mu(\theta)) R(Q(a)) - (\theta + \alpha\varphi(\theta)) H(\mu(\theta))] \\ &\quad -\lambda n \Pi^E(\mu(\theta), a(\theta), A(\theta))\} dF \end{aligned} \tag{8}$$

3.1 Coverage

We solve the relaxed problem where the monotonicity constraint $\mu'(\theta) \leq 0$ is initially ignored and we will check afterwards whether this constraint is met or not.

Pointwise optimization for $\mu^*(\theta)$ leads to:

$$\mu^*(\theta) = \begin{cases} 1 & \text{if } \theta \leq \hat{\theta}_n^{\lambda} \\ \frac{S+(1+\lambda)R-\lambda n\pi^E}{(1+\lambda)\theta+\lambda\varphi(\theta)} & \text{if } \theta > \hat{\theta}_n^{\lambda} \end{cases} \tag{9}$$

where $\hat{\theta}_n^{\lambda} \equiv \{\theta \,|(1+\lambda)\theta + \lambda\varphi(\theta) = S + (1+\lambda)R - \lambda n\pi^E\}$.[16] Comparison with the complete information coverage (2) shows that μ^* balances the same marginal social benefit of coverage $S + (1+\lambda)R - \lambda n\pi^E$ to a marginal social cost of coverage that now takes into account the increase in information rent of a unit increase of coverage, $\lambda\varphi(\theta)$, in addition to $(1+\lambda)\theta$.

Proposition 1 *Let $\hat{\lambda}(\theta) = \frac{\theta}{\varphi(\theta)} \frac{S+n\pi^E}{R-n\pi^E}$ be the shadow cost of public funds for which $\mu^*(\theta) = \mu^I(\theta)$. Under the assumption that the hazard rate φ is an increasing and convex function,*

a. $\mu^*(\theta) \leq \mu^C(\theta)$, $\forall\theta \in [\underline{\theta}, \bar{\theta}], \forall\lambda \geq 0$

[16]Since φ is strictly increasing, $\hat{\theta}_n^{\lambda}$ is unique. Note that nothing prevents $\hat{\theta}_n^{\lambda}$ from being greater than $\bar{\theta}$ or less than $\underline{\theta}$. In the first case, coverage would always be full, while there would never have full coverage in the second case. Note also that $\theta_n^{\lambda} = \hat{\theta}_n^{\lambda} + \alpha\varphi(\hat{\theta}_n^{\lambda}) \geq \hat{\theta}_n^{\lambda}$.

b. $\mu^*(\theta)$ *is non increasing in* θ

c. $\mu^*(\theta)$ *is non increasing in* λ

d. If $\lambda > \hat{\lambda}(\bar{\theta})$*, there exists a unique* $\tilde{\theta} \in (\underline{\theta}, \bar{\theta}]$ *such that* $\mu^*(\theta) < \mu^I(\theta)$, $\forall \theta \in [\tilde{\theta}, \bar{\theta}]$.

The first three statements recall that, compared to complete information, asymmetry of information introduces a trade-off between efficiency[17] and rent extraction that creates a downward coverage[18] distortion which is the greater the more inefficient is the firm and the greater is the shadow cost of public funds. Statement (b) checks that the relaxed constraint $\mu'(\theta) \leq 0$ is in fact met. Statement (c) highlights the traditional role of λ in determining the terms of the efficiency/rent trade-off.

Statement (d) reveals that a welfare maximizing coverage lower than the unregulated coverage can occur for relatively inefficient firms when the shadow cost of public funds is sufficiently high, so that the information rent is high.[19] In such a case, the imposition of the USO, which aims to extend coverage, has the perverse effect of reducing it.

3.2 Access Charges

Access charges can be used by the regulator to control the behaviour of entrants. Entrants have a positive impact on welfare as they reduce the incumbent's market power. However, the profits that they get are not used to finance the incumbent's network, so that, for a given coverage, these profits have to be compensated by costly public funds. Access charges have thus the dual objective (i) of controlling market power in order to improve allocative efficiency and to (ii) substitute industry internal funding to public funding.

Two-Part Access Charge

With a two-part access charge, the regulator possesses two instruments to reach these two objectives. The fixed charge is then used to eliminate any entrant profit, while the unit charge is used to reach the allocation reached under direct regulation.

Formally, in (8), $A(\theta)$ appears only in the entrant's profit and, since it is never advantageous to leave profit to an entrant, the optimal fixed charge is:

$$A(\theta) = m(a(\theta))q^E(a(\theta)), \forall \theta \tag{10}$$

[17] Since asymmetry of information is about fixed cost, this is productive efficiency.

[18] Note that it is possible that μ^* be equal to the complete information coverage for $\theta > \underline{\theta}$ because both μ^* and μ^C are equal to 1 when $\theta < \hat{\theta}_n^{\lambda}$.

[19] However, because the marginal information rent is low for efficient firms, there is always a range of relatively efficient firms for which optimal coverage is greater than the unregulated one.

i.e. that entrants' profits are entirely transferred to the incumbent since this profit transfer is made at no cost and is a substitute to the costly transfer from public funds. Second, with $\Pi^E = 0$, the first order condition with respect to $a(\theta)$ is independent of θ:[20]

$$(P + \lambda R')Q' = 0 \Rightarrow \eta(Q(a)) = \alpha \tag{11}$$

Hence, we have $Q(a) = Q^D$, i.e. the direct regulation outcome is attained whatever is the number of firms.

From Lemma 1, we get that:

$$a = P\left(1 - \frac{1}{n\lambda}\right) \Leftrightarrow \frac{P - a}{P} = \frac{1}{n\lambda} \tag{12}$$

This directly leads to the following proposition.

Proposition 2 *Under a two-part access charge, the access charge is increasing in the number of firms ($\dot{a} > 0$) and*

$$a \gtreqless 0 \text{ iff } n \gtreqless \frac{1}{\lambda}$$

To interpret (12) and Proposition 2, recall from Lemma 1 that reducing a increases industry output but reduces industry revenue, so that it increases public funding for a given coverage. The access charge must thus be set in order to induce entrants to supply the quantity such that the marginal social benefit of output turns out to be equal to the social cost of lost revenue, i.e. $P = -\lambda R'$, as in (1). Since Cournot competition implies that $-R' = n(P - a)$ whatever is a,[21] we thus have that a must be such that $P = n\lambda(P - a)$, which gives (12). If the unit access charge were equal to the incumbent's marginal cost of supplying access ($a = 0$), Cournot competition would rather lead to $P = -\frac{R'}{n}$, i.e. $P \lesseqgtr -\lambda R'$ as $n \gtreqless \frac{1}{\lambda}$, so that entrants' output has to be discouraged (encouraged) through access pricing above (below) the marginal cost of supplying access when n is greater (less) than $\frac{1}{\lambda}$.

Turning to the optimal transfer, we substitute (9), (10) and (12) in (3) to obtain:

$$T(\theta) = U(\theta) - \Pi^I(\mu^*(\theta), a, A, \theta)$$

where $U(\theta)$ is the incumbent's rent. If the sum of incumbent profit and transfers from entrants is greater than the incumbent's rent, the difference is "returned" to the regulator in order to save on the cost of public funds. If this sum is less than the incumbent's rent, the transfer from public funds eliminates the gap in order to meet the incentive compatibility constraint.

[20] In turn, this implies that the fixed charge A is also independent of θ.
[21] See (A.1) in Appendix.

Finally, note that because the entrants' profit is nil, optimal coverage amounts to $\frac{S+(1+\lambda)R}{(1+\lambda)\theta+\lambda\varphi(\theta)}$.

Uniform Access Charge

Assume that the regulator cannot make direct transfers among firms so that A is constrained to be 0. In absence of a fixed charge, internal industry transfers are now performed through the unit charge. The unit charge is unable to eliminate entrants' profit, so that this transfer shortfall to the incumbent must be compensated by public funds.

The FOC with respect to a becomes:

$$(P + \lambda R')Q' - \lambda n \frac{\partial \pi^E}{\partial a} = 0 \tag{13}$$

The first term of condition is the same as in the two-part tariff: the unit charge must still fine tune market power in order to balance output social value and public funding. The second term reflects the additional role of performing transfer of entrants' profit to the incumbent. As such transfer increases with the access charge, this means that this new role leads to an increase in the access charge and also brings an industry output which is less than the one under direct regulation.

Proposition 3 *For a given n, the access charge a is greater under uniform access pricing than under two part-access pricing.*

Note that, as in the case of a two-part access charge, the uniform access charge can be negative or positive. Propositions 2 and 3 imply that the uniform access charge is positive if $n\lambda \geq 1$.

Fixed Access Fee

Assume that the regulator is constrained to price access at marginal cost so that $a = 0$. The Cournot equilibrium becomes symmetric and we still have that A should transfer the entrants' profit to the incumbent, so that $A = P(Q)Q/(n+1)$. Following Proposition 2, overproduction (under-production) is done compared to the direct regulation allocation as the number of firms n is above (below) $\frac{1}{\lambda}$. Coverage still follows formula (9) with $a = 0$ and $\pi^E = 0$. As $S(Q^D)+(1+\lambda)\,R(Q^D) \geq S(Q(0))+(1+\lambda)\,R(Q(0))$ per definition of Q^D, coverage under the fixed fee cannot be greater than the coverage under direct regulation. This is so because the benefits of coverage are never greater while the costs stay identical.

3.3 Licensing

Assume now that the regulator can choose the number of firms, for instance, through the emission of licenses. As with the access charge, the determination of the optimal number of firms involves a trade-off between allocative efficiency and internal funding. The optimal number of firms then depends on the type of access charge available.

Two-Part Access Charge

Since the direct regulation allocation is already attainable through the two-part access charge, licensing is redundant: there already exists two instruments for dealing with allocative efficiency and funding. Then any $n \geq 0$ is optimal.

Unit Access Charge

When the fixed charge instrument is not available, entrants always obtain a positive profit. Profit left to entrants reduces welfare as its transfer to the incumbent could reduce the price or public funding. The only way to reduce entrants' profit is then to increase the number of firms. But, as this also decreases the incumbent's profit, and thus implies more public funding, this is welfare enhancing provided that λ is not too high.

Proposition 4 *If $\lambda < 1$, increasing the number of firms always increases welfare.*

Fixed Access Fee

In this case, profit to the entrants is kept to zero, but the access charge does not control allocative efficiency. This control is delegated to the market structure instrument, n. The optimal number results from a trade-off between allocative efficiency and internal funding that is based on the shadow cost of public funds.

Proposition 5 *With $a = 0$, the welfare-maximizing number of firms is given by $n^*(\lambda) = \frac{1}{\lambda}$.*

Here is the intuition of this result. Since the unit access charge is nil and entrants' profit can be directly transferred to the incumbent, internal funding comes from the industry revenue. Increasing the number of firms decreases industry revenue but increases consumers' surplus. The number of firms n^* must then be such that the marginal social value of output P equals the shadow cost of financing the lost incumbent's profit $-R'$ from increased output, i.e. $P = -\lambda R'$. But, with $a = 0$, Lemma 1 shows that Cournot competition leads to[22] $\eta(Q(0)) = \frac{1}{n+1}$, i.e. $R' = nP$, whatever is n. The Proposition thus

[22] This is a simple application of the standard symmetric Cournot equilibrium $\frac{P-C'}{P} = \frac{1}{(n+1)\eta}$ with a marginal cost C' equal to zero: each of the $(n+1)$ firms faces an elasticity of $(n+1)\eta$.

states that n^* is such that marginal social value of output P is equal to the marginal social cost of financing this output, $n\lambda P$. In brief, a high λ makes it advantageous to resort relatively more on internal funding: price must then be set higher, which is done through a low number of firms in the market.

Note that $n = n^*(\lambda) = \frac{1}{\lambda}$ implies that $\eta(Q(0)) = \alpha$, i.e. that the direct regulation allocation Q^D is reached. Since $\pi^E = 0$, this in turn implies $\mu^*(\theta) = \mu^D(\theta)$, $\forall\theta$. In other words, in presence of a fixed access fee, the market structure instrument n is a perfect substitute of the unit access charge a.

4 Extensions

4.1 Ubiquity Constraint

In practice, the USO generally requires that the incumbent ensures full coverage $\mu(\theta) = 1$, $\forall\theta$, rather than the welfare maximizing one. This is known as the ubiquity constraint. Compared to an optimal coverage policy, the ubiquity policy initially does not take into account the cost of service. This implies that it is possible that universal service turns out to be socially too costly and has to be abandoned. Consequently, the choice that the regulator makes when it imposes an ubiquity constraint is the probability of shutdown $x \in [0, 1]$. It thus offers a USO contract $\mathcal{C}(\theta) = \langle x(\theta), a(\theta), A(\theta), T(\theta)\rangle$.

The problem then boils down to the choice of the optimal cutoff type $\breve{\theta}_n^{\lambda}$, so that service is supplied if the firm is found to be of type $\theta \leq \breve{\theta}_n^{\lambda}$ and abandoned if $\theta > \breve{\theta}_n^{\lambda}$, implying an *ex ante* probability of shutdown of $1 - F(\breve{\theta}_n^{\lambda})$. This problem has a similar structure to problem (7) and thus yields similar results. In particular, (i) asymmetric information increases the probability of shutdown compared to a complete information benchmark because of the costs of information rents. (ii) The probability of shutdown is increasing with the shadow cost of public funds. (iii) If the cost of public funds exceeds a given threshold, there is a greater probability of shutdown if the incumbent is compensated for the USO rather than being forced to provide full coverage without compensation. This is because the payment of the information rent makes the service socially too costly even for relatively efficient firms. Then it would be socially advantageous to just impose ubiquity without funding the USO. (iv) When a is constrained to be equal to the incumbent's marginal cost of supplying access, the optimal number of licenses is still $\frac{1}{\lambda}$ as this still depends only on demand and not on the exact implementation of the USO.

4.2 Unregulated Market Profit as Outside Opportunity

Thus far, we have considered that the reservation utility of firms was zero. In practice, however, financial compensation for the USO is generally meant to cover the loss in profits incurred because of the USO. In other words, implementations of the USO take unregulated coverage profit as the outside opportunity. Within our framework, this translates into the following participation constraints:[23]

$$\forall \theta \in [\underline{\theta}, \bar{\theta}] : U(\theta) \geq \Pi^I(\mu^I(\theta), a, A, \theta) \text{ and } u(\theta) \geq \Pi^E(\mu^I(\theta), a, A)$$

This comes down to consider only Pareto-superior improvements to the unregulated coverage outcome when implementing the USO.

Because the incumbent's outside opportunity becomes dependent on type θ, one has to check for potential countervailing incentives. But, following standard developments found in Maggi and Rodríguez-Clare [19] and Jullien [17], it turns out that countervailing incentives are possible only for cases where coverage under the USO would be less than unregulated coverage; such cases are not feasible for the problem with the outside opportunity.[24] In other words, the incumbent is never led to understate θ even though its outside opportunity is decreasing with θ and the solution technique used for the case of zero outside opportunity is still valid.

Results for market coverage are the same as in Proposition 1 except for a minor change for cases where market coverage is less than unregulated coverage: coverage is then scaled up to unregulated coverage as it would otherwise become impossible to compensate for outside opportunities. For cases in Proposition 1 where market coverage is greater than unregulated coverage, coverage remains the same with the unregulated market outside opportunity as without it.

In brief, the motivation for the regulator to impose a lower coverage than the unregulated market coverage was to reduce the information rent. This cannot be done when it is not allowed to reduce the incumbent's rent below the unregulated profit. The regulator must then accept the unregulated coverage, in which case there is no transfer to the incumbent ($T = 0$). For cases where optimal coverage was greater than the unregulated coverage, it is as if government lost a lump-sum revenue equal to unregulated market profit.

[23] One could think that the regulator can ignore outside opportunities for entrants. The results we state hereafter still hold if $u(\theta) \geq 0, \forall \theta$.

[24] More precisely $\Pi^I(\mu^I(\theta), a, A, \theta)$ has a slightly convex profile with respect to θ in the sense of Maggi and Rodríguez-Clare [19]. Hence the participation constraint is binding for some types, but the optimal contract is still fully separating.

5 Conclusion

As mentioned in Laffont [18] (p. 510), "[r]egulators, whatever their objectives, are fundamentally constrained by their lack of information on the firms they are regulating". As universal service is a form of regulation whose efficiency depends on the costs of regulated firms, which is private information, taking into account information constraints is as important in characterizing optimal policy under USO as it was for the direct natural monopoly regulation that the imposition of the USO often replaces. In this paper, we have showed that the necessity to concede information rents leads to a lower USO coverage. We have also determined conditions under which asymmetry of information paradoxically makes coverage under a USO lower than the unregulated market outcome.

From a policy viewpoint, asymmetry of information provides an additional indictment of the net avoided cost (NAC)[25] approach used for implementing universal service. Cremer et al. [7] and Valletti et al. [24] have already observed that using the NAC as a measure of the profitability cost of a universal service is valid only when the market structure is stable. In our framework, even with a given market structure, using the NAC to compensate for a USO would incite the USO provider to overstate it (by announcing $\tau > \theta$). Optimal policy thus involves the payment of an information rent over and above the NAC.

A further contribution of the paper is to highlight the role of the shadow cost in determining the terms of a trade-off between internal industry funding and public funding of the USO. Because there is no asymmetry of information on variable costs in our model, allocative efficiency of served markets was independent of the adverse selection variable, so that the information rent/productive efficiency and the internal funding/public funding trade-offs are resolved recursively. An extension would be to introduce asymmetry of information on allocative efficiency[26] to analyse the interaction of both trade-offs in the determination of optimal coverage.

In this paper, quantity competition has been assumed so that the uniform pricing constraint is met *de facto*. Another extension would be to model price competition (*à la Bertrand*) in order to understand how this constraint can modify asymmetric information distortions.

[25] The NAC is "the total cost savings that the incumbent could get by withdrawing from the loss-making areas" (Valletti *et al.* [24]).

[26] This could be done by considering a cost function like $C(q, \mu, \theta) = \theta(cq + \mu)$.

Appendix

Proof of Lemma 1. (a) Let $\Xi \equiv \frac{P''(Q)Q}{P'(Q)}$ be the elasticity of the slope of the inverse demand and assume that $\Xi \geq -1$. Then a Cournot-Nash equilibrium exists and is unique (Novshek [21]). The Cournot-Nash equilibrium is such that the FOCs are verified: $P'(Q)q^I + P(Q) = 0$ and $P'(Q)q^E + P(Q) - a = 0$, for any entrant $i \in \{1, ...n\}$. Standard comparative statics shows that $q^{E\prime}(a) < 0$.
Summing the $n+1$ FOCs leads to:

$$P'(Q)Q + (n+1)P(Q) - na = 0. \tag{A.1}$$

Denote $Q(a)$ the solution in Q of (A.1) and let $p(a) = P(Q(a))$. Hence, at the Cournot equilibrium, we must have $\frac{p(a)-a}{p(a)} = \frac{1}{n}(\frac{1}{\eta(Q(a))} - 1)$.

(b) From (A.1),

$$Q'(a) = \frac{n+1}{P'(Q^*(a))(\Xi + n + 2)} < 0$$

since $\Xi \geq -1$ and $P'(Q) < 0$. We can then deduce that:

$$\begin{aligned} q^{E\prime}(a) &= \frac{Q'(a)}{n}(2 + \Xi s^I) < 0, \\ q^{I\prime}(a) &= Q'(a) - nq_E'(a) = -\left(1 + \Xi s^I\right) Q'(a) > 0 \end{aligned}$$

where $s^I \equiv \frac{q^I}{Q}$. Moreover, $p'(a) = P'(Q(a))Q'(a) = \frac{n+1}{(\Xi+n+2)} \in [0,1]$, $m'(a) = p'(a) - 1 \leq 0$ and $\frac{\partial r_n}{\partial a} = Q'(a)(P'(Q^*)Q^* + P'(Q^*)) - nm'(a)q^E - nmq^{E\prime} > 0$ since $Q' < 0$, $P'(Q)Q + P = nP'(Q)q^E < 0$ (from (A.1) and entrants' FOCs), $m'(a) \leq 0$ and $q^{E\prime} < 0$. Finally, $\frac{\partial \pi^e}{\partial a} = m'(a)q^E + mq^{E\prime} < 0$.

(c) Partially differentiating (A.1) with respect to n gives:

$$[(n+2)P' + P''Q]\dot{Q} + P - a = 0$$

Using $P - a = -\frac{P'Q+P}{n}$ from (A.1), we obtain:

$$\dot{Q}(a) = \frac{1}{n}Q\frac{1-\eta}{(\Xi + n + 2)} > 0$$

since $\eta < 1$ at equilibrium. Partially differentiating the incumbent's FOC with respect to n gives:

$$P''q^I\dot{Q} + P'\dot{q}^I + P'\dot{Q} = 0$$

so that

$$\dot{q}^I = -(\Xi s^I + 1)\dot{Q} < 0$$

and

$$\dot{Q} - \dot{q}^I = (2 + \Xi s^I)\dot{Q} > 0$$

■

Section 3: feasible mechanisms. Since $U(\theta,\tau)=\Pi_n^I(\mu(\tau),a(\tau),A(\tau),\theta)+T(\tau)$, from relation (5), θ must be the incumbent's best reply to $\mathcal{C}(\tau)$, that is:

$$\theta=\arg\max_{\tau\in[\underline{\theta},\bar{\theta}]}U(\theta,\tau)\Leftrightarrow\left\{\begin{array}{c}U_\tau'(\theta,\theta)=0\\ U_{\tau\tau}''(\theta,\theta)=-U_{\tau\theta}''(\theta,\theta)\leq 0\end{array}\right.$$

From the second (local) concavity condition, we can derive the second order IC:

$$U_{\tau\theta}''(\theta,\theta)=-g(\mu(\theta))\,\mu(\theta)\,\mu'(\theta)\geq 0\Leftrightarrow\mu'(\theta)\leq 0$$

Denoting $U(\theta)=U(\theta,\theta)$ and differentiating the first order condition $U_\tau'(\theta,\theta)=0$ with respect to θ leads to:

$$U'(\theta)=-\int_0^{\mu(\theta)}zg(z)\,dz=-H(\mu(\theta))<0.$$

By integration $U(\theta)=\int_\theta^{\bar{\theta}}H(\mu(\tau))\,d\tau+U(\bar{\theta})$ and $U\left(\bar{\theta}\right)=0$ is a sufficient condition to verify (4) in the text ($U(\theta)\geq 0,\forall\theta$). Now the expected welfare is:

$$\mathcal{E}W=\int_{\underline{\theta}}^{\bar{\theta}}\left[G(\mu(\theta))\,S(Q)+U(\theta)+nu(\theta)-(1+\lambda)\,T(\theta)\right]dF$$

Substituting $T(\theta)$ leads to:

$$\begin{aligned}\mathcal{E}W&=\int_{\underline{\theta}}^{\bar{\theta}}[G(\mu(\theta))\,S(Q)+U(\theta)+nu(\theta)\\&\quad-(1+\lambda)\,(U(\theta)-\Pi^I(\mu(\theta),a(\theta),A(\theta),\theta))]dF\end{aligned}\qquad\text{(A.2)}$$

Then integrating $\int_{\underline{\theta}}^{\bar{\theta}}U(\theta)\,f(\theta)d\theta$ by parts yields:

$$\int_{\underline{\theta}}^{\bar{\theta}}U(\theta)\,f(\theta)d\theta=\int_{\underline{\theta}}^{\bar{\theta}}\left(\int_\theta^{\bar{\theta}}H(\mu(\tau))\,d\tau\right)f(\theta)d\theta=\int_{\underline{\theta}}^{\bar{\theta}}H(\mu(\theta))\,F(\theta)d\theta.$$

Last substituting in (A.2) gives:

$$\begin{aligned}\mathcal{E}W&=\int_{\underline{\theta}}^{\bar{\theta}}\left\{G(\mu(\theta))\,S(Q)+(1+\lambda)\left[\Pi_n^I(\mu(\theta),a(\theta),A(\theta),\theta+\alpha\varphi(\theta))+nu(\theta)\right]-\lambda nu(\theta)\right\}dF\\&=\int_{\underline{\theta}}^{\bar{\theta}}\{G(\mu(\theta))\,S(Q)+(1+\lambda)[G(\mu)R(Q)-(\theta+\alpha\varphi(\theta))H(\mu)]\\&\quad-\lambda n\Pi^E(\mu(\theta),a(\theta),A(\theta))\}dF\end{aligned}\qquad\blacksquare$$

Proof of Proposition 1. **a.** If $\theta\leq\hat{\theta}_n^\lambda$, $\mu^*(\theta)=\mu^C(\theta)$. If $\hat{\theta}_n^\lambda<\theta\leq\theta_n^\lambda$, $\mu^*(\theta)<1=\mu^C(\theta)$. If $\theta>\theta_n^\lambda$, $\frac{\mu^C(\theta)}{\mu^*(\theta)}=1+\alpha\frac{\varphi(\theta)}{\theta}>1$.

b. From (9),

$$\frac{\partial \mu^*(\theta)}{\partial \theta} = \begin{cases} -\frac{[S+(1+\lambda)R-\lambda\pi^E][(1+\lambda)+\lambda\varphi'(\theta)]}{[(1+\lambda)\theta+\lambda\varphi(\theta)]^2} < 0 & \text{if } \theta > \hat{\theta}_n^\lambda \\ 0 & \text{if } \theta < \hat{\theta}_n^\lambda \end{cases}$$

At $\theta = \theta_n^\lambda$, μ^* is not differentiable with respect to θ, but it is clearly non-increasing as it is continuous and equal to 1 for $\theta \leq \theta_n^\lambda$ and less than 1 for $\theta > \theta_n^\lambda$.

c. Similarly,

$$\frac{\partial \mu^*(\theta)}{\partial \lambda} = \begin{cases} -\frac{S(\theta+\varphi(\theta))+\varphi R+\theta\pi^E}{[(1+\lambda)\theta+\lambda\varphi(\theta)]^2} < 0 & \text{if } \lambda > \lambda_n^\theta \\ 0 & \text{if } \lambda < \lambda_n^\theta \end{cases}$$

where $\lambda_n^\theta = \frac{S+R-\theta}{\theta+\varphi(\theta)-(R-\pi^E)}$. At $\lambda = \lambda_n^\theta$, μ^* is not differentiable with respect to λ, but it is clearly non-increasing as it is continuous and equal to 1 for $\lambda \leq \lambda_n^\theta$ and less than 1 for $\lambda > \lambda_n^\theta$.

d. Convexity of φ implies that $\varphi(\theta) \leq \varphi'(\theta)\theta, \forall\theta \in [\underline{\theta}, \bar{\theta}]$. Then,

$$\hat{\lambda}'(\theta) = \frac{S+\pi^E}{(R-n\pi^E)} \frac{(\varphi(\theta)-\varphi'(\theta)\theta)}{\varphi(\theta)^2} \leq 0$$

Assume that $\lambda > \hat{\lambda}(\bar{\theta})$. Since $\lim_{\theta \downarrow \underline{\theta}} \hat{\lambda}(\underline{\theta}) = \infty$, there exists a $\tilde{\theta} \in (\underline{\theta}, \bar{\theta}]$ such that $\lambda > \hat{\lambda}(\theta)$, $\forall\theta \in (\tilde{\theta}, \bar{\theta}]$. Since $\lambda > \hat{\lambda}(\theta) \Leftrightarrow \mu^*(\theta) < \mu^I(\theta)$, we have that $\mu^*(\theta) < \mu^I(\theta)$, $\forall\theta \in (\tilde{\theta}, \bar{\theta}]$. ■

Proof of Proposition 2. Differentiating (11) with respect to n, we have $\dot{a} = -\frac{\dot{Q}}{Q'}$, which is positive in virtue of Lemma 1. The second part of the proposition comes directly from (12). ■

Proof of Proposition 3. From (13),

$$\alpha \left(\frac{1}{\eta} + \frac{n\frac{\partial \pi^E}{\partial a}}{PQ'} \right) = 1$$

Since $\frac{\partial \pi^E}{\partial a} < 0$ and $Q' < 0$, this implies that $\eta > \alpha$. Since $\eta' < 0$ and $Q' < 0$, the comparison with (11) directly shows that that a is greater under a uniform access than under a two-part access charge. ■

Proof of Proposition 4. Substituting (9) in (8) leads to the following expected welfare function:

$$\begin{aligned} \mathcal{E}W &= \int_{\underline{\theta}}^{\hat{\theta}_n^\lambda} \left\{ S(Q(a)) + (1+\lambda)\left[R(Q(a)) - (\theta+\alpha\varphi(\theta))H(1)\right] - \lambda n\pi^E(a,0) \right\} dF \\ &\quad + \int_{\hat{\theta}_n^\lambda}^{\bar{\theta}} (1+\lambda)(\theta+\alpha\varphi(\theta))[G(\mu^*(\theta))\mu^*(\theta) - H(\mu^*(\theta))]dF \end{aligned}$$

Using the envelope theorem,

$$\frac{d\mathcal{E}W}{dn} = [P(Q)\dot{Q} - \lambda(P-a)(q^E + n\dot{q}^E)]F(\hat{\theta}_n^\lambda) + \int_{\hat{\theta}_n^\lambda}^{\bar{\theta}} (1+\lambda)(\theta + \alpha\varphi(\theta))G(\mu^*(\theta))\dot{\mu}^*(\theta)dF$$

where we used the facts that $P'Q = -n(P-a) - P$ and $P'q^E = -(P-a)$ from the firms' FOC. We consider both terms of the RHS in turn.

1. We have:

$$\begin{aligned} P(Q)\dot{Q} - \lambda(P(Q)-a)(q^E + n\dot{q}^E) &= P(Q)\dot{Q} - \lambda(P(Q)-a)(\dot{Q} - \dot{q}^I) \\ &= (1-\lambda)P(Q)\dot{Q} + \lambda a\dot{Q} + \lambda(P(Q)-a)\dot{q}^I \\ &> \lambda a\dot{Q} + \lambda(P(Q)-a)\dot{q}^I \text{ if } \lambda < 1 \text{ (since } \dot{Q} \geq 0) \\ &= \lambda a(\dot{Q} - \dot{q}^I) + \lambda P(Q) > 0 \end{aligned}$$

since $\dot{Q} - \dot{q}^I > 0$ from Lemma 1.

2. Since $(1+\lambda)(\theta + \alpha\varphi(\theta))\ \mu^*(\theta) = S + (1+\lambda)\,R - \lambda n\pi^E$, we have that $(1+\lambda)(\theta + \alpha\varphi(\theta))\dot{\mu}^*(\theta) = P(Q)\dot{Q} - \lambda(P-a)(q^E + n\dot{q}^E) > 0$, $\forall\theta$, as shown in the preceding case. ■

Proof of Proposition 5. Substituting (9), with $\pi^E = 0$, and (10) and in (8) leads to the following expected welfare function:

$$\begin{aligned} \mathcal{E}W &= \int_{\underline{\theta}}^{\hat{\theta}_n^\lambda} \{S(Q(0)) + (1+\lambda)\,[R(Q(0)) - (\theta + \alpha\varphi(\theta))H(1)]\}\,dF \\ &+ \int_{\hat{\theta}_n^\lambda}^{\bar{\theta}} (1+\lambda)(\theta + \alpha\varphi(\theta))[G(\mu^*(\theta))\mu^*(\theta) - H(\mu^*(\theta))]dF \end{aligned} \quad \text{(A.3)}$$

From (A.3),

$$\frac{d\mathcal{E}W}{dn} = \dot{Q}[(1+\lambda)P - \lambda P'Q]F(\hat{\theta}_n^\lambda) + \int_{\hat{\theta}_n^\lambda}^{\bar{\theta}} (1+\lambda)(\theta + \alpha\varphi(\theta))G(\mu^*(\theta))\dot{\mu}^*(\theta)dF \quad \text{(A.4)}$$

We first show that $\frac{d\mathcal{E}W}{dn} = 0$ for $n = \frac{1}{\lambda}$. We then show that $\mathcal{E}W$ is strictly quasi-concave in n.

1. Let $n = \frac{1}{\lambda}$. Then $(1+\lambda)P - \lambda P'Q = \frac{P}{n\eta}[(n+1)\eta - 1] = 0$ since $\eta(Q(0)) = \frac{1}{n+1}$ from Lemma 1. The first term in the RHS of (A.4) is thus nil. Moreover, $(1+\lambda)(\theta+\alpha\varphi(\theta))\mu^*(\theta) = S+(1+\lambda)\,R$, which implies that $(1+\lambda)(\theta+\alpha\varphi(\theta))\dot{\mu}^*(\theta) = (1+\lambda)P - \lambda P'Q$, so that the second term of the RHS is also nil when $n = \frac{1}{\lambda}$. As a result $n = \frac{1}{\lambda} \Rightarrow \frac{d\mathcal{E}W}{dn} = 0$.

2. Since $\dot{Q} > 0$, $\forall n$ from Lemma 1 and

$$(1+\lambda)P - \lambda P'Q = (1+\lambda)P[1-\alpha(n+1)] \gtreqless 0 \Leftrightarrow n \lesseqgtr \frac{1}{\lambda}$$

we have $\frac{d\mathcal{E}W}{dn} \gtreqless 0 \Leftrightarrow n \lesseqgtr \frac{1}{\lambda}$, i.e. that $\mathcal{E}W$ is strictly quasi-concave in n. As a result, $n = \frac{1}{\lambda}$ maximizes $\mathcal{E}W$. ■

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