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ABSTRACT

The literature on access prices and investment has suggested that firms under-invest when subject to an access provision obligation combined with a fixed access price per consumer. In this paper, I study an application of menu regulation in that the access price per consumer for an innovative service such as superfast broadband provided by a regulated firm is a function of its geographical coverage (indexation approach). I develop a model in which the indexation approach can enhance economic efficiency beyond what is achieved with a fixed access price. In particular, it can simultaneously induce the firms to set lower retail prices, lead to wider geographical coverage of innovative services and higher social welfare level as compared to a fixed access price. Moreover, in the model, the indexation may be used to achieve the Ramsey outcome, or the first-best coverage level. An impact assessment of the indexation approach on infrastructure duplication and areas of investment uncertainty is provided. Several extensions are investigated. I highlight the potential role of indexation as a tool to reduce the need for public subsidies and the associated tax distortions when compared to a fixed access price.

1 INTRODUCTION

Motivation. A key concern for Europe and the United States is the timely rollout of innovative high-speed broadband services. The European Commission has a target for all European homes to have access to a download speed of at least 100 Mbps by 2025, while the Federal Communications Commission has a goal for all US Americans to have access to affordable, high-quality broadband.[2] These high-speed services have the potential to offer considerable benefits to businesses to remain or become more competitive, allow consumers to benefit from advanced online services that improve their quality of life,[3] and induce significant growth across major economic sectors (Czernich *et al.*, 2011).

Fibre optics is one of the fastest technologies for content transmission (both downloading and uploading) allowing for significantly faster and wider transmission of information than current copper-based networks. However, the private sector has been reluctant to invest in a large-scale deployment of Next Generation Access Networks (NGA), namely fibre-based networks.[4] The investment in NGA has raised issues related to the ability of communications firms to finance such infrastructures. Insofar as the fibre roll-out cost increases substantially when population density falls, this has led to concerns on the ability of firms to extend geographical coverage outside major urban areas. Furthermore, to avoid adverse effects from monopolisation, the new infrastructures may be subject to access conditions[5] which may affect the firms' expected return from fibre deployment and reduce the investment incentives, particularly in areas of lower population density.

A regulator may address a market failure such as significant market power by implementing a price control during a given period. In such cases, it is common practice to adopt price-caps that do not adjust to investment made by the regulated firm throughout the price control period. In the introduction phase of innovative services requiring significant investment in geographical coverage such as high-speed broadband, regulators are likely to face a trade-off

[2] See http://europa.eu and https://apps.fcc.gov/edocs_public/attachmatch/FCC-16-6A1.pdf.

[3] Browsing, downloading, uploading, streaming television shows, movies and music, among other functions become more convenient and enjoyable with high-speed broadband. Also, in Europe the widespread availability of high-speed broadband is considered a key enabler of the digital internal market.

[4] Aside from fibre, there are a number of alternative technologies capable of supporting NGA such as: coaxial cable, mobile and fixed wireless networks. Since fibre is one of the fastest technologies for content transmission, debates on wired NGA have focused on fibre deployment. I will use "NGA" and "fibre-based networks" interchangeably.

[5] Setting access regulation in network industries is an essential issue for regulators to avoid anti-competitive behaviour on the part of the networks (bottleneck-facility owners). Access regulation is important to avoid entry deterrence, to provide competitors with reasonable access prices guaranteeing competitive parity among firms and to promote the statically efficient use of the network.

between static (price) and dynamic (coverage) efficiency. I question how such a trade-off can be softened. I investigate the impact of different access price controls on the firms' choices of geographical coverage of innovative services, and on downstream prices. The aim of this paper is to seek access price control rules that encourage further coverage without increasing downstream prices relative to a fixed price control approach.

Related literature. Rate-of-return regulation sets price-caps based on the firm's accounting costs and cost of capital. Its use in the United States dates to the late 19th Century to regulate the prices of utilities. It benefited from generalized support by investors and was primarily employed due to its long-run sustainability and flexibility to changes in the firm's conditions. Despite the initial success, the rate-of-return regulation was gradually replaced from the 1980s by "incentive regulation", in particular by price-caps (Braeutigam and Panzar, 1993). Averch and Johnson (1962) suggested that a profit-maximizing firm under rate-of-return regulation fails to minimize costs of production. Price-caps avoid this loophole by forecasting firm efficiency gains and efficient use of resources.[6] Should the firm be able to deliver the regulated services at a lower cost than had been forecast and be entitled to keep those cost savings, then a price-cap encourages the firm to improve efficiency over time. Consumers also benefit in the longer term to the extent that the efficiency gains can be shared through lower prices when the price-cap is reset.[7]

The introduction of competition into historical monopolies of telecommunications in many countries during the 1990s confronted sectoral regulators with the need to set access rules to allow new entrants to access the incumbent's network. This has motivated the publication of a number of research articles on access pricing issues. This paper draws from two different strands of literature. The first on the interplay between access price regulation and firms' investment,[8] especially on geographical deployment of new networks, and the second on performance compensation and menu regulation.

In the first stream of literature, Faulhaber and Hogendorn (2000), Foros and Kind (2003) and Valletti *et al.* (2002) are important contributions to the research on geographical deployment of

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[6] However, price-caps need to be periodically reviewed, e.g. it would be difficult for a regulator to accurately predict what efficiency gains will be possible within a decade. See Beesley and Littlechild (1989) for a detailed discussion on the use of price-caps in the UK.

[7] See Ofcom (2014) for an application of price-cap regulation in the fixed access markets in the UK.

[8] Imposing open access with a fixed access price calls to mind the classical free-riding problem in static frameworks; see Olson (1965), Chamberlin (1974) and McGuire (1974). The literature on free-riding points out that the investment level of equilibrium in public goods is lower than the Pareto efficient investment level. In a monopolistic market structure the free-riding problem vanishes. However, the retail price would become inflated, generating potential welfare losses.

broadband networks. The first article sets out the effect of universal service obligations, the second the effect of uniform retail pricing obligations, and the third the role of both types of obligations. However, these articles do not address the impact of access price regulation.

A common assumption in the access pricing literature is that access prices do not depend explicitly on investment levels.[9] Only exceptions such as Hurkens and Jeon (2008), Klumpp and Su (2010), Nitsche and Wiethaus (2011), Henriques (2011) and Sauer (2012) have considered the idea of access prices as a function of strategic variables, e.g. retail prices, quantities or investments/geographical coverage, as a means to improve welfare outcomes.

Lestage and Flacher (2010) pioneered the research of the impact of access regulation on geographical coverage within the context of competition for rolling out new telecommunications infrastructures. They proposed a model for the decision about "if" and "where" to deploy a new infrastructure. The authors showed that access regulation reduces the area of facility-based competition and extends the area where no firm is willing to invest. They also characterized the endogenous deployment of infrastructures, depending on the geographical area.

Henriques (2011) researched the idea of access prices as a function of NGA geographical coverage to improve social welfare assuming: two symmetric and non-overlapping regulated infrastructures, national retail prices and horizontal service differentiation à la Hotelling. This paper extends Henriques (2011) considering access price indexation under a different set of assumptions: asymmetric firms, only one regulated infrastructure, endogenous infrastructure duplication, geographical retail prices, homogeneity and vertical service differentiation. This paper also shows that the lack of regulatory commitment does not affect qualitatively the results set out in Henriques (2011).

The closest independent research work to this paper is Sauer (2012) comparing from the geographical coverage and social perspectives the performance of different regulatory access regimes. He showed that with access prices as a function of geographical coverage it was possible to reach the socially efficient investment level without distorting downstream competition. This paper differs at least in two major aspects. First, in this model, consumers may not be fully served with the innovative service depending on the price level, while Sauer used the Hotelling model with fully served consumers. Thus, market power does not generate welfare effects in Sauer's model. Second, he assumed that infrastructure duplication never happens in any area, while this paper considers the endogenous deployment of infrastructures

[9] See Valletti (2003), Guthrie (2006) and Cambini and Jiang (2009) for excellent reviews on how access pricing and network investments have been investigated by the theoretical literature. This literature points to the need to consider more deeply the impact of access regulation on investments and on welfare.

like in Lestage and Flacher (2010). Hence, in this model I can test the impact of different access rules not just on NGA geographical coverage but also on infrastructure duplication.

Flacher and Jennequin (2014) compared different regulatory regimes in terms of geographic coverage and welfare levels. They showed that geographic coverage, number of users as well as social welfare will be highest if both investment and access price decisions are taken by a welfare maximizing regulator. They suggested that the social optimum will be achieved through a call-for-tender process that includes deployment and access price requirements.

Bourreau, *et al.* (2015) proposed that access regulation should be tailored to each geographical area. They showed that geographically differentiated access prices can improve welfare and incentivize investment compared to a uniform access price. The authors also highlighted that when access provision in areas with facility-based competition were deregulated, welfare might decrease, because multiple inefficient equilibria at the wholesale level emerge, with either too little or too much investment.

The second body of literature related with this paper examines the choice of performance compensation and its effects on outputs. This literature suggests that paying on the basis of output has important incentive effects inducing agents to supply more output.[10] Menu regulation is an incentive mechanism that can embed the rationale of compensation on the basis of output in which regulated firms are offered a choice of regulatory contracts. The aim of menu regulation is to encourage firms to adopt a certain behaviour aligned with the regulator's objectives, e.g. to promote more investment in innovation.[11] To date, there are few regulatory implementations of these mechanisms. The UK is in the forefront of menu regulation, for example, with applications for electricity distribution and water.[12] Also, some regulators in Europe have proposed and implemented coverage obligations in spectrum

[10] Fernie and Metcalf (1999) found that when payment is contingent on performance, jockeys perform better than when payment does not depend on performance. Paarsch and Shearer (1996) find that tree planters in British Columbia produce higher levels of output when paid piece rates. Shearer (2003) found that in a large auto glass company paying on the basis of output, rather than hourly wages, had an effect on average levels of output per worker in the range of a 44-percent gain.

[11] Menu regulation can also be used to encourage regulated firms to report truthful cost information. Laffont and Tirole (1986) formulated a principal-agent model of cost-based procurement and regulation and showed that the principal can implement the optimal mechanism by offering the agent a menu consisting of a continuum of linear contracts.

[12] Ofgem introduced the Transmission Investment Incentives framework in April 2010 to provide project-specific, interim funding for critical, large-scale investment projects that the Transmission Owners justify as being both needed and ready to be taken forward within a transmission price control period. Ofwat (2013) set out menu-based cost incentives for the 2015/20 wholesale price controls for water and wastewater.

auctions resulting in less expensive licences for operators in exchange for wider mobile coverage.

Description of the paper. There are various reasons for under-investment in NGA coverage. One such reason relates to the inability of firms to capture the full social benefit from that investment. A main issue in access provision obligations is that they diffuse the investment benefits across access seekers and consumers while the cost is concentrated on the investor (infrastructure owner). Hence, infrastructure under-investment is aggravated by non-exclusivity imposed by regulation together with the fact that investment is costly. Another reason for under-investment could be the lack of access to finance. Financial markets may be unwilling to provide funding to firms to invest in deploying NGA infrastructure on terms that reflect the true costs and risks of investment.

There are a number of regulatory policy options to encourage investment in NGA which can be categorized in four distinct strategies listed below.

- Increasing the incremental net return on NGA services. This may be achieved by uplifting the value of copper equipment, given that low access prices for copper services could slow down the migration to NGA and stifle investment and take-up (e.g. see CRA, 2012).
- Guaranteeing the return on NGA investment. Regulatory certainty is particularly important for dynamic efficiency as that requires investors to be able to commit funds with confidence that the regulator will not act inconsistently in a way which would lead to the investor not having the opportunity to recover its costs.[13]
- Stimulating effective competition in NGA services. A policy of encouraging competing operators to invest progressively along the value chain draws on a concept known as the "ladder of investment". See Cave (2014) for more on the ladder of investment in Europe.
- Providing financial assistance to NGA services. For example: (i) direct funding using tax revenues; (ii) user tax on existing customers; and (iii) subsidizing consumption of superfast broadband services.

The strategy options set out above are not mutually exclusive. In some cases, the effects of certain options may be complimentary and a mix of strategies might be more appropriate. In this paper, I focus on access price controls, which fall within the category of guaranteeing the

[13] Under the utility model of investment, the regulator takes a view on the net benefits of particular investments and then sets the price controls to cover the cost of investments to deliver this. Price rises to cover such investments are generally spread over the entire customer base. Under the co-investment model the NGA investment is shared between several parties, e.g. firms, external investors, Government.

return on NGA investment. I compare the socially optimal fixed access price to a new access price rule (access price indexation) in terms of retail prices, infrastructure coverage and social welfare levels. Under the indexation approach the regulator defines the access price for an innovative service as an increasing function of the regulated firm's infrastructure coverage. In practice, this corresponds to a regulator setting out a menu of options in which the regulated firm faces a choice of access price-coverage regulatory contracts. In theory, a regulator could set prices and investments that maximize social welfare. However, in practice, firms face financial constraints and there is asymmetric information between regulators and regulated firms (see the "Discussion" section below). Setting out a menu of regulatory options, rather than exact levels of prices and investments, avoids regulatory risks, e.g. forcing the regulated firm to make an investment that cannot afford.

The indexation approach differs from standard utility regulation models. Generally, utility-style regulation would require a regulator to take a view on the net benefits of the utility and set the price caps to cover the desirable level of investment. This approach could impose costs on regulated firms in terms of potentially time-consuming negotiations with the regulator over the costs and benefits of potential investments. It may be difficult for a regulator to assess which investments in innovative services should be undertaken. Moreover, there is a risk that a utility-style approach could undermine existing competition insofar as the regulated firm is required to make certain investments, which are not imposed on other competitors (e.g. cable companies that also provide broadband services). Those competitors that are not subject to a price control could gain market share without having to lower their prices, reducing the effectiveness of the utility-style model as the regulated firm recovers less through regulated prices. Firms not subject to a price control could also compete less aggressively against the regulated firm, ultimately damaging economic efficiency. These complexities can be mitigated with access price indexation if the regulator offers a menu of feasible regulatory contracts and then leaves the investment choice with the regulated firm.

The main purpose of the indexation is to reward a regulated firm depending on the investment made. The firm is rewarded for covering a marginal area with an innovative service by increasing the access price in all (i.e. marginal and inframarginal) covered areas. Thus, the indexation grants an increasing competitive advantage at the downstream level as the regulated firm covers further areas. This approach helps the regulated firm to internalize the positive spillovers exerted from wider coverage. For example, by using a simple linear access pricing rule depending on coverage it can be created a causal link from geographical coverage of a service to retail price competition. A key factor influencing firms' incentives to invest and provide NGA services in an area is the incremental net revenues they can earn over and above providing their existing copper-based services in that area. Mechanisms which increase the incremental net revenues from NGA deployment can therefore have a positive effect on the geographical coverage of NGA services. Under a fixed access price and assuming copper-based services provided in a competitive basis at zero economic profit, the incremental net revenue of covering an additional area with NGA is the profit from that area only. However, under the indexation approach the incremental net revenue of covering an additional area with NGA is the profit from that area plus the incremental profit from all inframarginal areas already covered with the innovative service. Thus, to achieve the same level of geographical coverage, the firm will require a lower access price under indexation than with a fixed access price.

The main contribution of this paper is to show that the indexation of access prices to coverage can improve economic efficiency beyond what is feasible with a fixed access price approach. The indexation dominates a fixed access pricing rule in terms of retail price efficiency (i.e. the number of consumers served with a fibre connection), investment efficiency (i.e. the number of areas covered with fibre) and social welfare. Moreover, the indexation may be used to achieve the Ramsey outcome, or the first-best coverage level. Also, this paper provides an impact assessment of the indexation on infrastructure duplication and area of investment uncertainty (i.e. the area where it is profitable for only one firm to build infrastructure, however, it is unclear which one will do so). Infrastructure duplication may increase in virtue of indexation, while the impact on the investment uncertainty area is unclear.

The rest of the paper is organized as follows. In Section 2, I set out a service-based competition benchmark model to compare a fixed access price approach with access price indexation. In Section 3, I test the robustness of the findings under a facility-based competition model. In Section 4, I discuss further the features of access price indexation and the robustness of the results with regard to multiple regulated firms, national vs geographical retail prices, observability and verifiability, and uncertainty and asymmetric information. Section 5 concludes the paper. Proofs are in the Appendix.

2 SERVICE-BASED COMPETITION MODEL

In this section I set out a service-based competition model with an incumbent firm and a competitive fringe. I use this model, first to compute the first- and second-best outcomes and the free market equilibrium as benchmarks, and second to study the impact of different access price control rules on retail prices, geographical coverage of NGA services and welfare. I assume that consumers do not differentiate between the services provided by the incumbent and the competitive fringe, but it can be shown that the results extend qualitatively to differentiated services. Table 1 below summarizes the timing of the game. This structure is natural as firms decide on retail prices in the short-run and on investments in the long-run, while regulators decide on the access price strategy in the very long-run.

Table 1: Timing of the service-based competition model with a homogeneous service

I.	The sectoral regulator defines the access price control rules per consumer, a, for an innovative service provided by an incumbent firm on its NGA infrastructure.
II.	The incumbent firm chooses the areas to cover with NGA infrastructure. The accessing firms observe costlessly the NGA coverage.
III.	Firms compete simultaneously and non-cooperatively in retail prices for superfast broadband. With homogeneous services, consumers choose the service with the lowest price. If all services are priced the same, then consumers choose the one provided by the incumbent.

Below I describe each of the participants in the model: sectoral regulator, firms, and consumers.

Sectoral regulator. The regulator sets a uniform access price rule across all geographic areas, per consumer, a,[14] to the incumbent's NGA. This is likely a realistic assumption in light of various uniform price controls implemented in a number of countries. I assume that the regulator maximizes social welfare, W, i.e. the sum of the firms' profits and the consumer surplus,[15] and can credibly commit to an access price rule, i.e. the regulator cannot change the access price rule after the NGA deployment. The results extend qualitatively to the case where the regulator cannot commit to an access price rule.

Firms. I assume that there is a profit maximizing incumbent firm and a competitive fringe seeking access to the incumbent's NGA. A superfast broadband service can be offered in areas where the NGA infrastructure has been rolled out. The competitive fringe cannot bypass the incumbent's NGA to provide superfast broadband services. The country can be represented as a continuum of areas $z \in [0, \bar{K}]$ ordered by decreasing population density, but each with

[14] Regulators often need to set price controls for a number of complementary wholesale access services, e.g. cables, equipment accommodation, rentals, etc. The access price, a, in this model should be construed as the total price for the set of those complementary wholesale access services that are necessary to provide a service to a retail customer.

[15] The principal duty of some sectoral regulators, e.g. Ofcom in the UK, is to further the interests of consumers. Hence, it might be argued that more weight should be given to consumer surplus. However, firms' profits should also matter to the regulator to ensure the sustainability of the industry and because part of those profits may feed into future investments that will generate further surplus to consumers. I adopt a balanced assumption by giving equal weights to consumer surplus and the firms' profits.

identical demand for superfast broadband services.[16] The deployment cost of the NGA is convex in the sense that it is more expensive to cover peripheral areas with lower population density.[17] For simplicity, I assume that the cost of covering $0 \leq k \leq \bar{K}$ areas with NGA is

$$C(k) \equiv ck^2/2,$$

where $c > 0$ is a constant. I relax this assumption in the next section on "Facility-based competition model". Once an area z is covered with the NGA, the marginal cost of providing superfast broadband to a consumer is zero for the incumbent, while the accessing firms face a marginal cost equal to the access price, a. I assume that firms only charge consumers for accessing the network, e.g. a periodical subscription fee, i.e. firms set a retail price independently of the traffic volume exchanged in communications made by the consumer. This reflects the fact that currently in Europe and in the United States a number of broadband offers are flat rates.

The firms in the competitive fringe set their retail prices equal to the access price a and make zero profit. The incumbent's profit is defined as

$$\Pi(p,k) \equiv \begin{cases} pq(p)k - C(k), \text{if } p \leq a \\ aq(a)k - C(k), \text{if } p > a \end{cases}$$

where p and q denote, respectively, the superfast broadband retail price charged by the incumbent and demand in each NGA area. The demand, marginal cost per consumer, access rules and market structure are the same across areas covered with NGA. Hence, firms will choose uniform retail prices across NGA areas, even if they are able to differentiate retail prices per geographic area.

Consumers. In areas covered with a Current Generation Access Network (CGA) only, consumers use the standard broadband service and utility is normalized to zero. In an area z covered with NGA, the demand curve for superfast broadband is defined by

$$p(q) \equiv \alpha - \beta q$$

where $\alpha > 0, \beta > 0$ are constants, p denotes the lowest retail price for SFBB and $0 \leq q \leq (\alpha/\beta)$ is the respective mass of consumers. I abstract away from network externalities between consumers. This is because: (i) the gains from a faster broadband connection are more relevant for the purpose of services supplied by content providers (e.g. Ultra High Definition TV),

[16] The area $z = 0$ is the smallest and has the highest population density, while the area $z = \bar{K}$ is the largest and has the lowest population density.

[17] It is widely accepted that the geographical coverage cost increases for decreasing population densities. The convexity of costs also applies to postal services and some mobile telephone systems. See Foros and Kind (2003).

rather than for communication with other consumers; and (ii) NGA allows for such high connection speeds that congestion is not an issue (Sauer, 2012). Consumer surplus, CS, across areas covered by the NGA is given by

$$CS(q,k) \equiv \frac{(\alpha - p(q))^2}{2\beta} k.$$

2.1 First-best benchmark

In this section I solve the model for the first-best benchmark. Hereafter, a variable with FB in superscript refers to the model in the first-best, FOC stands for first-order conditions and SOC for second-order conditions. The welfare-maximizing regulator solves the following problem

$$\max_{a,k} W(a,k) \equiv CS(a,k) + \Pi(a,k) = \frac{(\alpha + a)(\alpha - a)}{2\beta} k - c\frac{k^2}{2}.$$

The first-best solution at which both the FOC and SOC of the regulator's problem are satisfied is

$$\begin{cases} k^{FB} = \dfrac{\alpha^2}{2c\beta} \\ a^{FB} = p^{FB} = 0 \\ q^{FB} = \dfrac{\alpha}{\beta} \\ \Pi^{FB} = -\dfrac{c}{2}\left(\dfrac{\alpha^2}{2c\beta}\right)^2 \\ CS^{FB} = \dfrac{1}{4}\dfrac{\alpha^4}{c\beta^2} \\ W^{FB} = \dfrac{1}{8}\dfrac{\alpha^4}{c\beta^2} \end{cases}$$

The efficient retail prices correspond to the marginal cost of serving a NGA service to a consumer, i.e. zero by assumption. It is socially optimal to supply NGA services to all consumers in areas covered with NGA. The efficient NGA coverage is driven by the demand parameters α and β, which affect the consumer surplus in an area covered with NGA, and the cost of NGA coverage, which is affected by parameter c. It is noteworthy that in the absence of lump-sum transfers the first-best is not feasible. This is because in the first-best, $p^{FB} = 0$, the incumbent makes zero-revenue, while the NGA coverage cost is strictly positive resulting in negative profit. Thus, the incumbent firm would prefer not to cover any area with NGA. Below I derive the Ramsey outcome by maximizing social welfare subject to non-negative profits to ensure the incumbent's participation.

2.2 Second-best benchmark: Ramsey outcome

In this section I solve the model for the second-best (Ramsey) benchmark. The Ramsey outcome sets out the retail price and NGA coverage a monopolist firm would set to maximize social welfare, subject to a constraint of non-negative profit. Hereafter, a variable with Ramsey in superscript refers to the model in the Ramsey outcome. The Ramsey problem is

$$\max_{a,k} W(a,k) \equiv CS(a,k) + \Pi(a,k) = \frac{(\alpha + a)(\alpha - a)}{2\beta} k - c\frac{k^2}{2}$$

$$\text{subject to } \Pi(a,k) \geq 0 \Leftrightarrow a\frac{\alpha - a}{\beta} k - c\frac{k^2}{2} \geq 0.$$

Given that in the first-best the incumbent's profit is negative, then $\Pi(a,k) \geq 0$ must be a binding constraint, i.e. $a(k) = \frac{\alpha}{2} - \frac{1}{2}\sqrt{\alpha^2 - 2c\beta k}$. The Ramsey problem can be re-written as

$$\max_{k} W(k) \equiv CS(a(k),k) + \Pi(a(k),k) = \frac{\big(\alpha + a(k)\big)\big(\alpha - a(k)\big)}{2\beta} k - c\frac{k^2}{2} \quad (1)$$

$$\text{subject to } a(k) = \frac{\alpha}{2} - \frac{1}{2}\sqrt{\alpha^2 - 2c\beta k}$$

and the Ramsey outcome is

$$\begin{cases} k^{Ramsey} = \frac{3}{8}\frac{\alpha^2}{c\beta} < k^{FB} \\ a^{Ramsey} = p^{Ramsey} = \frac{\alpha}{4} > p^{FB} \\ q^{Ramsey} = \frac{3}{4}\frac{\alpha}{\beta} < q^{FB} \\ \Pi^{Ramsey} = 0 > \Pi^{FB} \\ CS^{Ramsey} = \frac{27}{256}\frac{\alpha^4}{c\beta^2} < CS^{FB} \\ W^{Ramsey} = \frac{27}{256}\frac{\alpha^4}{c\beta^2} < W^{FB} \end{cases}$$

The Ramsey outcome suggests that to allow the incumbent to recover the NGA coverage cost it is necessary to set retail prices above the marginal cost. This results in inefficient consumption of NGA services and reduced consumer surplus and social welfare compared to the first-best.

2.3 Free market: monopoly case

In this section I compute the free market equilibrium to identify potential market failures (inefficiencies) in the pricing and coverage of NGA services and assess whether there is scope for regulatory intervention to improve social welfare. I use backward induction to solve the model for the subgame perfect Nash equilibrium. First, I solve the incumbent's problem to derive the profit maximizing retail and access prices (in a free market without regulatory intervention, the incumbent can also set the access price to its infrastructure). Second, I solve the incumbent's coverage problem. Hereafter, a variable with mon in superscript refers to the model in the free market (monopoly) case.

Stage III: retail price competition and access pricing

Firms in the competitive fringe set prices equal to the access price a. In the retail (and access) pricing stage, the incumbent's problem is

$$\max_{p,a} \Pi(p) \equiv \begin{cases} pq(p)k - C(k), \text{if } p \leq a \\ aq(a)k - C(k), \text{if } p > a \end{cases}.$$

If $p \leq a$, the incumbent sets the monopoly price at $p^{mon} = \frac{\alpha}{2}$ and supplies all consumers that wish the service at that price, $q^{mon} = \frac{\alpha}{2\beta}$. The competitive fringe is unable to compete with the incumbent with an access price equal or above the monopoly price. The incumbent makes a profit of $\Pi^{mon} = \frac{\alpha^2}{4\beta}k - C(k)$.

If $p > a$, consumers only buy the service from the competitive fringe. The incumbent sells access to the competitive fringe at a and its profit is $\Pi(p) = a\frac{\alpha - a}{\beta}k - C(k)$. Thus, maximizing with respect to a the incumbent sets the access price at $a^{mon} = \frac{\alpha}{2}$ and extracts the monopoly profit Π^{mon}.

In both cases, $p \leq a$ and $p > a$, the incumbent achieves the maximum profit level Π^{mon}.

Stage II: coverage

The incumbent's coverage problem is

$$\max_{k} \Pi(k) = \frac{\alpha^2}{4\beta}k - c\frac{k^2}{2}$$

and the free market (monopoly) equilibrium is

$$
\begin{cases}
p^{mon} = \dfrac{\alpha}{2} > p^{Ramsey} \\
q^{mon} = \dfrac{\alpha}{2\beta} < q^{Ramsey} \\
k^{mon} = \dfrac{\alpha^2}{4c\beta} < k^{Ramsey} \\
\Pi^{mon} = \dfrac{\alpha^4}{32c\beta^2} > \Pi^{Ramsey} \\
CS^{mon} = \dfrac{\alpha^4}{32c\beta^2} < CS^{Ramsey} \\
W^{mon} = \dfrac{\alpha^4}{16c\beta^2} < W^{Ramsey}
\end{cases}
$$

I can now compare the free market solution to the Ramsey outcome (the best feasible outcome for society as a whole in the absence of lump-sum transfers). In the free market equilibrium, the incumbent maximizes profit by setting higher retail prices and a narrower NGA coverage than in the Ramsey outcome. This results in inefficient levels of NGA consumption and underinvestment in coverage, as well as lower consumer surplus and social welfare.

Retail price inefficiency derives from the incumbent's market power to set access prices to the only available NGA infrastructure. Underinvestment in NGA is because the incumbent is unable to capture the full social benefit of investment. A fraction of that benefit is captured by consumers given their heterogeneity in willingness to pay for the NGA service and firms being unable to price discriminate to extract the consumers' full benefit. Hence, a regulatory intervention may be desirable from the social perspective to promote price and investment efficiencies.

Below I consider two types of price control interventions: fixed access prices and access prices indexed to NGA coverage. I compare and discuss the (in)efficiencies associated with each of these types of price controls below.

2.4 Fixed access price

In this section I solve the model for the subgame perfect Nash equilibrium under a fixed access price rule. Hereafter, a variable with $*$ in superscript refers to the model with a fixed access price.

Stage III: retail price competition

Firms in the competitive fringe set prices equal to the access price a. In the retail price stage, the incumbent's problem is

$$\max_p \Pi(p) \equiv \begin{cases} pq(p)k - C(k), \text{if } p \leq a \\ aq(a)k - C(k), \text{if } p > a \end{cases}.$$

If $p > a$, then the incumbent only sells access to the competitive fringe at a and $\Pi(p) = a\frac{\alpha-a}{\beta}k - C(k)$.

If $p \leq a$, given that $a < a^{mon} = \frac{\alpha}{2}$ as otherwise the regulator would not need to intervene, then $p^* = a$.

Stage II: coverage

The incumbent's coverage problem is

$$\max_k \Pi(k) = p^* \frac{\alpha - p^*}{\beta} k - c\frac{k^2}{2}$$

$$FOC\ :\ a\frac{\alpha - a}{\beta} - ck = 0 \Leftrightarrow k^*(a) = a\frac{\alpha - a}{c\beta}. \tag{2}$$

Stage I: regulatory regime

The welfare-maximizing regulator solves the following problem

$$\max_a W(a) \equiv CS(a) + \Pi(a) = a\alpha\frac{(a-\alpha)^2}{2c\beta^2}.$$

Hence, in equilibrium with a fixed access price

$$\begin{cases} a^* = \frac{\alpha}{3} \\ p^* = \frac{\alpha}{3} < \frac{\alpha}{2} = p^{mon} \\ q^* = \frac{2\alpha}{3\beta} > \frac{\alpha}{2\beta} = q^{mon} \\ k^* = \frac{2\alpha^2}{9c\beta} < \frac{\alpha^2}{4c\beta} = k^{mon} \\ \Pi^* = \frac{2\alpha^4}{81c\beta^2} < \frac{\alpha^4}{32c\beta^2} = \Pi^{mon} \\ CS^* = \frac{4\alpha^4}{81c\beta^2} > \frac{\alpha^4}{32c\beta^2} = CS^{mon} \\ W^* = \frac{6\alpha^4}{81c\beta^2} > \frac{\alpha^4}{16c\beta^2} = W^{mon} \end{cases}. \tag{3}$$

I can now compare the fixed access price outcome to the free market equilibrium. By setting a lower fixed access price the regulator can induce lower retail prices compared to the free market. However, this results in less NGA investment given the revenue that the incumbent can collect from consumers is limited by the price control at a^*. The regulator can set the fixed access price control such that the gains in price efficiency more than compensate the welfare losses from further underinvestment. In other words, welfare gains for consumers in NGA areas benefiting from lower retail prices will more than compensate the welfare losses for consumers that lose NGA access as a result of the fixed access price implementation.

In Proposition 1 below I claim that under the fixed access price rule the regulator cannot implement the first-, nor the second-best investment level, regardless of how much static efficiency is sacrificed.

Proposition 1 (underinvestment) *Under a fixed access price it is not possible to implement the first- nor the second-best investment level, i.e. there is underinvestment* $k^*(a) \leq k^{mon} < k^{Ramsey} < k^{FB}$.

Under a fixed access price, underinvestment results from the inability of the profit maximizing incumbent to capture the full social benefit of investment. This inability stems from retail price competition exerted by the competitive fringe and the difficulty to price discriminate between consumers. It is noteworthy that even if the fixed access price were set to maximize investment, rather than social welfare, the NGA coverage could not go above the monopoly level. This is because there are benefits captured by the consumers due to their heterogeneity in the willingness to pay for the NGA service combined with the fact that firms are unable to price discriminate to extract the consumers' full valuations. Moreover, even if firms were able to practice first-degree price discrimination, retail price competition would imply positive surplus to subscribers.

2.5 Access price indexation

In this section I analyze access prices that are indexed to NGA coverage to mitigate inefficiencies related to the use of a fixed access price. The access price indexation proposed has the purpose of increasing investment incentives in NGA coverage without sacrificing retail price efficiency and, ultimately, boosting social welfare.

I solve the game set out in Table 1 above using a simple linear access price indexation rule (i.e. the access price is linear in NGA coverage) and compare the outcome to the equilibrium obtained under a fixed access price. I show that the access price indexation can increase social welfare relative to fixed access pricing.

Also, I solve the game with generalized access price indexation (i.e. the access price is non-linear in NGA coverage) and show that under certain conditions the Ramsey outcome is feasible. Moreover, I address the case where the regulator's goal is to implement the first-best level of NGA coverage with the lowest possible retail pricing. I show that the generalized access price indexation under certain conditions can promote first-best coverage. This may be particularly relevant, for example, to meet universal service coverage obligations if these have been imposed.

2.5.1 Linear access price indexation

Let the access price charged by the incumbent per subscriber of the competitive fringe be defined by $a = rk$, where r is the regulatory parameter to be determined. Hereafter, a variable with $**$ in superscript refers to the model with linear access price indexation.

Stage III: retail price competition

This is identical to Stage III under the fixed access price solved above. Thus, $p^{**} = a^{**} = r^{**}k^{**}$.

Stage II: coverage

The incumbent's coverage problem is

$$\max_k \Pi(k) = a(k)\frac{\alpha - a(k)}{\beta}k - c\frac{k^2}{2} = rk\frac{\alpha - rk}{\beta}k - c\frac{k^2}{2}$$

and the optimal coverage is defined by

$$FOC: \frac{d\Pi}{dk} = \underbrace{\frac{\partial \Pi}{\partial k}}_{\text{"direct effect"}} + \underbrace{\frac{\partial \Pi}{\partial a}\frac{da}{dk}}_{\text{"indexation effect"}} = 0$$

while under the fixed access approach only the "direct effect" exists. The "direct effect" accounts for the marginal private benefit and marginal cost of covering an area with NGA assuming that the access price is held constant. The "indexation effect" accounts for the incumbent's profit variation due to changes in the access price via investment in NGA coverage.

Under a fixed access price the "indexation effect" is zero, $\frac{da}{dk} = 0$. Under access price indexation, the "indexation effect" is positive because $\frac{\partial \Pi}{\partial a} > 0$ for $a < p^{mon}$, and $\frac{da}{dk} = r > 0$given the purpose of the indexation to reward the regulated firm depending on the investment made. The indexation effect results from the fact that the incumbent's profit increases with access prices (for access prices below the monopoly level), while access prices increase with the incumbent's NGA coverage. From an investor's perspective, the marginal benefit of NGA coverage is higher with access price indexation than with a fixed access price.

Note that with access price indexation, the incumbent is rewarded with an increase in the access price in all (i.e. marginal and inframarginal) NGA areas for covering a marginal area with NGA. As a result, the incumbent has an incentive to invest more with the access price indexation than with a fixed access price. From the incumbent's FOC for NGA coverage, $k^{**} = \frac{2r\alpha - c\beta}{3r^2}$.

Stage I: regulatory regime

The welfare-maximizing regulator solves the following problem

$$\max_r W(r) \equiv CS(a(r)) + \Pi(a(r)) = (2r\alpha - c\beta)\frac{2c^2\beta^2 + 5r^2\alpha^2 - 2cr\alpha\beta}{54r^4\beta}.$$

Hence, in equilibrium with the linear access price indexation

$$\begin{cases} r^{**} = \frac{4c\beta}{5\alpha} \\ k^{**} = \frac{5}{16}\frac{\alpha^2}{c\beta} > \frac{2}{9}\frac{\alpha^2}{c\beta} = k^* \\ a^{**} = \frac{\alpha}{4} < \frac{\alpha}{3} = a^* \\ p^{**} = \frac{1}{4}\alpha < \frac{1}{3}\alpha = p^* \\ q^{**} = \frac{3}{4}\frac{\alpha}{\beta} > \frac{2}{3}\frac{\alpha}{\beta} = q^* \\ \Pi^{**} = \frac{5}{512}\frac{\alpha^4}{c\beta^2} < \frac{2}{81}\frac{\alpha^4}{c\beta^2} = \Pi^* \\ CS^{**} = \frac{45}{512}\frac{\alpha^4}{c\beta^2} > \frac{4}{81}\frac{\alpha^4}{c\beta^2} = CS^* \\ W^{**} = \frac{50}{512}\frac{\alpha^4}{c\beta^2} > \frac{6}{81}\frac{\alpha^4}{c\beta^2} = W^* \end{cases}. \quad (4)$$

It is noteworthy that $k^{**} = \frac{5}{16}\frac{\alpha^2}{c\beta} > \frac{1}{4}\frac{\alpha^2}{c\beta} = k^{mon}$, i.e. more areas will be covered with NGA under the linear access price indexation than in the monopoly case. Regulators have to make harsher compromises between their objectives when setting out a fixed access price, rather than a menu. The essential problem is that the number of regulatory instruments is less than the number of objectives with a fixed access price. Proposition 2 below summarizes the comparison between the equilibrium under the linear access price indexation and under fixed access prices.

Proposition 2 (linear indexation vs fixed access prices) *A linear access pricing rule depending on NGA coverage, $a = rk$, with $r = r^{**} > 0$ can simultaneously (i) expand geographical coverage of*

NGA, (ii) expand the mass of NGA consumers in each area covered with NGA, and (iii) enhance social welfare, as compared to a fixed access price $a^* > 0$.

The introduction of access price indexation creates a scheme of rewards to investors. In particular, by investing in further NGA coverage the incumbent can charge a higher access price. As a result of the additional incentives to NGA investment generated by the indexation, for a same equilibrium access price, the incumbent invests more with indexation than under a fixed access price.

The total mass of NGA consumers across all areas depends on the retail price level which in turn depends on the access price level. Therefore, if the equilibrium access price under the indexation rule is below the one defined under a fixed access price rule, the mass of NGA consumers will be higher under the former, rather than under the latter rule. Suppose that with a fixed access price rule the access price is set at a^*. Under the access price indexation the regulator can choose $r = r^{**}$ such that $a^{**} = r^{**}k^{**} = a^* - \varepsilon$, $\varepsilon > 0$, while for ε sufficiently small the investment k^{**} is above the equilibrium investment level under a fixed access price, k^*. Note that r can be set at a level such that it is sufficiently small to ensure that the access price will be below a^*, but sufficiently high to incentivize NGA coverage above k^*.

In relation to social welfare, I note that in equilibrium there are more NGA consumers in each NGA area under access price indexation than under a fixed access price. Consequently, both the gross consumer surplus in each NGA area and the marginal social benefit from NGA coverage increase. Under a fixed access price, in equilibrium the marginal social benefit from investment is positive implying that further NGA coverage would enhance social welfare. Hence, if the fixed access rule is the status quo, the social welfare variation due to the implementation of the access price indexation must be positive. This is explained by the increase of gross consumer surplus in each NGA area together with the expansion of the geographical coverage of NGA (to the extent that the coverage cost of an additional NGA area is lower than the gross consumer surplus generated).

2.5.2 Generalized access price indexation

Let the access price charged by the incumbent per consumer provided by the competitive fringe be defined by $a = a(k)$, where $a(k)$ is a function of k to be defined by the regulator. Proposition 3 below sets out the main achievements of a generalized access price indexation which would not be feasible under a simple linear access price indexation.

Proposition 3 (Ramsey outcome and first-best coverage) *A generalized access price indexation rule depending on NGA coverage can implement (i) the Ramsey outcome or (ii) the first-best coverage level.*

Below I compute the equilibrium under a generalized access price indexation and discuss how a regulator may implement the Ramsey outcome or the first-best coverage level.

Stage III: retail price competition

This is identical to Stage III under the fixed access price solved above. Thus, $p = a$.

Stage II: coverage

The incumbent's coverage problem is

$$\max_{k} \Pi(k) = a(k)\frac{\alpha - a(k)}{\beta}k - c\frac{k^2}{2}$$

$$FOC \ : \ \alpha\frac{a'(k)k + a(k)}{\beta} - \frac{2a(k)a'(k)k + \left(a(k)\right)^2}{\beta} - ck = 0.$$

where the SOC needs to be verified in equilibrium.

Solving the FOC above with respect to a, and given that $p^{mon} = \frac{\alpha}{2}$, thus

$$a(k) = \frac{\alpha}{2} - \frac{1}{2}\sqrt{\alpha^2 - 2c\beta k - \frac{4\beta\Psi}{k}}$$

where Ψ is a coefficient (or analytical expression) to be determined. Note that the solution above can also be computed by solving $\Pi(k) = a(k)\frac{\alpha - a(k)}{\beta}k - c\frac{k^2}{2}$ with respect to $a(k)$, thus, $\Psi = \Pi(k)$.

If the access price is set at the monopoly price, $a = \frac{\alpha}{2}$, the maximum coverage that can be achieved subject to the incumbent being able to recover the total cost is $k = k^{FB} = \frac{\alpha^2}{2c\beta}$. The regulator can set the functional form for $a(k)$ such that it shapes $\Pi(k)$ to induce the incumbent to choose a given $k^G \in [0; k^{FB}]$. In particular, the regulator needs to choose a functional form for $\Psi(k)$ concave in k and with maximum at $k = k^G$, i.e. k^G satisfies simultaneously the FOC and the SOC for the incumbent's problem. For example, the regulator can set $\Psi(k) \equiv \varepsilon k(2k^G - k)$ where $\varepsilon > 0$ is an arbitrarily small constant.

It is noteworthy that from the incumbent's profit function the access price can be written as

$$a(k) = \frac{C(k)}{q(a(k))k} + \frac{\Pi}{q(a(k))k},$$

thus, if $\Pi = 0$, $a(k)$ is simply the average total cost per NGA consumer.

Stage I: Ramsey outcome

The welfare-maximizing regulator solves the following problem with a generalized access price indexation

$$\max_{k^G} W(k, k^G\}) \equiv CS(a(k), k) + \Pi(a(k), k) = \frac{(\alpha + a(k))(\alpha - a(k))}{2\beta} k - c\frac{k^2}{2} \qquad (5)$$

$$\text{subject to } a(k) = \frac{\alpha}{2} - \frac{1}{2}\sqrt{\alpha^2 - 2c\beta k - \frac{4\beta\Psi}{k}}$$

$$\Psi(k) \equiv \varepsilon k(2k^G - k)$$

$$k = k^G.$$

If $\varepsilon \to 0$, then the solution of problem (5) converges to the solution of problem (1). This is because for a same objective function, W, as $\varepsilon \to 0$, the space (k, a) defined by the constraints in (5) converges to the space (k, a) defined by the constraint in (1).

For $\varepsilon \to 0$ the regulator can set

$$k^G = k^{Ramsey} = \frac{3}{8}\frac{\alpha^2}{c\beta}$$

if the values of the parameters are known, otherwise k^G may have to be based on the regulator's view regarding the social optimal NGA coverage. Thus,

$$a(k) = \frac{\alpha}{2} - \frac{1}{2}\sqrt{\alpha^2 - 2c\beta k - \left(\frac{4\varepsilon\beta k\left(\frac{3}{4}\frac{\alpha^2}{c\beta} - k\right)}{k}\right)} \qquad (6)$$

$$\text{and } \lim_{\varepsilon \to 0} a(k^{Ramsey}) = \frac{\alpha}{4} = a^{Ramsey}.$$

Hence, for $\varepsilon \to 0$ the Ramsey solution can be implemented via generalized access price indexation, for example, by defining the access price function as set out in (6).

Stage I revisited: first-best coverage level

A regulator may choose an access price rule with the purpose of implementing the first-best investment level, $k^{FB} = \alpha^2/(2c\beta)$. This action may result, for instance, from an objective of universal coverage of a service. The universal service is an economic, legal and business term used mostly in regulated industries, referring to the practice of providing a baseline level of services to all residents of a country at an affordable price. Examples of this concept may be found in the Telecommunications Act of 1996[18] and the Directive (2002/22/EC) of the European Parliament and of the Council of the European Union of 7 March 2012. In this section I suggest that the access price indexation may be used in pursuing an objective of universal coverage of a service.

The access price indexation regime can implement the first-best NGA coverage if at $k = k^{FB}$ three tests are simultaneously satisfied: (i) the incumbent's FOC, (ii) the SOC, and (iii) the non-negative profit condition. For example, if the regulator sets the access price as

$$a(k) = \begin{cases} \frac{\alpha}{2} - \frac{1}{2}\sqrt{\alpha^2 - 2c\beta k - \left(\frac{4\beta\Psi(k)}{k}\right)} & \text{if } \alpha^2 - 2c\beta k - \left(\frac{4\beta\Psi(k)}{k}\right) \geq 0 \\ \frac{\alpha}{2} \text{ otherwise} & \end{cases}$$

with $\Psi(k) \equiv \varepsilon k(2k^{FB} - k)$ and $\varepsilon \to 0$ all the three tests above are satisfied. As previously discussed, $\Pi(k) = \Psi(k)$ which is concave in k and has maximum at $k = k^{FB}$. Hence, it is straightforward that tests (i) and (ii) above are satisfied. At $k = k^{FB}$, $\lim_{\varepsilon\to 0} a(k^{FB}) = \frac{\alpha}{2} = p^{mon}$, thus $\lim_{\varepsilon\to 0} \Pi = p^{mon}q^{mon}k^{FB} - \frac{c(k^{FB})^2}{2} = \frac{\alpha}{2} \times \frac{\alpha}{2\beta} \times \frac{\alpha^2}{2c\beta} - \frac{c}{2}\left(\frac{\alpha^2}{2c\beta}\right)^2 = 0$ and test (iii) is satisfied as well. In this case, the incumbent receives the monopoly revenue from each NGA area and invests the total revenue in NGA coverage. In this particular case, in the absence of lump-sum transfers the maximum feasible level of NGA coverage is k^{FB}. In general, the first-best NGA coverage is defined by

$$\int_0^{q^{FB}} p(q)dq - \frac{dC(k)}{dk} = 0 \Leftrightarrow \int_0^{q^{FB}} p(q)dq = \frac{dC(k)}{dk} \tag{7}$$

while the maximum feasible level of NGA coverage under the generalized access price indexation is defined by

$$p^{mon}q^{mon}k - C(k) = 0 \Leftrightarrow p^{mon}q^{mon} = \frac{C(k)}{k}. \tag{8}$$

[18] The US Telecommunications Act of 1996 sets out the following goals: (i) to promote the availability of quality services at just, reasonable, and affordable rates; (ii) to increase access to advanced telecommunications services throughout the Nation; and (iii) to advance the availability of such services to all consumers, including those in low income, rural, insular, and high cost areas at rates that are reasonably comparable to those charged in urban areas.

Note that $\int_0^{q^{FB}} p(q)dq \geq p^{mon}q^{mon}$ given that the left-hand side of the inequality accounts for the full value generated by NGA coverage in an area in the first-best, while the right-hand side accounts only for the revenue captured by the monopolist in that same area. Also, $dC(k)/dk > C(k)/k$ given that the deployment cost of the NGA is convex by assumption. In general, the solutions of (7) and (8) with respect to k do not coincide, and the maximum feasible level of NGA coverage under the generalized access price indexation may be above or below the first-best.[19]

3 FACILITY-BASED COMPETITION MODEL

The service-based competition model set out in the previous section assumed: homogeneous NGA services, a single period of retail price competition, and a regulator capable of credibly committing to an access price rule. However, the main results are not dependent on those assumptions. The analysis can be extended to vertically differentiated NGA services, multiple periods of retail price competition, and a regulator lacking regulatory commitment, yet the result that an access price indexation is more efficient than a fixed access price still holds.

In this section I put to the test the robustness of the results set out in the previous section and allow for facility-based competition in a duopoly and two periods of retail price competition (for simplicity, the intertemporal discount factor is equal to 1). Table 2 below summarizes the timing of the facility-based competition model.

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[19] For example, if $p(q) = \alpha$ for $0 \leq q \leq 1$, then $\int_0^{q^{FB}} p(q)dq = p^{mon}q^{mon} = \alpha$, while, $dC(k)/dk = ck$, $C(k)/k = ck/2$. Thus, $k^{FB} = \alpha/c$, while the maximum feasible level of NGA coverage is $2\alpha/c = 2 \times k^{FB}$. However, changing the cost of NGA deployment to $C(k) = ck^{1.5}/1.5$ while keeping the linear demand function for superfast broadband services, the maximum feasible level of NGA coverage will be below the first-best level.

Table 2: Timing of the facility-based competition model

Period 1	I.	The sectoral regulator defines the access price control rules per consumer, $a_{i,t}$, for a new service provided by the incumbent, $i = 1$, for each period $t = 1,2$.
	II.	The two firms choose simultaneously whether to invest or not in each area z of the country. The coverage game in an area z is set out in Table 3 further below.
	III.	If the NGA infrastructures are unregulated in this period, both firms can set the respective access prices to the profit maximizing level. Firms compete simultaneously and non-cooperatively in retail prices. Each consumer chooses the service that maximizes his/her utility.
Period 2	I.	If the NGA infrastructures are unregulated in this period, both firms can set the respective access prices to the profit maximizing level. Firms compete simultaneously and non-cooperatively in retail prices. Each consumer chooses the service that maximizes his/her utility.

Below I describe each of the participants in the model: firms, consumers, and sectoral regulator.

Firms. I assume that there are two profit maximizing firms in the industry: an incumbent and an entrant, firm 1 and 2, respectively. The firms can offer superfast broadband in areas where NGA infrastructure has been rolled out. The country can be represented as a continuum of areas $z \in [0, K]$ ordered by decreasing population density, but each with identical demand (see footnote 16). The deployment cost of NGA is convex in the sense that it is more expensive to cover peripheral areas with lower population density (see footnote 17). The cost of deploying NGA in k areas is given by $C(k) \equiv \int_0^k c(z)\, dz$ with $C'(k) = c(k) > 0$ and $C''(k) = c'(k) > 0$, where $c(z)$ is the deployment cost of NGA in area z. I assume that $c(z)$ is the same for both firms.

In areas covered with NGA, the marginal cost of providing superfast broadband to a consumer is zero for the investing firm, while the accessing firm pays an access price $a_{i,t}$ to firm i, at time t, where $i = 1,2$. I assume that firms only charge consumers for accessing the network and can differentiate retail prices per area.[20] Let $p_{i,z,t}$ denote firm i's retail price to superfast broadband in area z, at time t. The respective mass of consumers is denoted by $q_{i,z,t} \geq 0$.

Table 3 below sets out the coverage game in an area z.

Table 3: Coverage game in an area z

		Firm 2	
		N	I
Firm 1	N	$\pi_{1,z}^{N,N}; \pi_{2,z}^{N,N}$	$\pi_{1,z}^{N,I}; \pi_{2,z}^{I,N} - c(z)$
	I	$\pi_{1,z}^{I,N} - c(z); \pi_{2,z}^{N,I}$	$\pi_{1,z}^{I,I} - c(z); \pi_{2,z}^{I,I} - c(z)$

The strategies "investing in new infrastructures" and "not investing" are denoted respectively by I and N. I denote firm i's profit (excluding any sunk coverage costs) in area z at time t by $\pi_{i,z,t}^{j,l}$ and $\pi_{i,z}^{j,l} \equiv \sum_{t=1}^{2} \pi_{i,z,t}^{j,l}$ where $j \in \{N, I\}$ is the strategy it has adopted and $l \in \{N, I\}$ the strategy of its competitor. Note that in the case where none of the firms invests, only standard broadband is available. The incentives to cover an area z are defined as the difference between the profits "with" and "without" investment. Each firm's incentive to cover an area depends on the strategy adopted by the competitor.

Consumers. In areas covered with CGA only, consumers have no alternative to standard broadband and their utility is normalized to zero. In areas covered with NGA, consumers' behaviour is represented by a vertical differentiation model à la Mussa and Rosen (1978). Each consumer indexed by $x \in [0,1]$ uniformly distributed in each area z with NGA, at time t, chooses the broadband service that maximizes the utility function given by

$$U(x) \equiv \begin{cases} x - p_{1,z,t}, \text{ if NGA with firm 1} \\ \gamma x - p_{2,z,t}, \text{ if NGA with firm 2,} \\ 0, \text{ if CGA} \end{cases}$$

where x and γx, with $0 < \gamma < 1$, measure the willingness to pay of consumer x to subscribe the NGA service of firm 1 and 2, respectively. Consumers have a higher willingness to pay for the incumbent's service due to first-mover advantages. Therefore, consumers perceive the

[20] Broadband operators may offer discounts on the catalog price which vary per geographical areas. Also, operators may offer different qualities of service (e.g. bandwidth) per geography, corresponding to different quality-adjusted prices.

entrant as of a lower quality service. I abstract away from network externalities between consumers for the reasons discussed in the service-based competition model. In areas with NGA, the demand curves in area z, at time t, for superfast broadband of firm 1 and 2 respectively are

$$q_{1,z,t}(p_{1,z,t}, p_{2,z,t}) = 1 - \frac{p_{1,z,t} - p_{2,z,t}}{1-\gamma};\ q_{2,z,t}(p_{1,z,t}, p_{2,z,t}) = \frac{p_{1,z,t} - p_{2,z,t}}{1-\gamma} - \frac{p_{2,z,t}}{\gamma}$$

while the remaining consumers, $p_{2,z,t}/\gamma$, use standard broadband. Note that the demands for NGA services in an area z, at time t, do not change with income. This follows the Marshallian notion that when a good represents a small fraction of the total expenditure of a consumer then income effects become negligible.[21] Consumer surplus in area z, at time t, $CS_{z,t}$, is defined as

$$CS_{z,t}(p_{1,z,t}, p_{2,z,t}) \equiv \int_{\frac{p_{2,z,t}}{\gamma}}^{\frac{p_{1,z,t}-p_{2,z,t}}{1-\gamma}} (\gamma x - p_{2,z,t})dx + \int_{\frac{p_{1,z,t}-p_{2,z,t}}{1-\gamma}}^{1} (x - p_{1,z,t})\, dx. \tag{9}$$

Sectoral regulator. As in the service-based competition model, I assume that the regulator maximizes social welfare and is able to credibly commit ex-ante to any price control rule. Given the asymmetry between firms, I focus on asymmetric regulation in that the regulator sets the access price for the incumbent but not for the entrant. This is a realistic assumption in light of various access price controls imposed on historical incumbents in a number of countries, however, not on entrants.

3.1 Free market: duopoly case

I assume that competition law applies in the free market case and a firm cannot make an agreement with another firm to only sell access, i.e. the former firm restricts its downstream sales to zero so that the latter is a monopolist. The description of the free market equilibrium is as follows. None of the firms is willing to invest in areas of low population density, while NGA duplication is expected in areas of high population density. In the areas of intermediate population density there are two possible coverage scenarios. If the competitive advantage for the incumbent is strong, then only the incumbent will invest in those intermediate areas. If the competitive advantage for the incumbent is not strong, then it will be uncertain which firm

[21] See Vives (1987) for a formalization of the Marshallian idea on small income effects. In 2008, telecommunications revenue as percentage of GDP was less than 2.6% in the Euro area and 4.3% in the UK. In 2005, the figure was slightly less than 3.1% in the US and less than 3.2% worldwide. Source: International Telecommunication Union World Telecommunication Development Report and database and World Bank estimates, available at http://www.econstats.com/wdi/wdiv_617.htm.

will invest in those intermediate areas, i.e. it is unprofitable to build a second NGA infrastructure in those areas, but it is unclear which firm will be the first.

3.2 Fixed access price

Two main reasons explain the need for regulation at the wholesale level in this facility-based competition model. One reason is significant market power which drives to static inefficiency, particularly in areas where only one firm has deployed NGA and the access price is set at the monopoly level. Another reason is because NGA coverage generates greater social welfare value than the value captured by the investing firms and some socially desirable NGA coverage will not be undertaken by firms which leads to investment inefficiency.

In this section I set out the coverage game equilibria in an area z with a fixed access price and the impact of access price regulation on static and investment efficiency. In the following section I set out the coverage game equilibria with access price indexation and compare the outcomes against those with a fixed access price.

Coverage game equilibria

Table 4 below sets out the payoffs of the coverage game in an area z with a fixed access price, where firm 2 can set its access price at $a_{2,t} = a_{2,t}^{I,N} = \frac{1}{2}\frac{\gamma^2+8}{\gamma+8}$ to maximize its profit, while $a_{1,t}$ is set by the regulator.

Table 4: Payoffs of the coverage game with fixed access prices in an area z

		Firm 2	
		N	I
Firm 1	N	0; 0	$\frac{4(1-\gamma)\sum_{t=1}^{2}\left(1-a_{2,t}\right)^2}{(4-\gamma)^2}$; $\frac{\sum_{t=1}^{2}\left(1-a_{2,t}\right)\left(\gamma(1-\gamma)+(\gamma+8)a_{2,t}\right)}{(4-\gamma)^2}-c(z)$
	I	$\frac{8\gamma(1-\gamma)+(8+\gamma)\sum_{t=1}^{2}a_{1,t}\left(\gamma-a_{1,t}\right)}{\gamma(4-\gamma)^2}-c(z)$; $\frac{(1-\gamma)\sum_{t=1}^{2}\left(\gamma-2a_{1,t}\right)^2}{\gamma(4-\gamma)^2}$	$\frac{8(1-\gamma)}{(4-\gamma)^2}-c(z); \frac{2\gamma(1-\gamma)}{(4-\gamma)^2}-c(z)$

Let $\tau_{i,l}^*$ denote the threshold regarding the coverage cost per area below which firm i chooses I, given the strategy l of the competitor.

If firm 2 chooses N, then firm 1 chooses I if $\frac{8\gamma(1-\gamma)+(8+\gamma)\sum_{t=1}^{2}a_{1,t}\left(\gamma-a_{1,t}\right)}{\gamma(4-\gamma)^2}-c(z)\geq 0 \Leftrightarrow \tau_{1,N}^*\equiv \frac{8\gamma(1-\gamma)+(8+\gamma)\sum_{t=1}^{2}a_{1,t}\left(\gamma-a_{1,t}\right)}{\gamma(4-\gamma)^2}\geq c(z)$, otherwise firm 1 chooses N.

If firm 2 chooses I, then firm 1 chooses I if $\frac{8(1-\gamma)}{(4-\gamma)^2}-c(z)\geq\frac{4(1-\gamma)\sum_{t=1}^{2}\left(1-a_{2,t}\right)^2}{(4-\gamma)^2}\Leftrightarrow \tau_{1,I}^*\equiv\frac{8(1-\gamma)}{(4-\gamma)^2}-\frac{4(1-\gamma)\sum_{t=1}^{2}\left(1-a_{2,t}\right)^2}{(4-\gamma)^2}\geq c(z)$, otherwise firm 1 chooses N.

If firm 1 chooses N, then firm 2 chooses I if $\frac{\sum_{t=1}^{2}\left(1-a_{2,t}\right)\left(\gamma(1-\gamma)+(\gamma+8)a_{2,t}\right)}{(4-\gamma)^2}-c(z)\geq 0\Leftrightarrow \tau_{2,N}^*\equiv\frac{\sum_{t=1}^{2}\left(1-a_{2,t}\right)\left(\gamma(1-\gamma)+(\gamma+8)a_{2,t}\right)}{(4-\gamma)^2}\geq c(z)$, otherwise firm 2 chooses N.

If firm 1 chooses I, then firm 2 chooses I if $\frac{2\gamma(1-\gamma)}{(4-\gamma)^2}-c(z)\geq\frac{(1-\gamma)\sum_{t=1}^{2}\left(\gamma-2a_{1,t}\right)^2}{\gamma(4-\gamma)^2}\Leftrightarrow \tau_{2,I}^*\equiv\frac{2\gamma(1-\gamma)}{(4-\gamma)^2}-\frac{(1-\gamma)\sum_{t=1}^{2}\left(\gamma-2a_{1,t}\right)^2}{\gamma(4-\gamma)^2}\geq c(z)$, otherwise firm 2 chooses N.

It can be shown that $\tau_{i,I}^*\leq\tau_{i,N}^*$ for any non-negative $a_{i,t}$. Note that $\pi_{i,z}^{I,I}$ is simultaneously the minimum of $\tau_{i,N}^*$ (reached at $a_{i,t}=0$) and the maximum of $\tau_{i,I}^*$ (reached at $a_{i,t}$ such that $\pi_{i,z}^{N,I}=0$). Also, $\tau_{2,I}^*<\tau_{1,N}^*$ for any $0\leq a_{1,t}\leq a_{1,t}^{I,N}=\frac{\gamma}{2}$.

Impact of access price regulation on static efficiency

In the absence of regulatory intervention, when the incumbent is the only investing firm in NGA infrastructure in an area, it preempts the market for NGA. In this case, the entrant firm can compete if and only if the access price is set below the monopoly price $a_{1,t}^{I,N} = \frac{\gamma}{2}$. Below I verify that access price regulation increases social welfare in geographical areas where only the incumbent has invested in NGA coverage.

The social welfare over the 2-period game in an area z where only the incumbent has invested in NGA coverage is $W(a_{1,1}, a_{1,2}) = CS_z(a_{1,1}, a_{1,2}) + \pi_{1,z}^{I,N}(a_{1,1}, a_{1,2}) - c(z) + \pi_{2,z}^{N,I}(a_{\{1,1\}}, a_{\{1,2\}})$, where $CS_z(a_{1,1}, a_{1,2}) \equiv \sum_{t=1}^{2} CS_{z,t}(a_{1,t})$ with $CS_{z,t}(p_{1,z,t}, p_{2,z,t})$ in (9), $p_{1,z,t}(a_{\{1,t\}}) = \frac{2(1-\gamma)+3a_{1,t}}{4-\gamma}$, $p_{2,z,t}(a_{1,t}) = \frac{(1-\gamma)\gamma+(2+\gamma)a_{1,t}}{4-\gamma}$, $\pi_{1,z}^{I,N} = \frac{8\gamma(1-\gamma)+(8+\gamma)\sum_{t=1}^{2} a_{1,t}(\gamma-a_{1,t})}{\gamma(4-\gamma)^2}$ and $\pi_{2,z}^{N,I} = \frac{(1-\gamma)\sum_{t=1}^{2}(\gamma-2a_{1,t})^2}{\gamma(4-\gamma)^2}$. Hence,

$$\frac{dW(a_{1,1}, a_{1,2})}{da_{1,t}} = -\frac{4\gamma(1-\gamma) + (5\gamma+4)a_{1,t}}{\gamma(4-\gamma)^2} < 0$$

implying that if the incumbent has a monopoly over the new infrastructure in an area z, the lower the access price is, the higher the social welfare will be. This is explained by the demand expansion for NGA services.

Impact of access price regulation on investment efficiency

Below I verify the impact of the incumbent's access price, $a_{1,t}$, on NGA coverage.

$$\frac{d\tau_{1,N}^*}{da_{1,t}} = (\gamma+8)\frac{\gamma-2a_{1,t}}{\gamma(4-\gamma)^2} \geq 0 \text{ for } a_{1,t} \leq \frac{\gamma}{2} \equiv a_t^{mon},$$

$$\frac{d\tau_{1,I}^*}{da_{1,t}} = \frac{d\tau_{2,N}^*}{da_{1,t}} = 0, \text{ and}$$

$$\frac{d\tau_{2,I}^*}{da_{1,t}} = 4(1-\gamma)\frac{\gamma-2a_{1,t}}{\gamma(4-\gamma)^2} \geq 0 \text{ for } a_{1,t} \leq \frac{\gamma}{2} \equiv a_t^{mon}.$$

The signs of the derivatives above show that setting the incumbent's access price below the monopoly level will result in less NGA investment than in the free market outcome. Such type of regulation extends the region where none of the firms wishes to invest, i.e. $\frac{d\tau_{1,N}^*}{da_{1,t}} \geq 0$. Furthermore, the area of facility-based competition is reduced even in areas with high population density, i.e. $\frac{d\tau_{2,I}^*}{da_{1,t}} \geq 0$.

The analysis above suggests the existence of a regulatory trade-off between increasing social welfare in areas where only the incumbent owns a NGA infrastructure and promoting NGA coverage. The optimal balance between static and investment efficiency may depend on whether infrastructure duplication is considered socially desirable. Duplication results in a waste of resources and is inefficient in the absence of regulatory costs insofar as the regulator can implement the equivalent to a competitive outcome while avoiding the cost of duplication. However, in practice, less facility-based competition may extend the need for access price regulation over time, which may entail significant regulatory cost.

3.3 Access price indexation

In this section I set out the coverage game equilibria with access price indexation and compare the outcome to that obtained under the fixed access price.

Let $\int_{\Omega} \Delta\pi_{1,z}(z)dz \geq 0$ denote the incremental profit for firm 1 from the set of inframarginal areas $\Omega \subset [0, \bar{K}]$ covered with NGA that firm 1 receives as a result of an increase of the access price $a_{1,t}$ when firm 1 covers a marginal area with NGA.

If firm 2 chooses N, then firm 1 chooses I if $\frac{8\gamma(1-\gamma)+(8+\gamma)\sum_{t=1}^{2} a_{1,t}(\gamma-a_{1,t})}{\gamma(4-\gamma)^2} - c(z) + \int_{\Omega} \Delta\pi_{1,z}(z)dz \geq 0 \Leftrightarrow \tau_{1,N}^{**} \equiv \frac{8\gamma(1-\gamma)+(8+\gamma)\sum_{t=1}^{2} a_{1,t}(\gamma-a_{1,t})}{\gamma(4-\gamma)^2} + \int_{\Omega} \Delta\pi_{1,z}(z)dz \geq c(z)$, otherwise firm 1 chooses N.

If firm 2 chooses I, then firm 1 chooses I if $\frac{8(1-\gamma)}{(4-\gamma)^2} - c(z) + \int_{\Omega} \Delta\pi_{1,z}(z)dz \geq \frac{4(1-\gamma)\sum_{t=1}^{2}(1-a_{2,t})^2}{(4-\gamma)^2} \Leftrightarrow \tau_{1,I}^{**} \equiv \frac{8(1-\gamma)}{(4-\gamma)^2} - \frac{4(1-\gamma)\sum_{t=1}^{2}(1-a_{2,t})^2}{(4-\gamma)^2} + \int_{\Omega} \Delta\pi_{1,z}(z)dz \geq c(z)$, otherwise firm 1 chooses N.

For firm 2, $\tau_{2,N}^{**} = \tau_{2,N}^{*}$ and $\tau_{2,I}^{**} = \tau_{2,I}^{*}$. Proposition 4 below summarizes the comparison between equilibria under access price indexation and fixed access prices.

Proposition 4 (indexation vs fixed access prices under facility-based competition) *Compared to a fixed access price, with an access price rule depending on NGA coverage for firm 1: (i) the total area with NGA coverage is at least the same and potentially wider, (ii) the NGA infrastructure duplication is at least the same and potentially higher, and (iii) the impact on the size of the multiple equilibria area, i.e. the area where it is uncertain by which of the firms it will be covered with NGA, is unclear.*

Given the conditions $\tau_{i,I}^{*} \leq \tau_{i,N}^{*}$ for any non-negative $a_{i,t}$, and $\tau_{2,I}^{*} < \tau_{1,N}^{*}$ for any $0 \leq a_{1,t} \leq a_{1,t}^{I,N} = \gamma/2$ derived above, Table 5 below sets out the only five feasible scenarios and the respective impact assessment of the indexation approach, compared to a fixed access price, under each one of them. Under indexation both $\tau_{1,I}^{*}$ and $\tau_{1,N}^{*}$ increase to $\tau_{1,I}^{**}$ and $\tau_{1,N}^{**}$, respectively, while $\tau_{2,N}^{**} = \tau_{2,N}^{*}$ and $\tau_{2,I}^{**} = \tau_{2,I}^{*}$. In Table 5, column "Areas with NGA" shows the variation in the total number of areas where at least one NGA has been deployed; column "NGA infrastructure duplication" shows the variation in the total number of areas where there is NGA infrastructure duplication; and column "Areas of uncertainty" shows the variation in the total number of areas where it is uncertain whether it will be covered with NGA by firm 1 or firm 2, i.e. these are the areas of multiple equilibria.

Table 5: Impact assessment of the indexation approach under each feasible scenario

Scenarios	Areas with NGA	NGA infrastructure duplication	Areas of uncertainty
1. $\tau^*_{2,I} < \tau^*_{1,I} < \tau^*_{2,N} < \tau^*_{1,N}$	+	=	-
2. $\tau^*_{2,I} < \tau^*_{2,N} < \tau^*_{1,I} < \tau^*_{1,N}$	+	=	=
3. $\tau^*_{1,I} < \tau^*_{2,I} < \tau^*_{2,N} < \tau^*_{1,N}$	+	+	= or -
4. $\tau^*_{1,I} < \tau^*_{2,I} < \tau^*_{1,N} < \tau^*_{2,N}$	+ or =	+	+ or = or -
5. $\tau^*_{2,I} < \tau^*_{1,I} < \tau^*_{1,N} < \tau^*_{2,N}$	+ or =	=	+ or = or -

Note: + (-) [=] means a positive (negative) [no] variation compared to a fixed access price.

In scenario 1, the total NGA coverage is defined by $\tau^*_{1,N}$ and with the indexation $\tau^*_{1,N}$ increases to $\tau^{**}_{1,N}$. Thus, it is straightforward that the total number of areas with NGA coverage will expand with indexation. The area of NGA infrastructure duplication, i.e. with equilibrium (I, I), is in the range $0 \leq c(z) \leq \tau^*_{2,I}$. Given that the indexation does not affect $\tau^*_{2,I}$, in scenario 1 there is no variation in infrastructure duplication due to indexation. The area of multiple equilibria is in the range $\tau^*_{1,I} \leq c(z) \leq \tau^*_{2,N}$, with $\tau^*_{1,I}$ increasing to $\tau^{**}_{1,I}$ under indexation where $\tau^{**}_{1,I}$ may be lower or higher than $\tau^*_{2,N}$. If $\tau^{**}_{1,I} \leq \tau^*_{2,N}$, it is straightforward that the area of multiple equilibria will be smaller with indexation, while if $\tau^*_{2,N} < \tau^{**}_{1,I}$, then this is equivalent to scenario 2, where no areas of uncertainty exist. A similar analysis can be done for each one of the remaining scenarios to derive the variations set out in Table 5 above.

The incentives for additional investment brought about by indexation result in at least the same but potentially wider NGA coverage and infrastructure duplication than with a fixed access price. However, the effects of indexation in terms of areas of multiple equilibria are unclear. On the one hand, indexation may break investment uncertainty in some areas by transforming multiple equilibria into single equilibrium areas where only firm 1 invests. On the other hand, the introduction of indexation may transform single equilibrium areas that would be covered by firm 2 only, into areas of multiple equilibria where either firm 1 or 2 (but not both) may deploy NGA. These results are robust to an assumption that firm 2 (not subject to a price control) can set a two-part access price in an area z, at time t. The results with two-part access prices are qualitatively similar to those obtained under linear access prices.

4 DISCUSSION

In this section I discuss further the features of access price indexation and the robustness of the results set out above with regard to: multiple regulated firms, national vs geographical retail prices, observability and verifiability, and uncertainty and asymmetric information.

4.1 Multiple regulated infrastructures

I assumed that only the incumbent firm is regulated. Henriques (2011) considered the case of two regulated symmetric infrastructures (firms) assuming no geographic overlap, but the main conclusions concerning economic efficiency are qualitatively similar to those in this paper. He studied access prices for infrastructures that increased with their own coverage, and simultaneously decreased with the rival's. The author showed that access prices indexed to the NGA coverage of both competing infrastructures incentivized further coverage from both firms when compared to a fixed access price. This is because a wider NGA coverage by a firm allows it to charge more for access to its infrastructure and simultaneously pay less when accessing the rival's, granting a competitive advantage in retail prices to the investing firm. Henriques (2011) showed that the additional investment attained due to indexation decreases with retail service differentiation (a competitive advantage in marginal costs is less important with higher service differentiation).

4.2 National vs geographical retail prices

I assumed that firms can price discriminate at the retail level across different geographies. Henriques (2011) considered the case of national retail prices, where geographical discrimination is difficult to implement for exogenous reasons, and horizontal differentiation à la Hotelling. The author showed that access price indexation can expand NGA coverage without increasing the national retail prices. National retail prices may be construed as an average across the retail prices that would have been set in the different geographical areas. Compared to fixed access prices, the national retail prices will decrease with access price indexation because it: (i) puts downward pressure on the access prices; and (ii) expands the NGA coverage while the marginal cost of serving a consumer decreases to zero in areas covered with own infrastructure.

4.3 Observability and verifiability

The assumption that geographical coverage of fibre broadband is observable and verifiable to a third party is fundamental for access price indexation to fulfil its intended outcomes. In this section, I discuss the reasonableness of that assumption, considering that firms may have an incentive to use the access price indexation to increase their own profits. To gain a competitive advantage at the downstream level and, ultimately, increase profits, a regulated firm may have an incentive to report a wider geographical coverage than it owns.

Regulators may at least partially observe and verify at some cost the coverage of fibre optic infrastructures. The economics of fibre deployment is usually characterized by high fixed costs of which the dominant component is the civil works: digging the roads (including obtaining construction permits) and laying ducts, whose existence is observable and verifiable.[22] Moreover, regulators engage with stakeholders in the sector. Therefore, if a regulated firm reports a fibre coverage that it does not own, eventually an access seeker will become aware of that fact and expose such misconduct.[23] Also, the quality of fibre networks may be inferred from fault rate information, consumer complaints and a number of websites that allow testing of broadband speeds.[24] Some regulators also produce maps showing accurate information on broadband take-up, speeds and availability.[25]

A further option to tackle potential unintended consequences of indexation is to attach a price floor and a price cap to the access price indexation rule. For example, the regulator may set a price cap equal to the expected optimal fixed access price and a price floor at the expected access price under the indexation approach. This guarantees that in the event of a mistaken calibration of the indexation rule or a coverage misreport by the regulated firm, the equilibrium access price will still be within a reasonable range, which to some extent reduces uncertainty to the industry.

4.4 Uncertainty and asymmetric information

The comparison between a fixed access price and access price indexation was set out on the basis that there is no uncertainty about cost or demand for NGA, and no asymmetric information between regulator and regulated firm. The analysis suggests that, with low levels of uncertainty and asymmetric information, the access price indexation is a more efficient

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[22] Pole distribution may be the norm in some areas; direct buried cable can be used as well.

[23] For example, when firms request access in an area that is allegedly covered with fibre by the regulated firm while, in fact, it is not. In this case, given the mechanics of access price indexation, access seekers have an incentive to report such type of misconduct to pay lower access prices. Other ways to obtain relevant information from the regulated firm include: obligation to publish regulatory statements on a regular basis, and formal information requests.

[24] For example, see http://www.speedtest.net.The process is as easy as a click of a button.

[25] For example, see http://maps.ofcom.org.uk/broadband,where broadband availability and speeds for any UK address can be checked. Ofcom also produces regular infrastructure report updates, e.g. https://www.ofcom.org.uk/research-and-data/infrastructure-research.

regulatory approach than fixed access prices, i.e. the regulator can achieve higher welfare levels with the former, rather than the latter.

Uncertainty is as much a problem under the indexation approach as it is under the fixed access price approach. If uncertainty is construed as an increase in the minimum expected return that a firm is willing to accept to cover an area with NGA, then it may be modelled as an increment of the cost curve of NGA coverage. In this case, if uncertainty does not alter the properties of $C(k)$ in the facility-based competition model (e.g. if uncertainty is decreasing and convex with population density) and information is symmetric between regulator and regulated firm, it is straightforward that the results on access price indexation extend to scenarios of uncertainty.[26] Moreover, the indexation approach may incentivize the NGA coverage of areas with higher levels of uncertainty. See Bourreau, Cambini and Hoernig (2018) on how regulatory regimes are affected in the presence of demand uncertainty.

For a regulator, the risks from inadvertently setting price controls either above or below actual cost are usually asymmetric. If the price control is set "too high" there is a sacrifice of static efficiency. If the price is set "too low", the sustainability of the firm is put at risk, and even if the firm is able to continue to operate it might strongly affect investment decisions in the sector in the long-run, and ultimately harm social welfare. For example, if the regulator is relatively more averse to set a price "too low", rather than "too high", it might base the price control decisions on a cost curve $C^{+}(k) > C(k)$, for $0 \leq k \leq \overline{K}$, to mitigate that risk. If regulator and firm hold the same information, it is expected that the indexation approach must weakly do better than a fixed price since with indexation the regulator can choose to set the same price at all investment levels. However, if the regulator's risk aversion to a "too low" price controls is sufficiently high, it may prefer not to set a price control at all.

Regulators are often at an informational disadvantage relative to regulated firms. In light of such asymmetry, a profit maximizing firm may have an incentive to overstate the cost and / or understate the demand to influence the regulator to set a "softer" price control (i.e. "gaming" the price control). This means that if the regulator was to set an indexation rule based on biased information, the firm could face a more favourable menu of options in terms of profit. The regulator may consider combining the indexation approach with other complementary regulatory instruments such as a price cap to mitigate the scope for gaming by the firm. In extreme cases of asymmetric information, e.g. the regulator only holds a forecast of the network cost at the national level, and not the cost of deploying NGA in uncovered areas, the indexation approach might prove impractical.

[26] This is subject to the existence of areas where the uncertainty-adjusted coverage cost is below the monopoly revenue. Otherwise, no NGA coverage would be feasible.

5 CONCLUSIONS

Investment incentives have been at the core of the access debate. Some authors argue that networks will not invest in facilities subject to strong access regulation, e.g. Sidak and Spulber (1996). Others have supported the idea of forced access because of the gains in static efficiency, but advise that the access price must take into account investment incentives, e.g. Laffont and Tirole (2001). This paper contributes to this debate with a suggestion of access price controls indexed to investments in geographic coverage.

The access price proposed as a function of geographic coverage exhibits features both from the rate-of-return and the incentive regulation approaches. In particular, a wider coverage entitles the regulated firm to charge higher prices (rate-of-return), but only to the extent that those investments are efficiently incurred (incentive regulation, i.e. the indexation incentivizes the regulated firm to minimize expenditure when covering additional areas). Also, the access price indexation is consistent with the "ladder of investment" insofar as access prices are expected to increase over time as the geographic coverage of the innovative service expands (Avenali et al, 2010). Thus, this signals to access seekers, particularly new entrants without a critical mass of customers, that their business models should not rely on the unlimited availability of low cost access services and that some form of facility-based competition is expected to take place in the future.

The results suggest that an access price indexation can improve investment efficiency without sacrificing retail price efficiency, and ultimately enhance social welfare vis-à-vis a fixed access price. This is possible because with the access price indexation the regulated firm is rewarded with an increase in the access price in all (i.e. marginal and inframarginal) areas for covering a marginal area with an innovative service. Under a fixed access price, the incremental net revenue of covering an additional area is the profit from that area only. However, under the indexation approach the incremental net revenue of covering an additional area is the profit from that area plus the incremental profit from all inframarginal areas already covered with the innovative service. Thus, to achieve the same level of geographical coverage, the regulated firm will require a lower access price under indexation than with a fixed access price or, alternatively, for a same equilibrium access price, the regulated firm invests more under indexation than with a fixed access price. The indexation may expand the area of infrastructure duplication promoting more facility-based competition than a fixed access price. This feature may reduce the need for access price regulation more quickly and save the respective regulatory cost. Moreover, in the model, the indexation may be used to achieve the Ramsey outcome, or the first-best coverage level. This suggests that access price indexation is a potential tool to reduce the need for public subsidies for fibre deployment and the respective tax distortions when compared to a fixed access price.

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http://www.speedtest.net

APPENDIX

Proof of Proposition 1 From (2) I have that $k^*(a) = a\frac{\alpha - a}{c\beta}$, while $k^{mon} = \frac{1}{4}\frac{\alpha^2}{c\beta}$, $k^{Ramsey} = \frac{3}{8}\frac{\alpha^2}{c\beta}$ and $k^{FB} = \frac{1}{2}\frac{\alpha^2}{c\beta}$. It is straightforward that $k^{mon} < k^{Ramsey} < k^{FB}$. The maximum level of coverage under a fixed access price is

$$\max_{a} k^*(a)$$

$$FOC: \frac{dk^*(a)}{da} = \frac{\alpha - 2a}{c\beta} = 0 \Leftrightarrow a = p^{mon} = \frac{\alpha}{2}$$

$$SOC: \frac{d^2k^*(a)}{da^2} = -\frac{2}{c\beta} < 0.$$

Hence, $k^*(a) \leq \max_{a} k^*(a) = k^*(p^{mon}) = k^{mon} < k^{Ramsey} < k^{FB}$.

Proof of Proposition 2 (i) From (3) I have that $k^* = \frac{2}{9}\frac{\alpha^2}{c\beta}$, while from (4) I have that $k^{**} = \frac{5}{16}\frac{\alpha^2}{c\beta}$. Hence, it is straightforward that $k^{**} > k^*$.

(ii) From (3) I have that $q^* = \frac{2}{3}\frac{\alpha}{\beta}$, while from (4) I have that $q^{**} = \frac{3}{4}\frac{\alpha}{\beta}$. Hence, it is straightforward that $q^{**} > q^*$.

(iii) From (3) I have that $W^* = \frac{6}{81}\frac{\alpha^4}{c\beta^2}$, while from (4) I have that $W^{**} = \frac{50}{512}\frac{\alpha^4}{c\beta^2}$. Hence, it is straightforward that $W^{**} > W^*$.

Proof of Proposition 3 (i) See Stage III: retail price competition, Stage II: coverage and Stage I: Ramsey outcome under the heading "Generalized access price indexation".

(ii) See Stage I revisited: first-best coverage level under the heading "Generalized access price indexation".

Proof of Proposition 4 See Table 5.

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