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Coexistence of copper and fiber unbundling: Access charges and investment incentives

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Abstract

We study the impact of the access charges of copper and fiber unbundling on an incumbent's incentives to invest in fiber access networks. Once the fiber deployment is in place, the incumbent and the entrant compete for consumers in both copper and fiber markets. We show that when the regulator can freely set either the copper or the fiber access charge, there is a positive correlation between the fixed fiber (respectively, copper) access charge and the copper (respectively, fiber) access charge that maximizes the incumbent's profit after the investment. On the contrary, when the regulator is free to set both access charges, the incumbent's profit is an increasing function of both access charges. However, the decision of the incumbent to undertake the investment in fiber deployment is not only affected by its profit after the investment, but also by the opportunity cost of the investment. This cost is reflected by the profits that the incumbent earns when it does not invest in fiber access networks, and hence, the two firms compete for the provision of only copper-based services. We find that the optimal regulatory policy in terms of investment incentives is to set the copper access charge at the cost of providing the access to the copper access network and the fiber access charge at the level that maximizes the incumbent's profit after the investment. It should be noted that the proposed regulatory policy confirms the methodology of the EC Recommendation (2013/466/EU) for setting the copper and fiber access charges in order to promote competition and enhance the broadband investment environment.

Keywords: Access regulation; Copper unbundling; Fiber unbundling; Investment incentives; Telecommunications.

JEL codes: L51; L96.

1. Introduction

The role of regulation in promoting investments in next generation fiber access networks has recently attracted much research interest since the advent of ultra-fast broadband services delivered via such networks are expected to positively affect the society and the economy as a whole (Czernich, Falck, Kretschmer, & Woessmann, 2011; Katz, Vaterlaus, Zenhäusern, & Suter, 2010). Given that the social benefits from investment in digital infrastructures by far exceed the private incentive for investment (EC, 2011), the European Commission (EC) has issued two complementary Recommendations for promoting the transition from copper access networks to fiber-based Next Generation Access (NGA) networks (EC, 2010a, 2013a).

The ultimate goal of the European Commission is to fulfill the objectives of the Digital Agenda for Europe (EC, 2010b) which seeks to ensure that, by 2020: (i) all Europeans will have access to much higher internet speeds of above 30Mbps; and (ii) 50% or more of European households will subscribe to internet connections above 100Mbps. Although broadband technologies capable of providing at least 30 Mbps are available to 53.8% of homes as of end of 2012, 100Mbps lines are really scarce in Europe since there is one line per 100 inhabitants, which translates to around 2% of homes (EC, 2013b).

Therefore, access regulation to NGA networks should clearly promote investments in fiber access infrastructures without distorting the competitive structure inherited from copper unbundling. In this respect, many theoretical and empirical articles focus on studying the impact of several forms of access regulation on firms' incentives to invest in fiber access networks.¹ The majority of these papers conclude that an access pricing policy that boosts efficient entry and promotes service-based competition within one network not only discourages operators to invest in new access infrastructures, but also results in a substantial deviation from the socially desirable outcomes in terms of network deployment and timing of investments, thus implying significant losses in dynamic efficiency (Bouckaert, van Dijk, & Verboven, 2010). All these studies focus on the regulation of the fiber access networks since they assume that the copper access networks are switched off immediately after the fiber deployment. In other words, consumers cannot choose between the old and the new technology, and hence, the migration from copper to fiber is not examined.

Only recently, a new stream of literature has studied the migration issue by explicitly taking into account that both technologies will coexist for a certain period of time. A first branch of this literature considers a setting in which the two technologies can coexist, but when an operator invests in fiber deployment, it completely replaces its copper access network. In this context, Bourreau, Cambini, & Doğan (2012) study the impact of the access charge (or access price) of copper unbundling on the decision of each firm to extend its fiber deployment to more geographic areas, whereas Brito, Pereira, & Varela (2012) assume that the fiber deployment covers all geographic

¹ See Tselekounis (2013, section 3.2.2) for a recent review of the literature focusing on the impact of cost-based regulation on operators' investment incentives and Tselekounis, Varoutas, & Martakos (2014) for a survey of the impact of alternative regulatory instruments on incentives to invest in NGA networks.

areas and the investment cost is fixed. Inderst & Peitz (2012) provide a more general picture of investment incentives covering a variety of settings.²

Contrary to the above articles which consider regulation of access only to the copper access networks, Bourreau, Cambini, & Doğan (2014) study the effect of the access prices for both copper and fiber access networks on firms' investment incentives. They find that when the incumbent (respectively, the entrant) is the leader in fiber deployment, the access price to the fiber network is positively (respectively, negatively) correlated with the access price to the copper network. The main policy implication is that the regulators cannot treat the two access prices independently. However, Bourreau, Cambini, & Doğan (2014) also assume that when an operator invests in NGA networks, it no longer employs the copper network to provide broadband services.

To the best of authors' knowledge, the only paper that considers coexistence of technologies and services is Bourreau, Lupi, & Manenti (2013). In particular, they assume that each firm provides two quality differentiated services, the lower (respectively, the higher) quality of which is based on the copper (respectively, fiber) technology. In addition, the incumbent initially owns a better quality copper access network, whereas the quality advantage in the fiber technology depends on the firms' investment decisions. As a result, consumers are vertically differentiated with respect to their preference for the quality of the existing services. They find that the access price to the copper access network might not be adequate to induce the efficient migration from copper to fiber access networks.

We complement the work of Bourreau, Cambini, & Doğan (2014) by assuming coexistence of services, as well as the work of Bourreau, Lupi, & Manenti (2013) by studying the interplay between the access prices to the copper and the fiber access networks. In other words, this paper is the first formal attempt to study the impact of copper and fiber access prices on an incumbent's NGA investment incentives when each operator provides two quality differentiated services over the copper and, respectively, the fiber access networks.

Our main finding is that the incumbent is more likely to undertake the investment in fiber access networks when the copper access charge is priced at the cost of providing the access to the copper access network and the fiber access charge is priced at the level that maximizes the incumbent's profit after the investment. This access pricing policy is in line with the EC Recommendation (EC, 2013a), which aims to present the basic principles for setting the copper and the fiber access charges so as to encourage the migration to NGA networks, and hence, the fulfillment of the objectives of the Digital Agenda for Europe.

The rest of the paper is structured as follows. Section 2 presents the basic assumptions and definitions of the model. Section 3 derives the equilibrium of the game when there is competition only for the copper-based broadband services (non-investment case) and when there is competition for both copper-based and fiber-based broadband services (investment case). Section 4 studies the impact of copper and fiber access charges on the incumbent's profit after the investment, whereas Section 5 discusses

² Cambini & Silvestri (2012), Neumann & Vogelsang (2013), Plum Consulting (2011) and WIK (2011) also study the impact of copper access price on firms' investment incentives using various approaches and focusing on alternative goals.

the regulatory implications of the derived results. The last section summarizes and proposes the directions for future research.

2. The model

The retail (downstream) market is characterized as an unregulated duopoly in which an incumbent ($i=I$) and an entrant ($i=E$) compete for consumers according to the standard Hotelling model. The incumbent owns the copper access (upstream) network, whereas the entrant seeks access to the incumbent's facilities in order to supply its consumers with its services. This implies that the two firms initially provide only horizontally differentiated services over the copper access network of the incumbent.

The two rivals are located at the two extremities of a horizontal axis of length 1 which represents the market of the basic broadband services. The incumbent is located at point $x_I = 0$ and the entrant is located at point $x_E = 1$. Consumers are uniformly distributed on the unit interval $[0,1]$ and are endowed with utility $U = v - p_i - t(x_i - x)$. The term p_i denotes the price at which each provider supplies its final service. The term $t|x - x_i|$ can be interpreted as the linear disutility for purchasing a service different from the most preferred one. The term v reflects the consumers' reservation price for purchasing the basic (copper-based) broadband services and it is assumed that it exceeds the sum of price and linear disutility in order to ensure that each consumer buys one unit of the final service. The entrant can have access to the incumbent's copper access network at a regulated per-unit price w^c , whereas the incumbent's unit cost of providing access to its facilities is denoted by c_I^c .

Now consider the case where the incumbent can invest in new fiber access infrastructures. The investment cost of deploying a fiber access network capable of providing a particular service of an enhanced quality is fixed and denoted by F . Each firm provides two quality differentiated services denoted by k : a horizontally differentiated copper-based service and a horizontally differentiated fiber-based service (thus $k = c, f$). The incumbent's unit cost of providing access to its copper and fiber access facilities are denoted, respectively, by c_I^c and c_I^f . The entrant provides its copper-based final service using the incumbent's copper access network at a regulated per-unit price w^c and its fiber-based final service using the incumbent's fiber access network at a regulated per-unit price w^f .

The whole industry is modeled as a unit square (see figure 1). The top horizontal axis represents the market of the basic broadband services provided over the incumbent's copper access network and the last horizontal axis represents the market of ultra-fast broadband services provided over the incumbent's fiber access network. The incumbent is located at the left corners of the square and the entrant is located at the right corners of the square. The locations of each firm are denoted by (x_i, y_j) , $i, j = I, E$. Therefore, the incumbent is located at $(0,0)$ and the entrant at $(1,0)$ along the top horizontal axis. Furthermore, the incumbent is located at $(0,1)$ and the entrant at $(1,1)$ along the last horizontal axis.

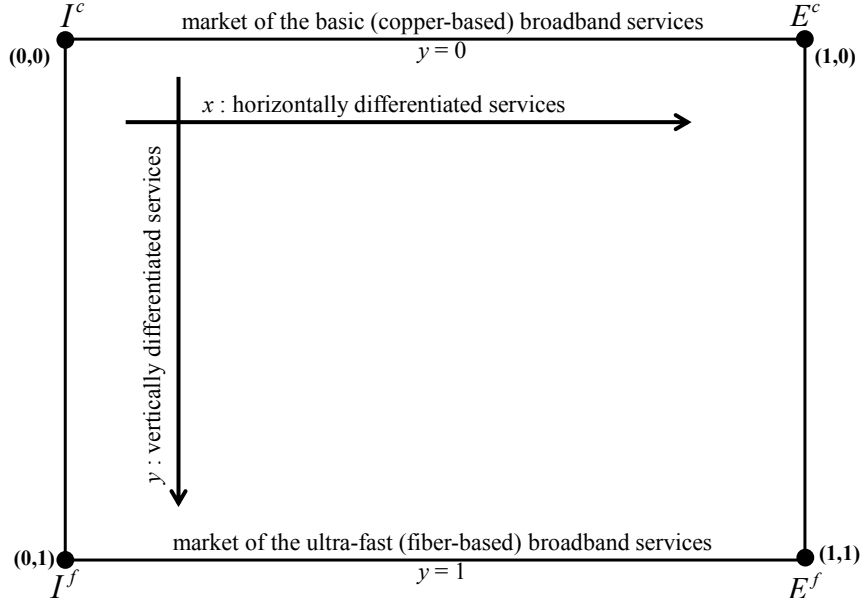


Figure 1: The whole industry modeled as a unit square

Consumers are uniformly distributed across the unit square. The location of each consumer is given by (x, y) with $x \in [0, 1]$ and $y \in [0, 1]$. This implies that once the fiber access network has been deployed, the consumers place a different valuation to the quality of the supplied services. Higher values of x imply a higher preference for the entrant's services, whereas higher values of y imply a higher valuation for the fiber-based services. This means that consumers are both horizontally and vertically differentiated according to their preference for the services supplied by each firm and the provided quality.

Therefore, each consumer is endowed with utility $U_j^k = V + \vartheta_j \cdot y - p_i^k - t|x - x_i| - s|y - y_j|$ according to its location (x, y) on the unit square. The term $t|x - x_i|$ can be interpreted as the linear disutility for purchasing a horizontally differentiated service different from the most preferred one, whereas the term $s|y - y_j|$ can be interpreted as the linear disutility which the consumer located at point $y \in [0, 1]$ incurs due to the use of a technology which is not the most preferred one. Note that the consumers' reservation price for the copper-based service increases by the term $(\vartheta_j \cdot y)$ as y increases as well. The term p_i^k represents the price at which each provider supplies each final service.

This modeling setup captures the fact that the market of broadband services is quite mature, and hence, the demand for ultra-fast broadband services provided over the fiber access networks will come from the consumers who already use the basic broadband services. However, given that each consumer places a different valuation to the fiber-based services, it is expected that each firm will provide both basic and ultra-fast broadband services. Therefore, the consumers have four options: (i) buy the basic, copper-based, service from the incumbent at price p_I^c ; (ii) buy the basic, copper-based, service from the entrant at price p_E^c ; (iii) buy the ultra-fast, fiber-based, service from the incumbent at price p_I^f ; and (iv) buy the ultra-fast, fiber-based, service from the entrant at price p_E^f .

The timing of the game is as follows: First, the regulator sets the access prices of the copper and fiber unbundling ensuring a non-negative profit margin for the incumbent in each access market. Thus, $w^c \geq c_I^c$ and $w^f \geq c_I^f$. Second, after observing these access prices, the incumbent decides whether to invest in new access facilities or not. Last, the incumbent and the entrant set the retail prices of the basic broadband services when the incumbent chooses not to invest, whereas the two firms set their prices for both basic and ultra-fast broadband services when the incumbent chooses to invest in fiber access facilities. Each consumer subscribes to one broadband service according to the available retail services and the corresponding retail prices.

3. Equilibrium of the game

This section provides the equilibrium of the game described in the previous section when: (i) the two firms provide only copper-based services (non-investment case); and (ii) each firm provides a horizontally differentiated copper-based service and a horizontally differentiated fiber-based service (investment case).

3.1. Non-investment case

Equating the utility derived when a consumer buys from the incumbent and the utility derived when a consumer buys from the entrant gives the location of the consumer who is indifferent between buying from the incumbent and the entrant. This indifferent consumer is located at \hat{x} and represents the market share of the incumbent (q_I).

$$q_I = \hat{x} = \frac{p_E - p_I}{2t} + \frac{1}{2} \quad (1)$$

Therefore, the market share of the entrant is given by $q_E = 1 - q_I$, where:

$$q_E = 1 - \hat{x} = \frac{p_I - p_E}{2t} + \frac{1}{2} \quad (2)$$

Figure 2 graphically presents the case where the two providers provide only horizontally differentiated services using the copper access network of the incumbent.

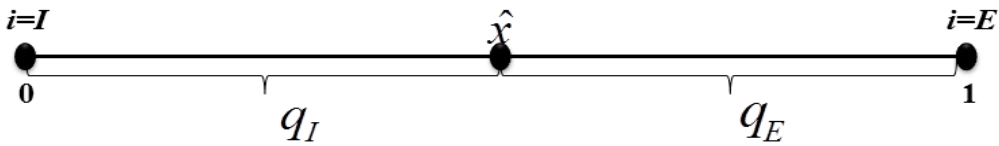


Figure 2: The retail market for only copper-based services

The profits functions for the incumbent and the entrant are given, respectively, by:

$$\Pi_I = [p_I - c_I^c]q_I + [w^c - c_I^c]q_E \quad (3)$$

$$\Pi_E = [p_E - w^c]q_E \quad (4)$$

Substituting Eqs. (1) and (2) into Eqs. (3) and (4), taking their first order condition with respect to p_I and p_E , respectively, and then solving together gives the profit-maximizing retail prices for the incumbent and the entrant:

$$p_I = t + w^c \quad (5)$$

$$p_E = t + w^c \quad (6)$$

Substituting Eqs. (5) and (6) into Eqs. (1) and (2) provides each provider's market share:

$$q_I = q_E = \frac{1}{2} \quad (7)$$

Moreover, substituting Eqs. (5), (6) and (7) into Eqs. (3) and (4) yields the profits for the incumbent and the entrant when they compete for providing only copper-based services:

$$\Pi_I = \frac{t}{2} + w^c - c^c \quad (8)$$

$$\Pi_E = \frac{t}{2} \quad (9)$$

3.2. Investment case

In this case, each firm provides a basic, copper-based, broadband service and an ultra-fast, fiber-based, broadband service. However, the two firms treat the two markets independently. This means that the retail prices for the basic broadband services are set by the firms according to the demand they face from the consumers located on the top horizontal axis, whereas the retail prices for the ultra-fast broadband services are set according to the demand they face from the consumers located on the last horizontal axis. In other words, the two firms set the retail price of their copper-based and fiber-based services by taking into account only the demand they face from the consumers who place the highest valuation to the basic (i.e. $y = 0$) and, respectively, the ultra-fast (i.e. $y = 1$) broadband service. The analytical solution of the latter case is given in Appendix A1.

The solution of the game concerning the market shares and the retail prices of the copper-based services is similar to the case where no investment has taken place since $\vartheta_j \cdot y = \vartheta_j \cdot 0 = 0$. Therefore, the consumer (located on the top horizontal axis) who is indifferent between buying the basic, copper-based, service from the incumbent and the entrant \hat{x}^c is given by:

$$\hat{x}^c = \hat{x} = \frac{1}{2} \quad (10)$$

whereas the retail prices are:

$$p_I^c = p_E^c = t + w^c \quad (11)$$

On the contrary, in the market of the fiber-based services we have that $\vartheta_j \cdot y = \vartheta_j \cdot 1 = \vartheta_j$, $j = I, E$. Therefore, the consumer (located at the last horizontal axis) who is indifferent between buying the ultra-fast, fiber-based, service from the incumbent and the entrant is given by:

$$\hat{x}^f = \frac{\vartheta_I - \vartheta_E + p_E^f - p_I^f}{2t} + \frac{1}{2} \quad (12)$$

The market shares of the incumbent and the entrant in the market where the consumers place the highest valuation to the provided ultra-fast broadband service (i.e. $y = 1$) are given, respectively, by:

$$\hat{x}^f = \frac{\vartheta_I - \vartheta_E + p_E^f - p_I^f}{2t} + \frac{1}{2} \quad (13)$$

$$1 - \hat{x}^f = \frac{1}{2} - \frac{\vartheta_I - \vartheta_E + p_E^f - p_I^f}{2t} \quad (14)$$

The profit-maximizing prices for incumbent and the entrant are given by:

$$p_I^f = \frac{\vartheta_I - \vartheta_E + 3w^f + 3t}{3} \quad (15)$$

$$p_E^f = \frac{\vartheta_E - \vartheta_I + 3w^f + 3t}{3} \quad (16)$$

Therefore, the market shares of the incumbent and the entrant in the fiber market represented by the last horizontal axis are given, respectively, by:

$$\hat{x}^f = \frac{\vartheta_I - \vartheta_E + 3t}{6t} \quad (17)$$

$$1 - \hat{x}^f = \frac{\vartheta_E - \vartheta_I + 3t}{6t} \quad (18)$$

However, the number of consumers who choose to buy each retail service is not only given by the consumers located at the two extreme horizontal axes of the unit square, but also by the consumers who are located at $\{(x, y)\} = \{[0, 1], (0, 1)\}$. In other words, this latter group of consumers is not located on the two extreme horizontal axes of the unit square. These are the consumers whose taste for quality is not captured by the basic broadband service provided over the copper access network nor the ultra-fast broadband service provided over the fiber access network. These consumers have to choose either the copper-based service or the fiber-based service, which is of a particular quality depending on the fiber deployment.

The consumer who is indifferent between buying the basic, copper-based, service from the incumbent at price p_I^c and the ultra-fast, fiber-based, service from the incumbent at price p_I^f is given by:

$$y_I = \frac{\vartheta_I - \vartheta_E + 3(w^f - w^c)}{6s} + \frac{1}{2} \quad (19)$$

In addition, the consumer who is indifferent between buying the basic, copper-based, service from the entrant at price p_E^c and the ultra-fast, fiber-based, service from the entrant at price p_E^f is given by:

$$y_E = \frac{\vartheta_E - \vartheta_I + 3(w^f - w^c)}{6s} + \frac{1}{2} \quad (20)$$

Assumption 1: Let $\vartheta_I > \vartheta_E$.

Assumption 1 states that the incumbent enjoys some perceived quality advantages over the entrant because it owns the fiber access network. Therefore, the consumer who has a particular taste for quality prefers to subscribe to the incumbent rather than to the entrant when the two firms set the same retail price. A straightforward result of the above assumption is:

Corollary 1. $y_I > y_E$ and $\hat{x}^f > \hat{x}^c$.

Proof. See Appendix A2. ■

Figure 3 presents a representative solution of the game with respect to each provider's market share in each market since the exact points of \hat{x}^f , y_I and y_E are affected by the particular levels of the access prices of copper and fiber unbundling, as well as the values of the parameters ϑ_I , ϑ_E , s and t .

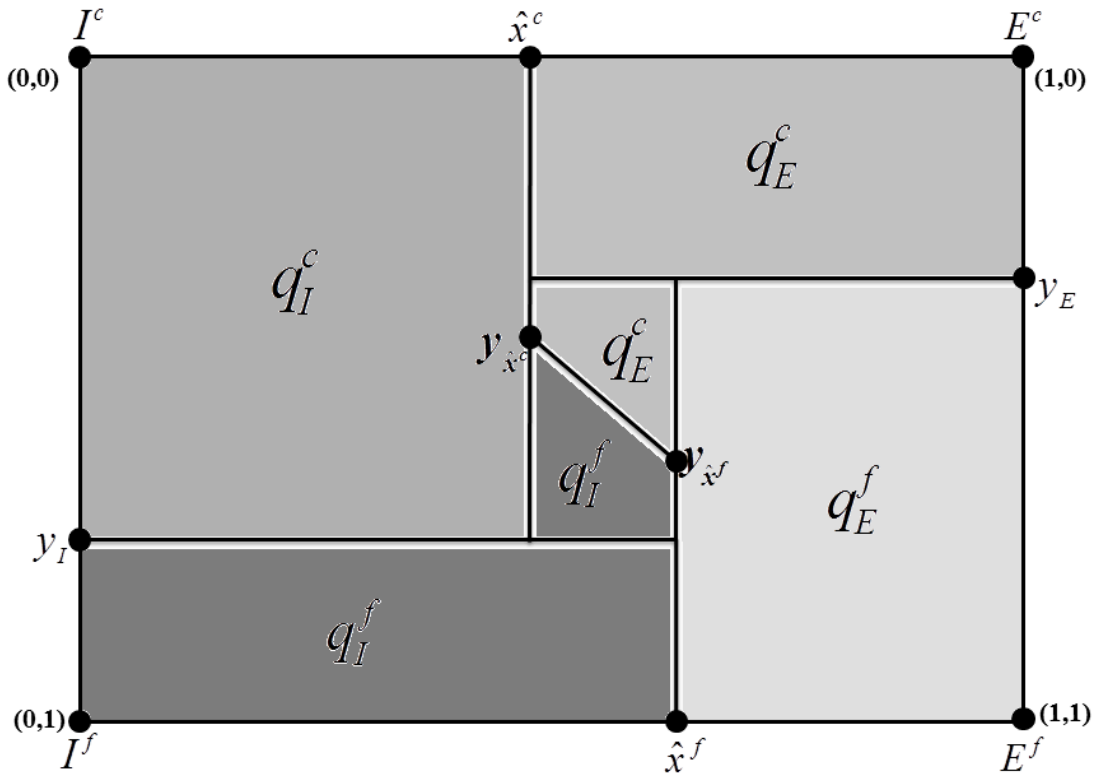


Figure 3: The retail market for copper-based and fiber-based services

It is obvious from the above figure that there are some consumers located at $\{(x, y)\} = \{ [\hat{x}^c, \hat{x}^f], [y_E, y_I] \}$ who are interested in migrating from the entrant's basic broadband service to the incumbent's ultra-fast broadband service. The indifferent consumer between choosing these two options is a function of x and is given by:

$$y = \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 6t \cdot x + 3s - 3t}{3(\vartheta_I - \vartheta_E + 2s)} \quad (21)$$

Since y is a linear function of x , we can estimate its slope by finding its values at $x = \hat{x}^c$ and at $x = \hat{x}^f$. The derived values are given, respectively, by:

$$y_{\hat{x}^c} = \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 3s}{3(\vartheta_I - \vartheta_E + 2s)} \quad (22)$$

$$y_{\hat{x}^f} = \frac{2\vartheta_I - 2\vartheta_E + 3w^f + 3w^c + 3s}{3(\vartheta_I - \vartheta_E + 2s)} \quad (23)$$

We can now calculate the number of consumers who choose to buy each service:

Lemma 1. *The number of consumers who choose to buy: (i) the incumbent's copper-based service, (ii) the incumbent's fiber-based service; (iii) the entrant's copper-based service; and (iv) the entrant's fiber-based service, are given, respectively, by:*

$$q_I^c = \frac{\vartheta_I - \vartheta_E + 3(w^f - w^c) + 3s}{12s} \quad (24)$$

$$q_I^f = \frac{6s^2t + s\vartheta_I^2 + 2\vartheta_I s^2 + s\vartheta_E^2 - 2s^2\vartheta_E - t\vartheta_I^2 - t\vartheta_E^2 + 6stw^c - 6stw^f - 2s\vartheta_I w^c - 2s\vartheta_I w^f}{12st(\vartheta_I - \vartheta_E + 2s)} + \frac{2s\vartheta_E w^c + 2s\vartheta_E w^f + 3t\vartheta_I w^c - 3t\vartheta_E w^c - 3t\vartheta_I w^f + 3t\vartheta_E w^f + st\vartheta_I - st\vartheta_E - 2s\vartheta_I \vartheta_E + 2t\vartheta_I \vartheta_E}{12st(\vartheta_I - \vartheta_E + 2s)} \quad (25)$$

$$q_E^c = \frac{3w^c \vartheta_E^2 - 3w^f \vartheta_I^2 + 3w^c \vartheta_I^2 - 3w^f \vartheta_E^2 + 18ts^2 + 2s\vartheta_I^2 + 2s\vartheta_E^2 - 3t\vartheta_I^2 - 3t\vartheta_E^2 + 3\vartheta_I \vartheta_E^2 - 3\vartheta_E \vartheta_I^2}{36st(\vartheta_I - \vartheta_E + 2s)} + \frac{\vartheta_I^3 - \vartheta_E^3 - 18stw^c + 18stw^f + 12s\vartheta_I w^c - 12s\vartheta_E w^c - 9t\vartheta_I w^c + 9t\vartheta_E w^c}{36st(\vartheta_I - \vartheta_E + 2s)} + \frac{6\vartheta_I \vartheta_E w^f + 3st\vartheta_I - 3st\vartheta_E - 4s\vartheta_I \vartheta_E + 6t\vartheta_I \vartheta_E + 9t\vartheta_I w^f - 9t\vartheta_E w^f - 6\vartheta_I \vartheta_E w^c}{36st(\vartheta_I - \vartheta_E + 2s)} \quad (26)$$

$$q_E^f = \frac{2\vartheta_I \vartheta_E - \vartheta_I^2 - \vartheta_E^2 - 3s\vartheta_I + 3s\vartheta_E + 3\vartheta_I w^f - 3\vartheta_E w^f - 3\vartheta_I w^c}{36st} + \frac{3\vartheta_E w^c - 3t\vartheta_E + 3t\vartheta_I + 9st - 9tw^f + 9tw^c}{36st} \quad (27)$$

Proof. See Appendix A3. ■

The total profit of the incumbent (Π_I^{inv}) is the sum of its revenues derived from the use of its copper (Π_I^c) and fiber (Π_I^f) access networks minus the investment cost F , where:

$$\Pi_I^c = [p_I^c - c_I^c]q_I^c + [w^c - c_I^c]q_E^c \quad (28)$$

$$\Pi_I^f = [p_I^f - c_I^f]q_I^f + [w^f - c_I^f]q_E^f \quad (29)$$

The total profit of the entrant (Π_E^{inv}) is the sum of its profit derived from using the incumbent's copper (Π_E^c) and fiber (Π_E^f) access networks:

$$\Pi_E^c = [p_E^c - w^c]q_E^c \quad (30)$$

$$\Pi_E^f = [p_E^f - w^f]q_E^f \quad (31)$$

4. Access charges of copper and fiber unbundling

The solution of the two games described in the previous section showed that the investment in new fiber infrastructures affects the distribution of consumers to each technology and each provider. In particular, when the two firms provide only basic broadband services over the copper access network of the incumbent, they share the market. Once the fiber investment is taken place, the consumers' valuation for the ultra-fast, fiber-based, broadband services varies. The combination of this variation and the retail price of each service forms the demand that each firm faces in each market.

In this section, we study the effect of the access charges of copper and fiber unbundling on each firm's profit. Our goal is to compare the incumbent's profit under the investment and the non-investment case in order to discuss the optimal access pricing policy that encourages the investment in fiber infrastructures. We also discuss the robustness of the access pricing policy under different values for the parameters s and t that affect the total profit of the firms.

In order to study the interplay between the access charges of copper and fiber unbundling, we discriminate between three cases. In the first case, the regulator sets a fixed access price for the copper access network, whereas the access price for the fiber access network is set to the level that maximizes the incumbent's profit. We will pay a particular attention to this case in the next section because it is in line with the latest EC Recommendation on consistent non-discrimination obligations and costing methodologies to promote competition and enhance the broadband investment (EC, 2013a). In the second case, the regulator sets a fixed access price for the fiber access network, whereas the access price for the copper access network is set to the incumbent's profit-maximization level. In the last case, both access prices are set to the level that maximizes the incumbent's profit. In all cases, the regulatory policy ensures that both firms are active in both markets.

Unfortunately, the complex forms of Eqs. (24)-(27) makes the profit functions given by Eqs. (28)-(31) too difficult to be analyzed with respect to their dependency on w^c and w^f . Therefore, the main part of the analysis that follows is conducted using numerical simulations in order to compare the profit of the incumbent under the non-investment and the investment case. The initial assumed values of the exogenous parameters are $c_I^c = 0.6$, $c_I^f = 0.9$, $\vartheta_I = 0.5$, $\vartheta_E = 0.25$, $s = 3$ and $t = 1$.

4.1. Fiber access charges

In this section, we study the case where the regulator focuses on the regulation of the access to the incumbent's fiber network given a fixed access price for the copper

unbundling. In particular, we study the impact of the fiber access charge on the incumbent's profit when $w^c = \{0.6, 0.9, 1.2\}$. Figure 4 graphically presents our findings.

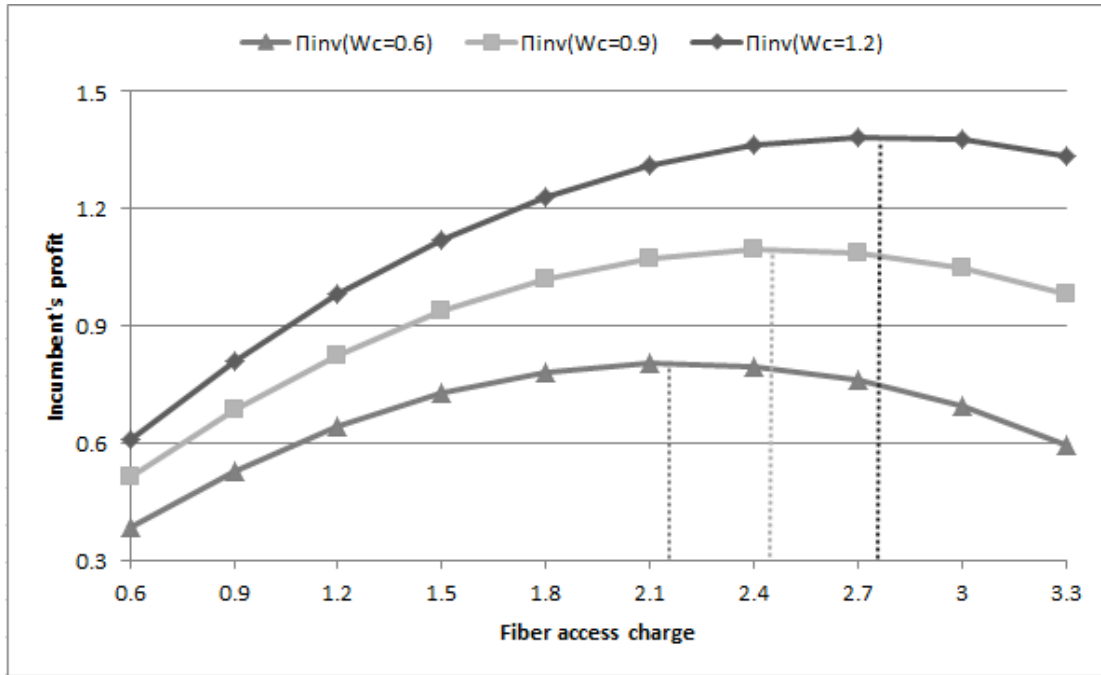


Figure 4: The incumbent's profit as a function of the fiber access charge

It is obvious that regardless of the particular level of the copper access charge, there is always a fiber access price that maximizes the incumbent's profit. The reason is that as the fiber access price increases, the retail prices of both firms' fiber-based services increase as well. Therefore, the number of consumers who choose the ultra-fast broadband services decreases as the basic broadband services become more attractive to consumers. This "business migration effect" decreases the profit of the incumbent from its fiber business. On the other hand, an increase in the fiber access price increases the profit margins of the incumbent in the retail and the wholesale fiber markets. This "fiber revenue effect" has a positive impact on the incumbent's profit from its activity in the fiber markets. For low values of the fiber access charge, the positive impact of the "fiber revenue effect" outweighs the negative impact of the "business migration effect". When the marginal impact of these two effects on the incumbent's profit is the same, then the level of the fiber access price that causes this result is the fiber access charge that maximizes the incumbent's profit from its fiber activity (Π_I^f).

In addition, an increase in the fiber access price does not affect the profit margins of the incumbent in the retail and the wholesale copper markets. Therefore, the "business migration effect" increases the profit of the incumbent from its copper activity (Π_I^c).

Given that the total profits of the incumbent (Π_I^{inv}) is the sum of its profits from the markets of basic and ultra-fast broadband services, it is reasonable that its total profit is maximized for a particular level of the fiber access charge. Table 1 shows the level of the fiber access charge that maximizes the incumbent's profit for $w^c = \{0.6, 0.9, 1.2\}$, as well as the derived levels of market shares and profits.

Table 1. The incumbent's profit-maximizing fiber access charges for $w^c = \{0.6, 0.9, 1.2\}$

w^c	w^f	q_I^c	q_E^c	q_I^f	q_E^f	Π_I^{inv}	Π_E^{inv}
0.6	2.184	0.388	0.383	0.113	0.114	0.804	0.488
0.9	2.472	0.387	0.386	0.110	0.115	1.094	0.492
1.2	2.760	0.386	0.389	0.107	0.116	1.385	0.495

Table 1 show that there is a positive correlation between the fixed access charge of copper unbundling and the fiber access charge that maximizes the incumbent's profit. This result is also graphically presented in figure 4. The interpretation of this result is based on the fact that for any given fiber access price, the incumbent's profit is higher when the exogenously set copper access charge is higher. In particular, a higher copper access charge does not affect the retail prices for the fiber-based services, but it increases the retail prices for the basic broadband services. Therefore, the fiber-based services become more attractive to consumers, which means that the incumbent increases its revenues from the fiber retail and wholesale markets since its fiber profit margins are not affected by an increase in the copper access price. In addition, the increase in the copper access price leads to a higher increase in the copper profit margins than the decrease in the consumers who choose the basic broadband services. As a result, an increase in the copper access price positively affects the profit of the incumbent from the copper markets. Therefore, the fiber access charge that equates the marginal impact of the two effects on the incumbent's profit increases with an increase in the exogenously given copper access charge.

The overall conclusion of the discussion of this section can be summarized in the following proposition:

Proposition 1. *There is a positive correlation between the fixed level of the copper access charge and the incumbent's profit-maximizing fiber access charge which leads to higher profit for the incumbent.*

It should be noted that the entrant's total profit always increases with an increase in the fiber access charge since it becomes more efficient competitor in the copper-based market where the access price becomes significantly lower than the fiber access price as the latter price increases.

4.2. Copper access charges

Contrary to the previous section, we now focus on the impact of the copper access price on the incumbent's profit. In other words, we assume a given fixed charge for fiber unbundling and we discuss the profit-maximizing copper access charge. In particular, we study the impact of the copper access charge on the incumbent's profit when $w^f = \{0.9, 1.2, 1.5\}$. Figure 5 graphically presents our findings.

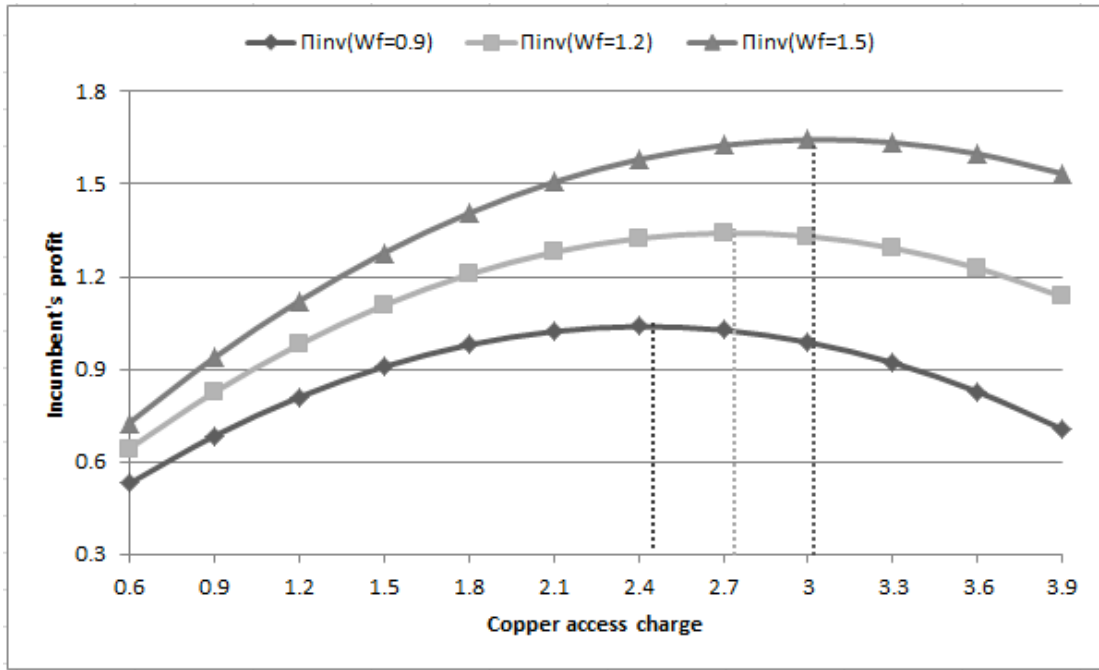


Figure 5: The incumbent's profit as a function of the copper access charge

From the above figure, it can be deduced that regardless of the particular level of the fiber access charge, there is always a copper access price that maximizes the incumbent's profit. The reason is that as the copper access charge increases, the retail prices for the firms' copper-based services increase as well. This result makes the market of copper-based services less attractive from the consumers' perspective since they migrate to the market of fiber-based services. This "business migration effect" decreases the profit of the incumbent from its copper business. On the other hand, an increase in the copper access price increases the profit margins of the incumbent in the retail and the wholesale copper access markets. This "copper revenue effect" has a positive impact on the incumbent's profit from its activity in the copper markets. For low values of the copper access charge, the positive impact of the "copper revenue effect" outweighs the negative impact of the "business migration effect". When the marginal impact of these two effects on the incumbent's profit is the same, then the level of the copper access price that causes this result is the copper access charge that maximizes the incumbent's profit from its copper activity (Π_I^c).

In addition, the incumbent's profits from the retail and wholesale fiber markets increase with an increase in the copper access price. The reason is that the profit margins of the incumbent in the retail and the wholesale fiber markets are not affected by an increase in the copper access charges, and hence, the "business migration effect" increases the profit of the incumbent from its fiber activity (Π_I^f). Given that the total profit of the incumbent (Π_I^{inv}) is the sum of its profits from the markets of basic and ultra-fast broadband services, it is reasonable that its total profit are maximized for a given level of the copper access charge. Table 2 presents the level of the copper access charge that maximizes the incumbent's profit for $w^f = \{0.9, 1.2, 1.5\}$, as well as the derived levels of market shares and profits.

Table 2.The incumbent's profit-maximizing copper access charges for $w^f = \{0.9, 1.2, 1.5\}$

w^f	w^c	q_I^c	q_E^c	q_I^f	q_E^f	Π_I^{inv}	Π_E^{inv}
0.9	2.423	0.129	0.149	0.368	0.351	1.038	0.472
1.2	2.736	0.128	0.152	0.365	0.352	1.341	0.476
1.5	3.049	0.127	0.155	0.362	0.353	1.644	0.480

Table 2 shows that there is a positive correlation between the fixed access charge for fiber unbundling and the copper access charge that maximizes the incumbent's profit. Indeed, from figure 4, we can deduce that for any given level of the copper access charge, the incumbent's profit is higher when the exogenously set fiber access charge is higher. The reason is that a higher fiber access charge leads to higher retail prices for the fiber-based services, but it does not affect the retail prices for the basic broadband services. Therefore, the copper-based services become more attractive to consumers which means that the incumbent increases its revenues from the copper retail and wholesale markets since its copper profit margins are not affected by an increase in the fiber access price. In addition, the increase in the fiber access price leads to a higher increase in the fiber profit margins than the decrease in the consumers who choose the ultra-fast broadband services. As a result, an increase in the fiber access price positively affects the profit of the incumbent from the fiber markets. Therefore, the copper access charge that equates the marginal impact of the two effects on the incumbent's profit increases with an increase in the exogenously given fiber access charge.

The overall conclusion of the discussion of this section can be summarized in the following proposition:

Proposition 2. *There is a positive correlation between the fixed level of the fiber access charge and the incumbent's profit-maximizing copper access charge which leads to higher profit for the incumbent.*

It should be noted that the entrant's total profit always increases with an increase in the copper access charge since it becomes more efficient competitor in the fiber-based market where the access price becomes significantly lower than the copper access price as the latter price increases.

4.3. Copper and fiber access charges

Contrary to the previous cases where the regulator could set the access charge of either the copper or the fiber unbundling, we study the case where the regulator can freely set the access charges of both copper and fiber unbundling in order to maximize the incumbent's profit. Figure 6 graphically presents our findings.

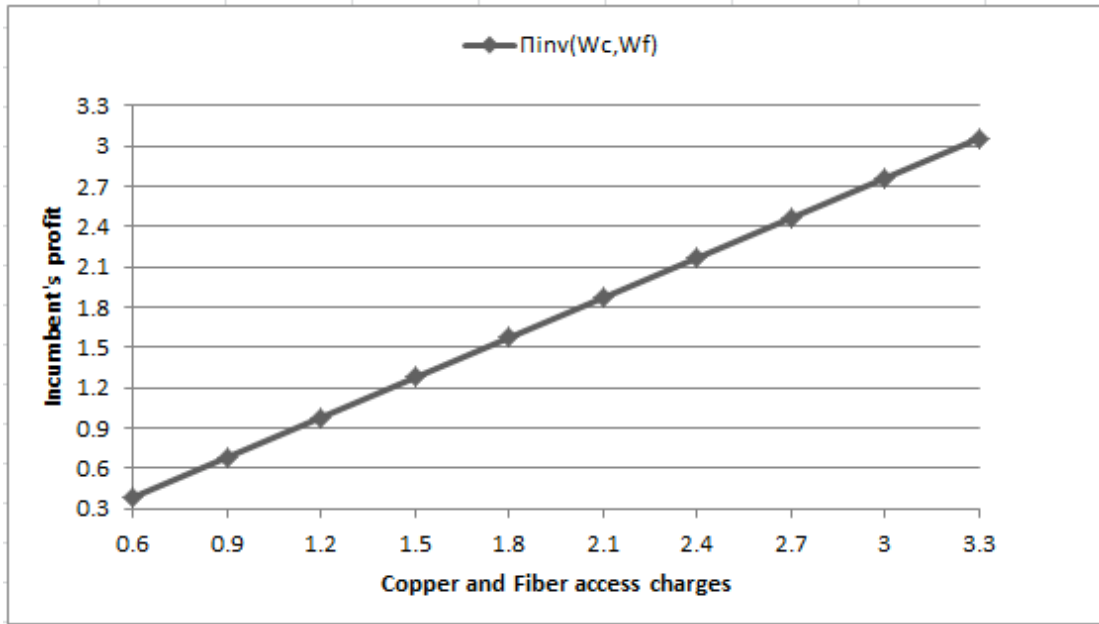


Figure 6: The incumbent's profit as a function of both copper and fiber access charges

Figure 6 shows that as the copper and the fiber access prices increase, the incumbent's profit increases as well. In particular, the profit of the incumbent is maximized when it becomes a pure reseller of its upstream services. In other words, the incumbent is better off by not supplying its final services to its consumers and only providing access to its access networks at very high access prices. In particular, the levels of copper and fiber access charges that make the incumbent inactive in the retail markets are $w^c = 40.604$ and $w^f = 37.520$. Note that the entrant's profit also increases as the copper and the fiber access prices increase since the retail prices increase as well, but its profit is much lower than the incumbent's profit because the incumbent has a very high profit margin in both copper and fiber access markets.

5. Regulatory implications

In the previous sections, we studied the impact of copper and fiber access charges on the incumbent's profit when the two firms can supply both basic and ultra-fast broadband services over the copper and the fiber access networks of the incumbent. Although the previous analysis derived some very interesting results, it neglects the fact that the incumbent undertakes the fiber investment when its profit after the investment is higher than its profit before the investment. In other words, the incumbent is expected to invest in new fiber access infrastructures when the expected profit from the investment case is higher than the investment cost plus the opportunity cost of the investment (i.e. $\Pi_I^{inv} = \Pi_I^c + \Pi_I^f - F > \Pi_I$).

For a given investment level F , the incumbent is more likely to undertake the investment for a higher difference between Π_I^{inv} and Π_I . Put it differently, as $\Delta\Pi_I = (\Pi_I^c + \Pi_I^f - \Pi_I)$ increases, the incumbent is willing to undertake a higher investment in quality and/or a larger geographic deployment of the fiber access network.

In this section, we study the regulatory policy that encourages the incumbent to undertake the fiber deployment. This means that we are interested in assessing the

access charges of copper and fiber unbundling that maximize $\Delta\Pi_I$. Note that the copper access price affects the incumbent's profit in both the investment and the non-investment case. This is reasonable since the incumbent chooses whether to invest or not after the imposition of the access charges of the copper and the fiber unbundling. Figure 7 provides the values of $\Delta\Pi_I$ for the cases we discussed in the previous sections.

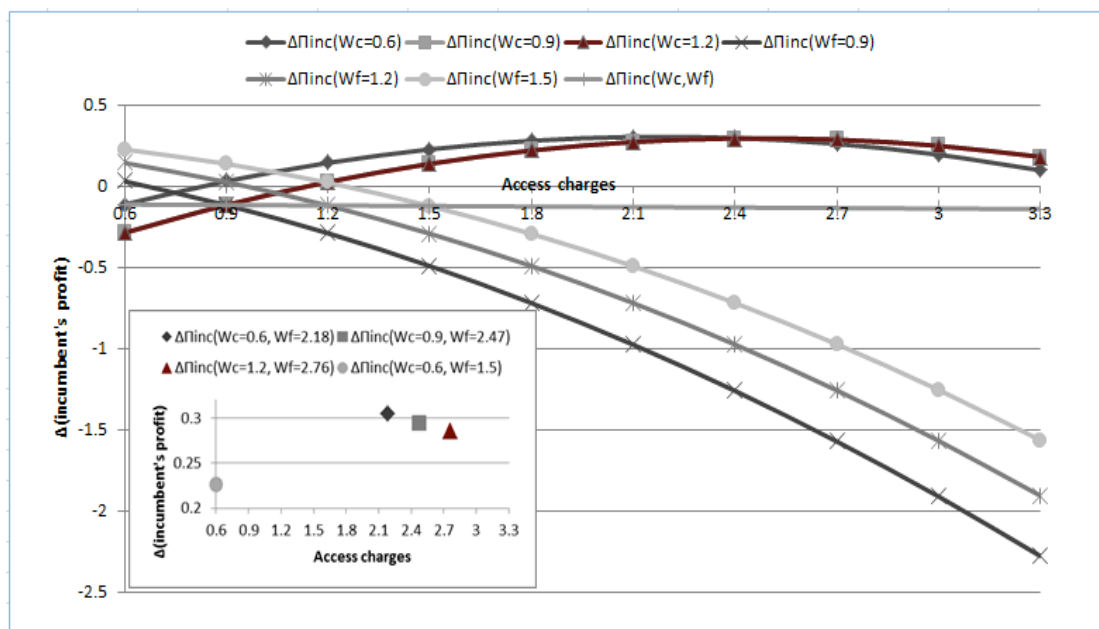


Figure 7: The difference of the incumbent's profit before and after the investment

The first significant finding from the above figure is that when the regulator increases both access charges in order to maximize the incumbent's profit after the investment, it also increases the opportunity cost of the investment. The reason is that the incumbent forgoes the increasing profit from the case where the two firms provide only copper-based services since the retail price of the basic broadband services is positively affected by an increase in the copper access price. Therefore, the incumbent chooses not to invest in fiber access networks.

Moreover, when the fiber access price is set to a particular level, and hence, the only available instrument to the regulator is the copper access price, the cost-based copper access charge ensures that $\Delta\Pi_I$ is maximized. This implies that the regulator should set $w^c = c_I^c = 0.6$ in order to ensure that the incumbent is more likely to undertake the investment in fiber access infrastructures. However, note that this optimal level is different than the level of the copper access price that maximizes the incumbent's profit derived from the investment (Π_I^{inv}). In particular, when Π_I^{inv} is maximized, the incumbent chooses not to invest since $\Delta\Pi_I < 0$. Obviously, the reason for this distortion is that a deviation from the cost-based copper access price in order to maximize Π_I^{inv} cause a higher increase in the opportunity cost of the investment (Π_I).

Another significant finding concerns the case where the copper access price is set to a particular level, and hence, the only available instrument to the regulator is the fiber access price. The numerical simulations show that the fiber access charge that maximizes $\Delta\Pi_I$ is equal to the fiber access charge that maximizes Π_I^{inv} . This is a

reasonable result since Π_I is not affected by a change in the fiber access price. However, the fixed level of the copper access price affects the maximization of $\Delta\Pi_I$. In particular, we find that the difference $\Delta\Pi_I = (\Pi_I^c + \Pi_I^f - \Pi_I)$ takes its maximum value when $w^c = c_I^c = 0.6$ and $w^f = 2.184$. The table below summarizes the above results.

Table 3. Summary of the incumbent's profit-maximizing copper and fiber access charges

w^c	w^f	Π_I^c	Π_I^f	Π_I^{inv}	$\Delta\Pi_I$	Π_E^{inv}	$\Delta\Pi_E$
0.6	2.184	0.388	0.416	0.804	0.304	0.488	-0.012
0.9	2.472	0.620	0.474	1.094	0.294	0.492	-0.008
1.2	2.760	0.852	0.533	1.385	0.285	0.495	-0.005
2.423	0.9	0.639	0.399	1.038	-1.284	0.472	-0.028
2.736	1.2	0.730	0.611	1.341	-1.294	0.476	-0.024
3.049	1.5	0.822	0.822	1.644	-1.304	0.480	-0.020
40.604	37.520	21.154	17.254	38.408	-2.094	0.960	0.460

Indeed, allowing the regulator to freely set both copper and fiber access charges in order to maximize $\Delta\Pi_I$, shows that the optimal regulatory policy is to set the copper access price at the cost of providing the access at the copper access network (i.e. $w^c = c_I^c = 0.6$) and the fiber access charge at the level that maximizes the incumbent's profit after the investment (i.e. $w^f = 2.184$). This finding is very significant since it supports the EC Recommendation on consistent non-discrimination obligations and costing methodologies to promote competition and enhance the broadband investment environment (EC, 2013a).

In particular, the EC (2013a) states that *"the costing methodology should reflect the need for stable and predictable wholesale copper access prices over time in order to provide a clear framework for investment and be capable of generating cost-oriented wholesale copper access prices serving as an anchor for NGA services, and deal appropriately and consistently with the impact of declining volumes caused by the transition from copper to NGA networks"*. It is obvious that our modeling setup explicitly takes into account the migration issue and proposes a regulatory policy resulting in stable cost-oriented wholesale copper access prices.

Regarding the regulation of the access to the fiber access network, our proposal encourages the incumbent to invest in NGA networks since the respective access price provides a sufficient profit margin in the fiber access market. This view is also implicitly supported by the EC Recommendation since *"it allows the investing firms in NGA networks a certain degree of pricing flexibility to test price points and conduct appropriate penetration pricing provided that there is a demonstrable retail price constraint resulting from a price anchor stemming from cost-oriented wholesale copper access prices"*. Our model shows that the cost-based copper access price ensures a competitive outcome in both basic and ultra-fast broadband markets since our proposed regulatory policy leads the two firms have almost the same market share in each market, as well as only marginally affects the entrant's profit compared to its profit derived by the non-investment outcome.

In summary:

Proposition 3. *The regulatory policy that leads to a cost-based access charge and a fiber access price which maximizes the incumbent's profit after the investment reflects the optimal regulatory policy in terms of investment incentives without affecting the competition between the two firms in a negative way.*

5.1. Robustness of the regulatory implications

The optimal regulatory policy discussed in the previous section is based on the initial assumed values for the parameters s and t . In this section, we examine the robustness of the proposed copper and fiber access charges for different values of the parameters s and t . The following table presents the combination of copper and fiber access charges that maximizes the incumbent's profit.

Table 4. The impact of t and s on the incumbent's profit-maximizing access charges

t	s	w^c	w^f	Π_I^c	Π_I^f	Π_I^{inv}	$\Delta\Pi_I$	Π_E^{inv}	$\Delta\Pi_E$
0.5	3	0.6	2.159	0.194	0.350	0.544	0.294	0.238	-0.012
1	3	0.6	2.184	0.388	0.416	0.804	0.304	0.488	-0.012
1.5	3	0.6	2.192	0.584	0.473	1.057	0.307	0.738	-0.012
1	2	0.6	1.685	0.396	0.281	0.677	0.177	0.492	-0.008
1	3	0.6	2.184	0.388	0.416	0.804	0.304	0.488	-0.012
1	4	0.6	2.683	0.385	0.545	0.930	0.430	0.486	-0.014

It is obvious that although the particular level of the fiber access price changes with a change in s and/or t , the optimal regulatory policy stated in proposition 3 is independent of the particular values of these parameters.

6. Conclusions

The fulfillment of the goals of the Digital Agenda for Europe (EC, 2010b) requires the migration from copper access networks to fiber-based, Next Generation Access, networks. Although this issue is at the center of the policy debate, the impact of the access charges of copper and fiber unbundling on firms' investment incentives and consumers' migration to fiber-based services only recently received much attention. This paper contributed to this literature by studying an incumbent's incentives to invest in fiber access networks when the incumbent and the entrant compete for consumers in both copper and fiber markets. This implies that each firm provides a basic broadband service and an ultra-fast broadband service, both provided via the copper and, respectively, the fiber access network of the incumbent. Therefore, each consumer subscribes to one of the four available broadband services.

We studied three different cases according to the regulator's freedom to set each access price so as to maximize the incumbent's profit after the investment. We found that when the regulator can freely set either the copper or the fiber access price, there is a positive correlation between the fixed level of the fiber (respectively, copper) access charge and the incumbent's profit-maximizing copper (respectively, fiber)

access charge. On the contrary, when the regulator is free to set both access prices, the incumbent's profit is an increasing function of both access prices. It should be noted that in the latter case, the incumbent is better off by forgoing its retail business and focusing on providing access to its copper and fiber access networks.

However, the decision of the incumbent to undertake an investment in fiber deployment is not only affected by its expected profit after the investment, but also by the opportunity cost of the investment. This cost is reflected by the profit from the non-investment case that the incumbent forgoes when it invests in fiber access networks.

It is obvious that the incumbent's profit after the investment, as well as its profit before the investment, are both affected by the level of the copper access price. We found that the incumbent is more likely to undertake the investment in fiber access networks when the copper access charge is priced at the cost of providing the access to the copper access network and the fiber access charge is priced at the level that maximizes the incumbent's profit after the investment. This access pricing policy reflects the optimal regulatory intervention in terms of investment incentives without affecting the competition between the two firms in a negative way.

Our main finding is that the proposed regulatory policy is in line with the EC Recommendation (EC, 2013a), which aims to present the basic principles for setting the copper and the fiber access charges so as to encourage the migration to the NGA networks, and hence, the fulfillment of the goals of the Digital Agenda for Europe.

However, the goal of regulator is not only to encourage the deployment of fiber access networks, but also to ensure the competition outcome inherited from the regulation of the legacy copper networks. Therefore, the main direction for future research is to assess the impact of the proposed regulatory policy on the socially efficient outcomes, both from a static and a dynamic perspective.

Appendix A

A1. The analytical solution of the investment case

The solution of the game concerning the market shares and the retail prices of the copper-based services is similar to the case where no investment has taken place since $\vartheta_j \cdot y = \vartheta_j \cdot 0 = 0$. Therefore, substituting Eq. (11) into Eq. (1), gives Eq. (10) which provides the consumer (located at the top horizontal axis, i.e. when $y = 0$) who is indifferent between buying the copper-based service from the incumbent and the entrant:

$$\hat{x}^c = \hat{x} = \frac{p_E - p_I}{2t} + \frac{1}{2} \Rightarrow \hat{x}^c = \frac{t + w^c - t - w^c}{2t} + \frac{1}{2} \Rightarrow \hat{x}^c = \frac{1}{2} \quad (\text{A1})$$

In addition, equating the utility derived when a consumer buys the incumbent's fiber-based service and the utility derived when a consumer buys the entrant's fiber-based service, provides the consumer (located at the last horizontal axis, i.e. when $y = 1$) who is indifferent between buying the ultra-fast, fiber-based, service from the incumbent and the entrant:

$$\begin{aligned}
U_I^f &= U_E^f \Rightarrow \\
V + \vartheta_I \cdot y - p_I^f - t \cdot x - s \cdot (1-y) &= V + \vartheta_E \cdot y - p_E^f - t \cdot (1-x) - s \cdot (1-y) \Rightarrow \\
\vartheta_I \cdot y - p_I^f - t \cdot x &= \vartheta_E \cdot y - p_E^f - t + t \cdot x \Rightarrow \\
2t \cdot x &= \vartheta_I - \vartheta_E + p_E^f - p_I^f + t \Rightarrow \\
\hat{x}^f &= \frac{\vartheta_I - \vartheta_E + p_E^f - p_I^f}{2t} + \frac{1}{2} \tag{A2}
\end{aligned}$$

Therefore, the market shares of the incumbent and the entrant in the market described by the last horizontal axis (i.e. when $y = 1$) are \hat{x}^f and $1 - \hat{x}^f$, respectively. The two firms set the retail price of their fiber-based services according to the demand they face in this market. Therefore, the profit of the incumbent and the entrant from this market ($y = 1$) are given, respectively, by:

$$\Pi_{I(y=1)}^f = [p_I^f - c_I^f] \hat{x}^f + [w^f - c_I^f] (1 - \hat{x}^f) \tag{A3}$$

$$\Pi_{E(y=1)}^f = [p_E^f - w^f] (1 - \hat{x}^f) \tag{A4}$$

Substituting Eq. (A2) into (A3) and (A4), taking the first order condition of the incumbent's and the entrant's profits with respect to p_I^f and p_E^f , respectively, and then solving together gives the profit-maximizing retail prices for the incumbent and the entrant:

$$\begin{aligned}
\frac{\partial \Pi_I}{\partial p_I^f} &= 0 \Rightarrow \\
\vartheta_I - \vartheta_E + p_E^f - 2p_I^f + w^f + t &= 0 \Rightarrow 2p_I^f = \vartheta_I - \vartheta_E + p_E^f + w^f + t \Rightarrow \\
p_I^f &= \frac{\vartheta_I - \vartheta_E + p_E^f + w^f + t}{2} \Rightarrow \dots \Rightarrow \\
p_I^f &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3t}{3} \tag{A5}
\end{aligned}$$

and

$$\begin{aligned}
\frac{\partial \Pi_E}{\partial p_E^f} &= 0 \Rightarrow \\
t - \vartheta_I + \vartheta_E - 2p_E^f + p_I^f + w^f &= 0 \Rightarrow 2p_E^f = t - \vartheta_I + \vartheta_E + p_I^f + w^f \Rightarrow \\
p_E^f &= \frac{\vartheta_E - \vartheta_I + p_I^f + w^f + t}{2} \Rightarrow \dots \Rightarrow \\
p_E^f &= \frac{\vartheta_E - \vartheta_I + 3w^f + 3t}{3} \tag{A6}
\end{aligned}$$

Therefore, the market shares of the incumbent and the entrant in the market described by the last horizontal axis (i.e. when $y = 1$) are given, respectively, by:

$$\hat{x}^f = \frac{\vartheta_I - \vartheta_E + 3t}{6t} \tag{A7}$$

$$1 - \hat{x}^f = \frac{\vartheta_E - \vartheta_I + 3t}{6t} \quad (\text{A8})$$

Equation (19) is given by equating the utility derived when a consumer buys the incumbent's copper-based service and the utility derived when a consumer buys the incumbent's fiber-based service:

$$\begin{aligned} U_I^c &= U_I^f \Rightarrow \\ V + \vartheta_I \cdot y - p_I^c - t \cdot x - s \cdot y &= V + \vartheta_I \cdot y - p_I^f - t \cdot x - s \cdot (1 - y) \Rightarrow \\ -p_I^c - s \cdot y &= -p_I^f - s + s \cdot y \Rightarrow \\ 2s \cdot y &= p_I^f - p_I^c + s \Rightarrow \\ y_I &= \frac{\vartheta_I - \vartheta_E + 3(w^f - w^c)}{6s} + \frac{1}{2} \end{aligned} \quad (\text{A9})$$

In addition, Eq. (20) is derived by equating the utility derived when a consumer buys the entrant's copper-based service and the utility derived when a consumer buys the entrant's fiber-based service:

$$\begin{aligned} U_E^c &= U_E^f \Rightarrow \\ V + \vartheta_E \cdot y - p_E^c - t \cdot (1 - x) - s \cdot y &= V + \vartheta_E \cdot y - p_E^f - t \cdot (1 - x) - s \cdot (1 - y) \Rightarrow \\ -p_E^c - s \cdot y &= -p_E^f - s + s \cdot y \Rightarrow \\ 2s \cdot y &= p_E^f - p_E^c + s \Rightarrow \\ y_E &= \frac{\vartheta_E - \vartheta_I + 3(w^f - w^c)}{6s} + \frac{1}{2} \end{aligned} \quad (\text{A10})$$

However, there are some consumers located at $\{(x, y)\} = \{[\hat{x}^c, \hat{x}^f], [y_E, y_I]\}$ who are interested in migrating from the entrant's basic broadband service to the incumbent's ultra-fast broadband service. Hence, equating the utility derived when a consumer buys the incumbent's fiber-based service and the utility derived when a consumer buys the entrant's copper-based service gives the indifferent consumer between choosing these two options, as it is shown in Eq. (21) in the text:

$$\begin{aligned} U_I^f &= U_E^c \Rightarrow \\ V + \vartheta_I \cdot y - p_I^f - t \cdot x - s \cdot (1 - y) &= V + \vartheta_E \cdot y - p_E^c - t \cdot (1 - x) - s \cdot y \Rightarrow \\ \vartheta_I \cdot y - p_I^f - t \cdot x - s + s \cdot y &= \vartheta_E \cdot y - p_E^c - t + t \cdot x - s \cdot y \Rightarrow \\ y(\vartheta_I - \vartheta_E + 2s) &= p_I^f - p_E^c + 2t \cdot x + s - t \Rightarrow \\ y(\vartheta_I - \vartheta_E + 2s) &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3t}{3} - t + w^c + 2t \cdot x + s - t \Rightarrow \\ y &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 6t \cdot x + 3s - 3t}{3(\vartheta_I - \vartheta_E + 2s)} \end{aligned} \quad (\text{A11})$$

Since y is a linear function of x , we can estimate its slope by finding its values at

$x = \hat{x}^c = \frac{1}{2}$ and $x = \hat{x}^f = \frac{\vartheta_I - \vartheta_E + 3t}{6t}$. The respectively derived values are:

$$\begin{aligned}
y &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 6t \cdot x + 3s - 3t}{3(\vartheta_I - \vartheta_E + 2s)} \Rightarrow \\
y &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 6t \left(\frac{1}{2}\right) + 3s - 3t}{3(\vartheta_I - \vartheta_E + 2s)} \Rightarrow \\
y_{\hat{x}^c} &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 3s}{3(\vartheta_I - \vartheta_E + 2s)} \tag{A12}
\end{aligned}$$

and

$$\begin{aligned}
y &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 6t \cdot x + 3s - 3t}{3(\vartheta_I - \vartheta_E + 2s)} \Rightarrow \\
y &= \frac{\vartheta_I - \vartheta_E + 3w^f + 3w^c + 6t \left(\frac{\vartheta_I - \vartheta_E + 3t}{6t}\right) + 3s - 3t}{3(\vartheta_I - \vartheta_E + 2s)} \Rightarrow \\
y_{\hat{x}^f} &= \frac{2\vartheta_I - 2\vartheta_E + 3w^f + 3w^c + 3s}{3(\vartheta_I - \vartheta_E + 2s)} \tag{A13}
\end{aligned}$$

The levels of the indifferent consumers \hat{x}^c , \hat{x}^f , y_I and y_E , as well as the values of $y_{\hat{x}^c}$ and $y_{\hat{x}^f}$ forms the total demand of each firm in each market. Figure 3 graphically presents the demand for each retail service and Lemma 1 numerically provides each demand (see also Appendix A3).

Substituting Eqs. (11), (24) and (26) into (28) gives the incumbent's profit from the copper market:

$$\begin{aligned}
\Pi_I^c &= [p_I^c - c_I^c]q_I^c + [w^c - c_I^c]q_E^c \Rightarrow \\
\Pi_I^c &= \frac{t^2(18s^2 + 3\vartheta_I^2 + 3\vartheta_E^2 + 15s\vartheta_I - 15s\vartheta_E - 6\vartheta_I\vartheta_E - 18sw^c + 18sw^f - 9\vartheta_Iw^c + 9\vartheta_Ew^c + 9w^f\vartheta_I - 9w^f\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\
&+ \frac{\vartheta_E^3(c^c - w^c) + \vartheta_I^3(w^c - c^c) + (w^c)^2(3\vartheta_I^2 + 3\vartheta_E^2 - 6\vartheta_I\vartheta_E - 36st + 12s\vartheta_I - 18t\vartheta_I - 12s\vartheta_E + 18\vartheta_E t)}{36st(\vartheta_I - \vartheta_E + 2s)} \\
&+ \frac{w^c(3\vartheta_I\vartheta_E^2 - 3\vartheta_E\vartheta_I^2 - 3w^f\vartheta_I^2 - 3w^f\vartheta_E^2 + 36ts^2 + 2s\vartheta_I^2 + 2s\vartheta_E^2 + 18st\vartheta_I - 18st\vartheta_E - 4s\vartheta_I\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\
&+ \frac{w^c \cdot c^c(-3\vartheta_I^2 - 3\vartheta_E^2 + 36st - 12s\vartheta_I + 12s\vartheta_E + 18t\vartheta_I - 18t\vartheta_E + 6\vartheta_I\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\
&+ \frac{c^c(18st\vartheta_E - 18st\vartheta_I + 4s\vartheta_I\vartheta_E - 36ts^2 - 2s\vartheta_I^2 - 2s\vartheta_E^2 - 3\vartheta_I\vartheta_E^2 + 3\vartheta_E\vartheta_I^2)}{36st(\vartheta_I - \vartheta_E + 2s)} \\
&+ \frac{c^c \cdot w^f(-36st - 18t\vartheta_I + 18t\vartheta_E + 3\vartheta_I^2 + 3\vartheta_E^2 - 6\vartheta_I\vartheta_E) + w^c \cdot w^f(36st + 18t\vartheta_I - 18t\vartheta_E + 6\vartheta_I\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \tag{A14}
\end{aligned}$$

Substituting Eqs. (11) and (26) into (30) gives the entrant's profit from the copper market:

$$\begin{aligned}\Pi_E^c &= [p_E^c - w^c]q_E^c \Rightarrow \\ \Pi_E^c &= \frac{3\vartheta_I^2 w^c + 3\vartheta_E^2 w^c - 3\vartheta_I^2 w^f - 3\vartheta_E^2 w^f + 18s^2 t + 2s\vartheta_I^2 + 2s\vartheta_E^2 - 3t\vartheta_I^2 - 3t\vartheta_E^2}{36s(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{3\vartheta_I\vartheta_E^2 - 3\vartheta_E\vartheta_I^2 + \vartheta_I^3 - \vartheta_E^3 - 18stw^c + 18stw^f + 12s\vartheta_I w^c - 12s\vartheta_E w^c - 9t\vartheta_I w^c}{36s(\vartheta_I - \vartheta_E + 2s)}\end{aligned}\quad (A15)$$

Substituting Eqs. (15), (25) and (27) into (29) gives the incumbent's profit from the fiber market:

$$\begin{aligned}\Pi_I^f &= [p_I^f - c_I^f]q_I^f + [w^f - c_I^f]q_I^f \Rightarrow \\ \Pi_I^f &= \frac{t^2(18s^2 - 3\vartheta_I^2 - 3\vartheta_E^2 + 3s\vartheta_I - 3s\vartheta_E + 6\vartheta_I\vartheta_E + 18sw^c - 18sw^f + 9w^c\vartheta_I - 9w^c\vartheta_E - 9w^f\vartheta_I + 9w^f\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{\vartheta_I^3(s - t + c^f - w^f) + \vartheta_E^3(t - s - c^f + w^f) + w^f(3\vartheta_I^2 + 3\vartheta_E^2 - 6\vartheta_I\vartheta_E - 18t\vartheta_I + 18t\vartheta_E - 36st)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{w^f(3\vartheta_E\vartheta_I^2 - 3\vartheta_I\vartheta_E^2 + 36s^2t - 4s\vartheta_I^2 - 4s\vartheta_E^2 - 3t\vartheta_I^2 - 3t\vartheta_E^2 + 6st\vartheta_I - 6st\vartheta_E + 8s\vartheta_I\vartheta_E + 6t\vartheta_I\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{c^f w^f(36st - 3\vartheta_I^2 - 3\vartheta_E^2 + 18t\vartheta_I - 18t\vartheta_E + 6\vartheta_I\vartheta_E) + w^c(3t\vartheta_I^2 + 3t\vartheta_E^2 - 2s\vartheta_I^2 - 2s\vartheta_E^2 + 4s\vartheta_I\vartheta_E - 6t\vartheta_I\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{w^c w^f(12s\vartheta_E - 3\vartheta_I^2 - 3\vartheta_E^2 + 18t\vartheta_I - 18t\vartheta_E + 6\vartheta_I\vartheta_E + 36st - 12s\vartheta_I)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{c^f(3\vartheta_I\vartheta_E^2 - 36s^2t + 2s\vartheta_I^2 + 2s\vartheta_E^2 - 3\vartheta_I^2\vartheta_E - 18st\vartheta_I + 18st\vartheta_E - 4s\vartheta_I\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{c^f w^c(12s\vartheta_I - 36st - 12s\vartheta_E - 18t\vartheta_I + 18t\vartheta_E - 6\vartheta_I\vartheta_E + 3\vartheta_I^2 + 3\vartheta_E^2)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{s^2(2\vartheta_I^2 + 2\vartheta_E^2 + 12t\vartheta_I - 12t\vartheta_E - 4\vartheta_I\vartheta_E)}{36st(\vartheta_I - \vartheta_E + 2s)} \\ &+ \frac{s \cdot t(4\vartheta_I^2 - 8\vartheta_I\vartheta_E + 4\vartheta_E^2) + s(3\vartheta_I\vartheta_E^2 - 3\vartheta_I^2\vartheta_E) + t(3\vartheta_I^2\vartheta_E - 3\vartheta_I\vartheta_E^2)}{36st(\vartheta_I - \vartheta_E + 2s)}\end{aligned}\quad (A16)$$

Substituting Eqs. (16) and (27) into (31) gives the entrant's profit from the fiber market:

$$\begin{aligned}\Pi_E^f &= [p_E^f - w^f]q_E^f \Rightarrow \dots \Rightarrow \\ \Pi_E^f &= \frac{[(3t - \vartheta_I + \vartheta_E)^2(3w^c - 3w^f + 3s + \vartheta_I - \vartheta_E)]}{108st}\end{aligned}\quad (A17)$$

The total profit of the incumbent (Π_I^{inv}) is the sum of its revenues derived from the use of its copper (Π_I^c) and fiber (Π_I^f) access networks minus the investment cost F ,

whereas, the total profit of the entrant is the sum of its profit derived from using the incumbent's copper (Π_E^c) and fiber (Π_E^f) access networks.

A2. Proof of Corollary 1

Let assume that $\vartheta_I > \vartheta_E$. Then:

$$\hat{x}^f > \hat{x}^c \Rightarrow \frac{\vartheta_I - \vartheta_E + 3t}{6t} > \frac{1}{2} \Rightarrow \vartheta_I - \vartheta_E + 3t > 3t \Rightarrow \vartheta_I > \vartheta_E \text{ (which always hold true).}$$

In addition, given that $\vartheta_I > \vartheta_E$, the following inequality holds:

$$y_I = \frac{\vartheta_I - \vartheta_E + 3(w^f - w^c)}{6s} + \frac{1}{2} > \frac{\vartheta_E - \vartheta_I + 3(w^f - w^c)}{6s} + \frac{1}{2} = y_E \Rightarrow$$

$$\vartheta_I - \vartheta_E > \vartheta_E - \vartheta_I \Rightarrow \vartheta_I > \vartheta_E$$

A3. Proof of Lemma 1

Figure 3 graphically presents the distribution of the consumers to each retail service supplied by each firm. Hence, calculating the area of the respective shape gives the number of consumers who choose to buy each service by which firm.

Calculating the area of the rectangle at the top left of the unit square gives the number of consumers who choose to buy the incumbent's copper-based service:

$$q_I^c = (\hat{x}^c \cdot y_I) = \frac{\vartheta_I - \vartheta_E + 3(w^f - w^c)}{12s} + \frac{1}{4} \Rightarrow$$

$$q_I^c = \frac{\vartheta_I - \vartheta_E + 3(w^f - w^c) + 3s}{12s} \quad (\text{A18})$$

Summing the area of the rectangle at the bottom left and the area of the respective trapezium gives the number of consumers who choose to buy the incumbent's fiber-based service:

$$q_I^f = [\hat{x}^f \cdot (1 - y_I)] + \left[\left((y_I - y_I') + (y_I - y_E') \right) \cdot (\hat{x}^f - \hat{x}^c) \right] / 2 \Rightarrow$$

$$\hat{x}^f \cdot (1 - y_I) + \left[(2y_I - y_I' - y_E') (\hat{x}^f - \hat{x}^c) \right] / 2 \Rightarrow$$

$$\frac{6s^2t + s\vartheta_I^2 + 2\vartheta_I s^2 + s\vartheta_E^2 - 2s^2\vartheta_E - t\vartheta_I^2 - t\vartheta_E^2 + 6stw^c - 6stw^f - 2s\vartheta_I w^c + 2s\vartheta_E w^c - 2s\vartheta_I w^f}{12st(\vartheta_I - \vartheta_E + 2s)}$$

$$+ \frac{2s\vartheta_E w^f + 3t\vartheta_I w^c - 3t\vartheta_E w^c - 3t\vartheta_I w^f + 3t\vartheta_E w^f + st\vartheta_I - st\vartheta_E - 2s\vartheta_I\vartheta_E + 2t\vartheta_I\vartheta_E}{12st(\vartheta_I - \vartheta_E + 2s)} \quad (\text{A19})$$

Furthermore, summing the area of the rectangle at the top right of the unit square and the respective area of the trapezium provides the number of consumers who choose to buy the entrant's copper-based service:

$$\begin{aligned}
q_E^c &= y_E \cdot (1 - \hat{x}^c) + \left(\frac{[(y_E' - y_E) + (y_I' - y_E)] \cdot (\hat{x}^f - \hat{x}^c)}{2} \right) \Rightarrow \\
q_E^c &= \frac{3w^c \vartheta_E^2 - 3w^f \vartheta_I^2 + 3w^c \vartheta_I^2 - 3w^f \vartheta_E^2 + 18ts^2 + 2s\vartheta_I^2 + 2s\vartheta_E^2 - 3t\vartheta_I^2 - 3t\vartheta_E^2 + 3\vartheta_I \vartheta_E^2 - 3\vartheta_E \vartheta_I^2}{36st(\vartheta_I - \vartheta_E + 2s)} \\
&+ \frac{\vartheta_I^3 - \vartheta_E^3 - 18stw^c + 18stw^f + 12s\vartheta_I w^c - 12s\vartheta_E w^c - 9t\vartheta_I w^c + 9t\vartheta_E w^c}{36st(\vartheta_I - \vartheta_E + 2s)} \\
&+ \frac{6\vartheta_I \vartheta_E w^f + 3st\vartheta_I - 3st\vartheta_E - 4s\vartheta_I \vartheta_E + 6t\vartheta_I \vartheta_E + 9t\vartheta_I w^f - 9t\vartheta_E w^f - 6\vartheta_I \vartheta_E w^c}{36st(\vartheta_I - \vartheta_E + 2s)} \tag{A20}
\end{aligned}$$

Last, calculating the area of the rectangle at the bottom right of the unit square yields the number of consumers who choose buy the entrant's fiber-based service:

$$\begin{aligned}
q_E^f &= (1 - y_E) \cdot (1 - \hat{x}^f) = \left(1 - \frac{\vartheta_E - \vartheta_I + 3w^f - 3w^c + 3s}{6s} \right) \cdot \left(1 - \frac{\vartheta_I - \vartheta_E + 3t}{6t} \right) \Rightarrow \\
q_E^f &= \frac{2\vartheta_I \vartheta_E - \vartheta_I^2 - \vartheta_E^2 - 3s\vartheta_I + 3s\vartheta_E + 3\vartheta_I w^f - 3\vartheta_E w^f - 3\vartheta_I w^c + 3\vartheta_E w^c - 3t\vartheta_E + 3t\vartheta_I + 9st - 9tw^f + 9tw^c}{36st} \tag{A21}
\end{aligned}$$

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