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# A model of international roaming regulation and competition in European mobile markets

*Very preliminary draft - Please Do Not Cite or Quote Without Permission*

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## Abstract

This paper investigates the impacts of the current roaming rules on domestic competition and welfare. We consider a model for two countries in which each country has two operators that compete in the retail market for access services and also in the wholesale market for roaming. We first derive equilibrium prices in the two markets when operators are not subjected to regulatory restrictions. We then introduce Roaming Like At Home (RLAH) obligation and show how retail tariffs and wholesale roaming charges can be sensitive to this regulatory regime. Since introducing a fair use clause in roaming regulation can be a tool to avoid permanent roaming, we study different cases depending on whether RLAH is accompanied by a fair use safeguard or not. We emphasize the most interesting results, considering the role played by cost and demand asymmetries between operators and countries.

*JEL Codes: L13, L51, L96*

*Key words: International roaming, mobile telecommunications, roaming like at home, fair use policy, interconnection*

## 1 Introduction

International roaming - which refers to a mobile customer's ability to send receive calls and data when travelling to a foreign country - has given rise to intense debates on regulatory

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reviews in the European Union. International roaming requires mobile operators to sign roaming agreements with foreign operators, specifying both the technical conditions and wholesale tariffs charged by the visited network operator. Several studies have shown that roaming markets in Europe are traditionally characterized by a lack of competition that makes roaming prices, that are largely greater than pertinent costs at both the wholesale and retail levels (see OECD, 2011; Infante and Vallejo, 2012 for instance). Thus the European Commission (EC 2007) introduced roaming regulation in 2007 that included price caps for roaming services. Since 2007, roaming regulation has been revised several times leading to price cap adjustments, as roaming prices remain greater than domestic prices. The European policy target is to allow customers to consume roaming services at domestic prices while travelling in another EU country, i.e., the so-called RLAH (Roaming Like At Home) obligation. The objective established by the "Telecom Single Market" regulation is to enable the abolition of retail roaming charges by June 2017. The debate has recently focused on the review of wholesale roaming and fair use policies dedicated to the anomalous usage that may come from the implementation of RLAH obligation. Therefore, the EU Council set June 2017 as the deadline to end roaming surcharges and to ensure that operators offer roaming services similar to domestic services. However, several questions can arise when discussing the RLAH obligation in the EU. Because it extends domestic prices to roaming services, RLAH could distort competition in domestic markets and thereby cause potential negative impacts in the long-run. This risk could be reinforced if the RLAH obligation is not accompanied by a fair use policy that controls the unusual behaviours that could lead to permanent roaming<sup>1</sup>. Additionally, operators' ability to offer RLAH should be linked to wholesale regulation, i.e. price caps on the wholesale roaming services.

Despite the widespread policy debate over international roaming and the large body of economic literature examining mobile competition, a formal analysis of international roaming regulation has remained limited. Salsas and Koboldt (2004) considered a model of two countries, the home country, in which operators compete in the retail market for roaming services, and the visited country, in which operators compete only in the roaming wholesale market. They found that wholesale roaming charges are very sensitive to the number of visited networks and that the visited country cannot have any incentive to lower

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<sup>1</sup>The recent European regulatory review of the international roaming also discussed other safeguards against abuse based on clear principles, e.g., the criterion of residence.

its roaming charge. Finally, they also showed that cross-border mergers cannot correct this situation. Lupi and Manenti (2009) studied a two-country two-operator which studies the impact of traffic management allowing by traffic direction techniques. They show that traffic steering cannot improve market efficiency and that a price cap mechanism can partially restore efficiency in the wholesale market. These papers<sup>2</sup> were the first attempts to analyse the impacts of international roaming, but they did not consider retail competition and the possible relationships between domestic and roaming markets at both the retail and wholesale levels. More recently, Bühler (2015) developed a model of international roaming in which operators competed on both the wholesale and retail market to offer roaming services. In a setup of two equally sized countries and two operators in each, the paper focused particularly on the impact of international roaming alliances. The main results showed that operators have incentives to form alliances and to provide roaming services at inefficiently high wholesale prices. These alliances can then be seen as an efficient tool to avoid the competitive pressure that arises from the development of roaming steering technologies.

The present literature on international roaming has interesting policy implications but does not consider the possible interactions between roaming and domestic markets for access nor addresses the recent debate on the impacts of the RLAH obligation and fair use policy. This paper intends to help fill this void in the literature and to provide guidance for regulatory policy on international roaming.

More precisely, we develop a model in which two mobile network operators compete on the retail market in each of the two countries. These operators provide access services to subscribers in the home country and roaming services when these subscribers seek access from abroad. Each operator's network covers only the home country. Therefore, in each country operators compete on the wholesale market to provide roaming service to foreign operators. We then compare retail and wholesale pricing according to whether mobile operators are subjected to the RLAH obligation. Without RLAH, operators are free to set different retail prices for domestic and roaming access services, while under the RLAH obligation, operators cannot price-discriminate, and thus, subscribers pay the same price at home and abroad. We consider that RLAH regulations can include safeguards that prevent potential abusive uses, particularly when consumers with domestic subscrip-

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<sup>2</sup>Other papers in the same vein have studied international roaming, see for instance Ambjornsen et al. (2011).

tions in their home countries remain abroad permanently. The fair use safeguard clause therefore exists to ensure that consumers do not abuse roaming by subscribing or buying inexpensive SIM-cards from foreign operators and using them permanently in their home countries. Thus, European regulations might allow visited networks operators to specify measures to prevent such abusive behaviours and, if necessary, to prohibit the usage of SIM cards from specific countries. To simplify the analysis, we consider two contrasting cases when examining the impact of the RLAH obligation. First, we investigate the regulatory regime in which RLAH is accompanied by a strict safeguard clause that prohibits consumers' ability to subscribe to foreign operators (limited RLAH). We then relax this prohibition and allow consumers to subscribe to foreign operators (unlimited RLAH). Consequently, in this setting, all four of the operators compete in the retail market in each country.

The remainder of this paper is organized as follows. Section 2 presents the basic model and main assumptions. Section 3 characterizes the benchmark case, in which operators are not subjected to roaming regulations. Section 4 examines the change in retail tariffs and wholesale roaming charges from the implementation of the RLAH obligation accompanied by a fair use policy. Section 5 determines equilibrium in the unlimited RLAH regime. Finally, section 6 reviews the general results and provides potential directions for future research.

## 2 The basic model

We establish a model with two countries,  $x$  and  $y$ , with two mobile operators in each. Let us denote  $x_i$  and  $y_i$  as the home operators, in countries  $x$  and  $y$  respectively, with  $i = 1, 2$ . Each operator's network covers only the home country and each operator provides wholesale roaming services to foreign operators. More precisely, every operator participates in two related markets. First, each operator competes with the home rival in the retail market. Second, the home operators compete with each other in the wholesale market to provide roaming services to foreign operators. We assume that each operator signs roaming agreements with the two foreign operators. Hereafter, we denote by subscript " $\hat{\cdot}$ " all of the variables and parameters of country  $y$ .

**Roaming flows, costs and prices.** We consider that subscribers seek network access

both from the home country and abroad, and we assume that roaming flows are exogenous and country-specific. Additionally, we denote  $\gamma$  (resp.  $\hat{\gamma}$ ) the probability for subscribers who live in country  $x$  (resp.  $y$ ) to use their mobile when travelling. The probability  $\gamma$  can be explained both by country economic characteristics (e.g. level of GDP per capita, structure and intensity of trade between both countries) and subscribers' individual socio-economic characteristics. Therefore, subscribers from country  $x$  (resp.  $y$ ) seeks access in the home market with probability  $1 - \gamma$  (resp.  $1 - \hat{\gamma}$ ) and when travelling with probability  $\gamma$  (resp.  $\hat{\gamma}$ ).

Each operator bears a same marginal cost when subscribers seek network access from the home country. We denote  $c$  (resp.  $\hat{c}$ ) the unit marginal cost for home operators  $xi$  (resp.  $yi$ ). Without loss of generality, we assume hereafter that  $c > \hat{c}$ , that is country  $x$  is the high cost country and country  $y$  the low cost country<sup>3</sup>. To allow its subscribers to seek access while travelling, each operator must buy roaming services on the wholesale market from foreign operators. Thus, in each country home operators compete on the wholesale market to provide roaming services to foreign operators. We denote  $a_{xi}$  (resp.  $\hat{a}_{yi}$ ) the wholesale roaming charge set by home operator  $xi$  (resp.  $yi$ ) and paid by foreign operators to allow their subscribers to seek access from abroad. We assume that travelling subscribers' traffic is distributed over the two visited operators depending on the strength and quality of signals received from their networks<sup>4</sup>. We thus consider that operators are unable to direct roaming traffic to a particular visited network. Network selection is then operated by handset selection or directly by subscribers who manually select the visited network. Consequently, wholesale demand for roaming services is directly derived from retail demand (depending on the probability of travelling) and the roaming cost for operators corresponds to the weighted average wholesale roaming charges set by visited operators. Finally, we denote by  $\rho_{xi}$  (resp.  $\hat{\rho}_{yi}$ ) the probability of the roaming traffic to roam onto operator  $xi$ 's network (resp.  $yi$ ). Due to the symmetry between operators in each country, the roaming marginal cost is then set at  $c_x = \hat{\rho}_{y1}\hat{a}_{y1} + \hat{\rho}_{y2}\hat{a}_{y2}$ , for home operators in country  $x$ , and  $\hat{c}_y = \rho_{x1}a_{x1} + \rho_{x2}a_{x2}$ , for home operator in country  $y$ .

**Demand structure.** We consider Chen and Riordan's (2007) spokes model, in which

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<sup>3</sup>The cost bearing by operators is made of the sum between retail costs and network costs. Countries have usually different costs because they have different densities, coverage obligations, costs of license, labour costs, etc.

<sup>4</sup>We do not consider here a situation in which operators can negotiate with foreign operators on the wholesale charges (and the roaming volume) at which they provide roaming services. This is left for future research.

there are  $N = 4$  possible varieties of network access services, each provided by a single operator. Each variety is located at the origin of a spoke of length  $l_s = \frac{1}{2}$ , with  $s = 1, \dots, 4$ . The market is thus composed of a set of 4 spokes with a common core in each country. In each country, we assume that consumers are uniformly distributed on the spokes network with a total mass of consumers normalized to unity so the density of consumers per spoke is  $\frac{1}{2}$  ( $= \frac{2}{N}$ ). Hereafter, we will consider two cases according to whether or not the RLAH obligation is considered. When operators are not subjected to the RLAH obligation, they cover only their home markets so there are only two operators (i.e. home operators) located on the spokes network in each country whereas there are  $N = 4$  possible varieties of network access services for consumers, i.e. two varieties are not offered. Under RLAH, operators cannot discriminate between consumers adopting home and roaming access services. If RLAH is accompanied with a (strict) fair use clause, regulation prohibits consumers from subscribing to foreign operators, then still only two varieties are supplied in each country. In the absence of a fair use clause, operators can provide services to consumers in both countries. Hence, all four varieties are supplied and the model allows to locate the 4 operators on the spokes network in each country without modifying how consumers are distributed on the spokes.

Let us now consider the case in which the RLAH obligation is not introduced. Without loss of generality, we assume that in country  $x$  (resp.  $y$ ) operators  $x_1$  and  $x_2$  (resp.  $y_1$  and  $y_2$ ) are located at the extremity of lines  $l_1$  and  $l_2$ , respectively. Then, in both countries only service varieties 1 and 2 are supplied to consumers, while the other two are not. We follow Chen and Riordan (2007) by assuming that consumers prefer only two varieties. That is, a consumer in country  $x$  who likes the service variety offered by operator  $x_1$  has a second preferred variety, which can be the variety provided by operator  $x_2$  or one of the two other varieties that are not available (located at the extremities of lines  $l_3$  and  $l_4$ ). The same applies for consumers who live in country  $y$ , which indicates that we must distinguish two types of consumers: consumers who have preference for two supplied varieties and captive consumers for which only one of the preferred varieties is available. Note that since there are also consumers for which the two preferred varieties are not available, the market is not fully covered.

Let us consider country  $x$  and denote  $t$  the unit transportation cost in the choice of operator<sup>5</sup>. Given  $v > 0$  the standalone utility that consumers obtain from having network

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<sup>5</sup>For the sake of simplicity, we assume that the unit transportation costs are the same in both countries.

access and  $w_{xi}$  the indirect utility from joining operator  $xi$ , and the utility of consumers located at  $\alpha \in [0, \frac{1}{2}]$  on line  $l_1$  are set to  $v + w_{x1} - t\alpha$ , if they join operator  $x1$  and  $v + w_{x2} - t(1 - \alpha)$ , if they join operator  $x2$ . The marginal consumer  $\alpha$  between operators  $x1$  and  $x2$  (the first type of consumers) is thus given by  $w_{x1} - t\alpha = w_{x2} - t(1 - \alpha)$ . We denote  $\sigma = \frac{1}{2t}$  the substitutability parameter, the market share of operator  $x1$  from such consumers is

$$\frac{1}{2} \times \frac{1}{3} \left( \frac{1}{2} + \sigma(w_{x1} - w_{x2}) \right)$$

where  $\frac{1}{2}$  is the density of consumers on each spoke and  $\frac{1}{3}$  ( $= \frac{1}{N-1}$ ) is the proportion of consumers for which the two preferred varieties are supplied.

For the second type of consumers, we assume that the standalone utility  $v$  is sufficiently high to ensure that all captive consumers are served. That is, the market share from such consumers for operator  $xi$  is  $\frac{2}{3} \times \frac{1}{2} = \frac{1}{3}$ , where  $\frac{2}{3}$  ( $= \frac{N-2}{N-1}$ ) is the proportion of consumers for which one of the two preferred varieties is not available, and  $\frac{1}{2}$  is the density of consumers on each spoke.

Summing up and rearranging terms, the market share in country  $x$  is  $\alpha_{xi} = \frac{5}{12} + \frac{\sigma}{6}(w_{xi} - w_{xj})$  for operator  $xi$  with  $i \neq j$ . The market shares in country  $y$  can be deduced by symmetry and are then given by  $\hat{\alpha}_{yi} = \frac{5}{12} + \frac{\sigma}{6}(\hat{w}_{yi} - \hat{w}_{yj})$ . Note that  $\alpha_{x1} + \alpha_{x2} < 1$  and  $\hat{\alpha}_{y1} + \hat{\alpha}_{y2} < 1$ ; that is, the market is not fully covered in the two countries.

Each operator  $xi$  offers a three-part tariff  $\mathbf{p}_{xi} = (p_{xi}, r_{xi}, F_{xi})$ , where  $p_{xi}$  is the unit retail price for home access,  $r_{xi}$  the roaming retail price, and  $F_{xi}$  the subscription fee. Therefore, given tariff  $\mathbf{p}_{xi}$  and  $\gamma$ , the roaming flows of country  $x$ , the indirect utility from joining operator  $xi$  is given by:

$$w_{xi} = v + (1 - \gamma)v(p_{xi}) + \gamma v(r_{xi}) - F_{xi} \quad (1)$$

where  $v$  is the fixed utility from access,  $v(p) = u(q(p)) - pq(p)$  is the indirect utility associated with  $p$ ,  $q(p)$  is the individual demand, and  $u(q)$  is the utility from  $q$  access units. In the following, we consider a constant elasticity demand function. Therefore, the demand function is given by  $q(p) = d - p$ , and the indirect utility is written as  $v(p) = \frac{(d-p)^2}{2}$ . similarly, in country  $y$ , the indirect utility from joining operator  $yi$  is  $\hat{w}_{yi} = \hat{v} + (1 - \hat{\gamma})\hat{v}(\hat{p}_{yi}) + \hat{\gamma}\hat{v}(\hat{r}_{yi}) - \hat{F}_{yi}$ , where  $\hat{v}(p) = u(\hat{q}(p)) - p\hat{q}(p)$  and  $\hat{q}(p) = \hat{d} - p$ . Hereafter, we consider that the fixed utility parameter is the same in the two countries,



$v = \widehat{v}$ . Finally, we assume that  $d \geq \widehat{d}$ , that is country  $x$  is the high demand country and country  $y$  the low demand country. Hence, because  $c > \widehat{c}$ , we assume that country  $x$  is the high-demand and high-cost country and country  $y$  is the low-cost and low-demand country.

**Profit functions.** The total profit of operator  $xi$  is  $\Pi_{xi} = \pi_{xi}^r + \pi_{xi}^w$ , where  $\pi_{xi}^r$  and  $\pi_{xi}^w$  are the retail profit and the wholesale roaming profit, respectively. Hence, for operator  $xi$ , the total profit  $\Pi_{xi}$  is obtained considering the retail profit

$$\pi_{xi}^r = \alpha_{xi} \{ (1 - \gamma)(p_{xi} - c)q(p_{xi}) + \gamma(r_{xi} - c_x)q(r_{xi}) + F_{xi} \}, \quad (2)$$

and its wholesale profit

$$\pi_{xi}^w = \rho_{xi} \widehat{\gamma} (a_{xi} - c) \{ \widehat{\alpha}_{y1} \widehat{q}(\widehat{r}_{y1}) + \widehat{\alpha}_{y2} \widehat{q}(\widehat{r}_{y2}) \}. \quad (3)$$

By symmetry, the operator  $yi$  offers a tariff  $\widehat{\mathbf{p}}_{yi} = (\widehat{p}_{yi}, \widehat{r}_{yi}, \widehat{F}_{yi})$  and its total profit  $\widehat{\Pi}_{yi} = \widehat{\pi}_{yi}^r + \widehat{\pi}_{yi}^w$  is deduced from (2) and (3).

The next section determines the Nash equilibrium prices  $(p_{xi}, r_{xi}, F_{xi})$  and  $(\widehat{p}_{yi}, \widehat{r}_{yi}, \widehat{F}_{yi})$  for each operator for a given set of wholesale roaming prices.

### 3 The benchmark: No regulation

In this section, we set up as a benchmark the regime in which operators can freely price-discriminate against consumers in the retail market according to whether they seek access from home or while travelling, i.e. the no regulation regime. We consider a two-stages game: in the first stage, operators non cooperatively choose the wholesale roaming prices that foreign operators pay when their consumers seek access from abroad; in the second stage, home operators in the two countries set their retail prices for domestic and roaming access services. In the following, we solve the game by backward induction. First, we derive the retail equilibrium prices in the two countries. Then, we characterize the wholesale roaming charges considering both countries  $x$  and  $y$ .

### 3.1 Retail market equilibrium

Assuming subgame perfect equilibrium, we begin by solving the second stage of the game. In this stage, operators set retail prices, taking the roaming charges as given. We then characterize equilibrium prices in the retail market, market shares and equilibrium profits. For simplicity, we determine equilibrium only for country  $x$  and then deduce by symmetry the equilibrium for country  $y$ .

Using (1), it is convenient to express the profit functions in terms of retail unit prices  $(p_{xi}, r_{xi})$  and the indirect utility  $w_{xi}$ . The fixed fee of operator  $xi$  is then given by  $F_{xi} = (1 - \gamma)v(p_{xi}) + \gamma v(r_{xi}) + v - w_{xi}$ , and retail profit becomes:

$$\pi_{xi}^r = \alpha_{xi} \{ (1 - \gamma)(p_{xi} - c)q(p_{xi}) + \gamma(r_{xi} - c_x)q(r_{xi}) + (1 - \gamma)v(p_{xi}) + \gamma v(r_{xi}) + v - w_{xi} \}, \text{ for } i = 1, 2$$

The first order conditions for operator  $xi$  with respect to  $p_{xi}$  and  $r_{xi}$  are

$$\frac{\partial \pi_{xi}^r}{\partial p_{xi}} = \alpha_{xi} \{ (1 - \gamma)(p_{xi} - c)q'(p_{xi}) + (1 - \gamma)q(p_{xi}) + (1 - \gamma)v'(p_{xi}) \} = 0$$

and

$$\frac{\partial \pi_{xi}^r}{\partial r_{xi}} = \alpha_{xi} \{ \gamma(r_{xi} - c_x)q'(r_{xi}) + \gamma q(r_{xi}) + \gamma v'(r_{xi}) \} = 0$$

Using  $v'(p) = -q(p)$ , the first order conditions yield to the equilibrium unit prices. We obtain equilibrium prices that are symmetric for operators in the same country, that is  $(p_x^*, r_x^*)$  and  $(\hat{p}_y^*, \hat{r}_y^*)$ , respectively, for countries  $x$  and  $y$ :

$$\begin{aligned} p_x^* &= c & \text{and} & & r_x^* &= c_x \\ \hat{p}_y^* &= \hat{c} & \text{and} & & \hat{r}_y^* &= \hat{c}_y \end{aligned} \quad (4)$$

Provided that operators  $xi$  and  $yi$  set usage prices (4), their profits can be expressed with respect to subscription fees  $F_{xi}$  and  $\hat{F}_{yi}$  and become  $\pi_{xi}^r = \alpha_{xi} F_{xi}$  and  $\hat{\pi}_{yi}^r = \hat{\alpha}_{yi} \hat{F}_{yi}$ .

We now determine operators' choices of subscription fees  $F_{xi}$  and  $\hat{F}_{yi}$ . In each country, each operator optimally chooses its subscription fee, taking the other operator's fee as a given. The first order conditions for operator  $xi$ 's profit maximization are:

$$\frac{\partial \pi_{xi}}{\partial F_{xi}} = \alpha_{xi} + \frac{\partial \alpha_{xi}}{\partial F_{xi}} F_{xi} = 0 \text{ for } i = 1, 2.$$

Solving the system for the two first order conditions, we find that the two home operators in country  $x$  set the same subscription fee  $F_x^* = \frac{5}{2\sigma}$  at equilibrium. By symmetry and since the substitutability parameters are the same in both countries, the symmetric equilibrium fee for home consumers in country  $y$  is  $\widehat{F}_y^* = F_x^* = \frac{5}{2\sigma}$ .

The following lemma summarizes the results.

**Lemma 1 .** *The retail equilibrium in the two countries is  $\mathbf{p}_x^* = (c, c_x, F_x^*)$  and  $\widehat{\mathbf{p}}_y = (\widehat{c}, \widehat{c}_y, \widehat{F}_y^*)$ , where  $c_x = \widehat{\rho}_{y1}\widehat{a}_{y1} + \widehat{\rho}_{y2}\widehat{a}_{y2}$  and  $\widehat{c}_y = \rho_{x1}a_{x1} + \rho_{x2}a_{x2}$ , and the subscription fees are  $F_x^* = \widehat{F}_y^* = 5/(2\sigma)$ .*

This lemma indicates that equilibrium usage prices are equal to the perceived marginal costs for both home and roaming services in the two countries, which is now well known. More interestingly, it appears that the roaming price ( $r_x^*$  and  $\widehat{r}_y^*$ ) is not necessarily greater than the domestic price ( $p_x^*$  and  $\widehat{p}_y^*$ ) in both countries. The ranking between both usage prices depends directly on how the unit cost of home access ( $c$  and  $\widehat{c}$ ) compares to the cost of roaming access ( $c_x$  and  $\widehat{c}_y$ ) and particularly on whether or not wholesale roaming charges are relatively high. Hence, if wholesale charges are sufficiently high, home consumers pay more for roaming than for domestic services. In contrast, if wholesale charges are set at cost, then domestic prices in both countries are greater than roaming retail prices. This situation can arise if wholesale roaming charges are cost-based regulated or if they are set in a standard Bertrand competition between home operators on the wholesale market. Finally, note that the symmetric equilibrium subscription fees are equal to  $5/(2\sigma)$  and then decrease in accordance with the intensity of competition between home operators (i.e., decreasing with  $\sigma$ ). Ultimately, the symmetric equilibrium of retail profits is independent of wholesale roaming charges and is equal to  $\pi_x^* = \widehat{\pi}_y^* = 25/(24\sigma)$ .

### 3.2 Wholesale market equilibrium

Let us now consider the case in which operators non cooperatively choose their roaming charges to maximize their wholesale roaming profits  $\pi_{xi}^w$  and  $\widehat{\pi}_{yi}^w$ . Considering (4), the retail prices for roaming are symmetric at equilibrium, and then, symmetric market shares

are equal to  $\alpha_x^* = \hat{\alpha}_y^* = 5/12$ . Hence, wholesale roaming profits (3) become  $\pi_{xi}^w = 2\hat{\alpha}_y^* \rho_{xi} \hat{\gamma} (a_{xi} - c) \hat{q}(\hat{r}_y^*)$ , for home operators in country  $x$  and  $\hat{\pi}_{yi}^w = 2\alpha_x^* \hat{\rho}_{yi} \gamma (\hat{a}_{yi} - \hat{c}) q(r_x^*)$  for home operators in country  $y$ .

The first order conditions for operator  $xi$  profit maximization are written as:

$$\hat{q}(\hat{r}_y) + (a_{xi} - c) \hat{q}'(\hat{r}_y) \frac{\partial \hat{r}_y}{\partial a_{xi}} = 0, \text{ for } i = 1, 2 \quad (5)$$

The f.o.c. (5) can be rewritten as:

$$\frac{\hat{q}(\hat{r}_y)}{\hat{q}'(\hat{r}_y)} + \left( \frac{a_{xi} - c}{a_{xi}} \right) \left( \frac{\hat{q}'(\hat{r}_y)}{\hat{q}(\hat{r}_y)} \hat{r}_y \right) \left( \frac{a_{xi} \frac{\partial \hat{r}_y}{\partial a_{xi}}}{\hat{r}_y} \right) = 0, \text{ for } i = 1, 2$$

Rearranging terms, the equilibrium wholesale roaming charges  $a_{xi}^*$  are given by:

$$\frac{a_{xi}^* - c}{a_{xi}^*} = \frac{1}{\hat{\varepsilon} \cdot \eta_{\hat{r}}}, \text{ for } i = 1, 2 \quad (6)$$

where  $\hat{\varepsilon}$  is the price elasticity of (roaming) demand for home consumers in country  $y$  and  $\eta_{\hat{r}} = \frac{a \hat{r}'_y(a)}{\hat{r}_y(a)}$  is the elasticity of the roaming retail price  $\hat{r}$  with respect to the wholesale charge  $a$ . Note that the term  $\hat{\varepsilon} \cdot \eta_{\hat{r}}$  represents the elasticity of the roaming demand of operator  $xi$  with respect to the wholesale charge. Then, if we denote  $Q_{xi} = 2\hat{\alpha}_y^* \rho_{xi} \hat{\gamma} \hat{q}(\hat{r}_y^*)$  as the roaming demand hosted by operator  $xi$ , the elasticity with respect to the wholesale charge is  $-aQ'_{xi}/Q_{xi} = \hat{\varepsilon} \cdot \eta_{\hat{r}}$ . Similarly, we can deduce wholesale charges  $\hat{a}_{yi}$  of home operators in country  $y$ , i.e.  $(\hat{a}_{yi}^* - \hat{c})/\hat{a}_{yi}^* = 1/(\varepsilon \cdot \eta_r)$ .

The following proposition states the result.

**Proposition 1** . *The wholesale roaming charges are given by the Lerner index as characterized by equation (6). In the two countries, the roaming charges are greater than the marginal cost of service. These mark-ups decrease both with the price elasticity of roaming demand and with the elasticity of the foreign retail price. With a linear demand function, the equilibrium wholesale roaming charges are explicitly given by  $a_{xi}^* = \frac{\hat{d} - \rho_{xj}c + 2\rho_{xi}c}{3\rho_{xi}}$  and  $\hat{a}_{yi}^* = \frac{d - \hat{\rho}_{yj}\hat{c} + 2\hat{\rho}_{yi}\hat{c}}{3\hat{\rho}_{yi}}$ , for  $i = 1, 2$ .*

First, note that equilibrium roaming charges are higher than the corresponding marginal cost ( $a_{xi}^* > c$  and  $\widehat{a}_{yi}^* > \widehat{c}$ ). Equation (6) clearly shows how the equilibrium mark-ups on roaming charges are affected both by the price elasticity of demand and the elasticity of the roaming retail price in the foreign country. As expected, the mark-ups decrease with the price elasticity of demand. Note that what matters here is foreign consumers' demand for roaming services. Expression (6) also shows how mark-ups are linked to the elasticity of the roaming retail price set by foreign operators. Hence, mark-ups and wholesale charges decrease with this elasticity (i.e.,  $\eta_{\widehat{r}}(a_{xi}^*)$  or  $\eta_r(\widehat{a}_{yi}^*)$ ). More precisely, greater elasticity of the roaming price offered to consumers in the foreign country reduces wholesale charges by home operators in the visited country, and the elasticity of the retail price depends on how roaming traffic is split between visited operators. We can easily show that  $\eta_{\widehat{r}}(a_{xi})$  and  $\eta_r(\widehat{a}_{yi})$  increase with  $\rho_{xi}$  and  $\widehat{\rho}_{yi}$ , respectively, i.e., the quality of signals from visited networks. This finding may explain why operators might have incentives to lower their investments in network quality; they would aim to under-invest in order to reduce the elasticity of foreign operators' roaming retail prices and thus to relax competition in the wholesale market.

Plugging (6) into (3), we obtain the explicit wholesale roaming profits at equilibrium ( $\pi_x^w$ ) $^* = \frac{5}{54}\widehat{\gamma}(\widehat{d} - c)^2$  and ( $\widehat{\pi}_y^w$ ) $^* = \frac{5}{54}\gamma(d - \widehat{c})^2$ , and quantities are  $q_x^* = \frac{d-c}{3}$  and  $\widehat{q}_y^* = \frac{\widehat{d}-\widehat{c}}{3}$ . Combined with  $\pi_x^*$  and  $\widehat{\pi}_y^*$ , we obtain the total profits for home operators in both countries at the equilibrium, i.e.,  $\Pi_x^*$  and  $\widehat{\Pi}_y^*$ .

## 4 Limited RLAH

In this section, we consider that operators are subjected to the RLAH obligation which does not allow operators to price-discriminate consumers between home and roaming access services. Thus, consumers pay the same price at home and abroad. The regulatory debate has raised questions about potentially abusive use of roaming, which might particularly be the case if consumers subscribe to foreign operators and permanently seek access in their home countries. This usage is considered unusual behaviour that can lead to so-called "permanent roaming" and thus create competition distortions on the domestic market, particularly when very low-cost businesses can be developed on this basis. The recent European regulatory review offered several solutions to avoid unusual roaming behaviour from subscribers. In the debate, several stakeholders exerted pressure to intro-

duce into the RLAH regulation a fair use safeguard clause that would allow operators to apply an additional charge to their roaming subscribers using more than the fair use in order to avoid such unusual roaming use<sup>6</sup>.

In the following section, we consider the possibility for the RLAH obligation to be coupled with a fair use safeguard. For simplicity, we consider a strict version of the safeguard rule that assumes that operators cannot provide access services to consumers living abroad, i.e. the limited RLAH regime. Hereafter, we denote by subscript "L" the equilibrium outcomes. We first compare competition in the retail market by examining the equilibrium in the wholesale roaming market, and then make comparisons with equilibrium outcomes in the benchmark case.

## 4.1 Competition in retail markets

Let us first determine equilibrium prices in the retail market in each country. We state the result for country  $x$  and then deduce the result for country  $y$ . Therefore, we depart from the benchmark case, now assuming that operators cannot price-discriminate between consumers accessing services from the home country and those accessing from abroad. Each operator  $xi$  now sets a same unit retail price for home and roaming access, which is denoted as  $p_{xi}$ , and then offers a two-part tariff  $\mathbf{p}_{xi} = (p_{xi}, F_{xi})$ . Similarly, in country  $y$ , each operator offers a two-part tariff  $\widehat{\mathbf{p}}_{yi} = (\widehat{p}_{yi}, \widehat{F}_{yi})$  to its home consumers.

The indirect utility from joining operator  $xi$  is now equal to  $w_{xi} = v + v(p_{xi}) - F_{xi}$ . Substituting  $F_{xi} = v + v(p_{xi}) - w_{xi}$  and plugging  $r_{xi} = p_{xi}$  into (2), the retail profit of operator  $xi$  becomes

$$\pi_{xi}^r = \alpha_{xi} [p_{xi} - (1 - \gamma)c - \gamma c_{xi}] q(p_{xi}) + \alpha_{xi} [v(p_{xi}) + v - w_{xi}], \text{ for } i \neq j \quad (7)$$

Expression (7) shows that no discrimination between home and roaming access results in clear interdependence between home and roaming profits. Thus, it appears that the perceived cost for a unit of access is a combination between the marginal cost of home access and the marginal cost of access from abroad. That is, the domestic retail price

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<sup>6</sup>We couple RLAH here with a regulatory tool that avoids permanent roaming by domestic subscribers. In fact, RLAH and allowing or prohibiting permanent roaming are two distinct regulatory tools. In this paper, we consider a regulatory policy that can mix both tools, but in the absence of RLAH, permanent roaming could also be an issue.

will be based on the wholesale roaming charges set by foreign operators. This finding directly illustrates how the RLAH obligation can affect domestic retail prices and lead to distortion in competition.

From (7), we can write the first order condition for operator  $xi$  with respect to  $p_{xi}$ :

$$\frac{\partial \pi_{xi}^r}{\partial p_{xi}} = \alpha_{xi} q(p_{xi}) + \alpha_{xi} [p_{xi} - (1 - \gamma)c - \gamma c_x] q'(p_{xi}) + \alpha_{xi} v'(p_{xi}) = 0,$$

and the symmetric equilibrium retail prices in both country are:

$$p_x^L = (1 - \gamma)c + \gamma c_x \quad \text{and} \quad \hat{p}_y^L = (1 - \hat{\gamma})\hat{c} + \hat{\gamma}\hat{c}_y \quad (8)$$

which reflects a weighted average of true marginal costs.

The next lemma summarizes the results.

**Lemma 2 .** *Under limited RLAH, the retail equilibrium in the two countries is  $\mathbf{p}_x^L = (p_x^L, F_x^L)$  and  $\hat{\mathbf{p}}_y^L = (\hat{p}_y^L, \hat{F}_y^L)$ , where  $p_x^L = (1 - \gamma)c + \gamma c_x$  and  $\hat{p}_y^L = (1 - \hat{\gamma})\hat{c} + \hat{\gamma}\hat{c}_y$ , and the subscription fees are unchanged compared to the regime without obligation.*

Again, the equilibrium usage prices are equal to their perceived marginal costs. Note that because each operator now achieves a retail price depending on the marginal cost of access from abroad, the wholesale roaming charges set by foreign operators directly impact the domestic demand for home access services. When looking at the potential effects of RLAH on retail prices, a primary insight can be noted. Hence, comparisons between (4) and (8) show that the RLAH obligation increases domestic prices for home access and decreases roaming retail price for home consumers in high-cost country  $x$  when  $c < c_x$ , i.e.,  $p_x^* < p_x^L < r_x^*$ . Note that this outcome depends on the wholesale market in the foreign country. More precisely, the effect of RLAH on retail prices is directly linked to the manner in which roaming traffic is split between visited networks and the level of wholesale roaming charges (i.e.,  $c_x = \hat{\rho}_{y1}\hat{a}_{y1} + \hat{\rho}_{y2}\hat{a}_{y2}$ ). This connection indicates that the potential effect of RLAH is closely linked to the degree of competition in wholesale roaming or to wholesale price regulation. Surprisingly, it appears that if wholesale roaming charges are cost-based in the low-cost country  $y$  (i.e.,  $\hat{a}_{yi} = \hat{c}$ ), the roaming cost of operator  $xi$  is set to  $c_x = \hat{c}$ , and thus, because  $c > \hat{c}$  under RLAH, home consumers in the high-cost

country  $x$  pay even more when they seek access from abroad. The opposite is true for the price paid by consumers when they seek access from home: RLAH decreases the domestic price in the high-cost country. Additionally, remember that in this case, the domestic usage price is higher than the roaming price,  $p_x^* > r_x^*$ . These findings indicate that RLAH might reduce the price that home consumers pay when they seek access from abroad only if certain conditions of roaming charge levels are satisfied. For instance, in the case in which, in the absence of obligation, domestic prices are lower than roaming prices in both countries, RLAH reduces roaming access price that all consumers pay if roaming charges are higher than the marginal cost  $c$  in high-cost country  $x$ .

Because home operators in each country set same retail usage prices at equilibrium under RLAH, the market share is  $\alpha_{xi} = \frac{5}{12} + \frac{\sigma}{6}(F_{xj} - F_{xi})$  for home operator  $xi$  and  $\hat{\alpha}_{yi} = \frac{5}{12} + \frac{\sigma}{6}(\hat{F}_{yj} - \hat{F}_{yi})$  for home operator  $yi$ . Substituting (8) into (7) and rewriting the profit function of operator  $xi$  with respect to  $F_{xi}$ , we have  $\pi_{xi}^r = (\frac{5}{12} + \frac{\sigma}{6}(F_{xj} - F_{xi}))F_{xi}$ . Hence, the first-order conditions for the profit-maximization problem result in the same equilibrium subscription fees as in the absence of RLAH obligation. Therefore, the subscription fees are  $F_x^L = \hat{F}_y^L = \frac{5}{2\sigma}$ , and market shares are also unchanged, i.e.,  $\alpha_x^L = \hat{\alpha}_y^L = 5/12$ . Then, retail profits appear to be insensitive to the introduction of the RLAH obligation, which is a result similar to neutrality-like result, i.e.,  $\pi_x^L = \pi_x^*$  and  $\hat{\pi}_y^L = \hat{\pi}_y^*$ .

## 4.2 Equilibrium in the wholesale market and benchmark comparison

Let us now examine equilibrium in the wholesale market by determining the wholesale roaming charges that maximize operators' profits. Wholesale profits are obtained by putting  $r_{xi} = p_x^L$  and  $\hat{r}_{yi} = \hat{p}_y^L$  into (3). After substituting the equilibrium retail prices stated in lemma 2 we retail prices under RLAH, we have  $\pi_{xi}^w = 2\hat{\alpha}_y^L \rho_{xi} \hat{\gamma} (a_{xi} - c) \hat{q}(\hat{p}_y^L)$  for home operators in country  $x$  and similarly  $\hat{\pi}_{yi}^w = 2\alpha_x^L \hat{\rho}_{yi} \gamma (\hat{a}_{yi} - \hat{c}) q(p_x^L)$  for home operators in country  $y$ .

From the first-order condition for operator  $xi$  and by rearranging the terms, we obtain the same pricing rule for wholesale roaming charges as in the absence of RLAH. Now, the difference is that the roaming charges depend on the uniform retail price's elasticity in the foreign country, which is the retail price paid by home consumers for both domestic and roaming services. That is, the wholesale roaming charges now impact not only the



retail market for roaming services but also the domestic market. The wholesale roaming charges are implicitly set considering the following pricing rule:

$$\frac{a_{xi}^L - c}{a_{xi}^L} = \frac{1}{\widehat{\varepsilon} \cdot \eta_{\widehat{p}}}, \text{ for } i = 1, 2 \quad (9)$$

where  $\widehat{\varepsilon}$  and  $\eta_{\widehat{p}}$  are the price elasticity of demand and the elasticity of the retail price  $\widehat{p}$ , respectively. Note that  $\widehat{\varepsilon} \cdot \eta_{\widehat{p}}$  is the elasticity of the roaming demand addressed to operator  $xi$ .

The following proposition states the result.

**Proposition 2** . *Under limited RLAH, the roaming charges are given by the Lerner index as characterized by equation (9). With a linear demand function, the equilibrium wholesale roaming charges are  $a_{xi}^L = a_{xi}^* + \frac{1 - \widehat{\gamma} \widehat{d} - \widehat{c}}{\widehat{\gamma} 3\rho_{xi}}$  and  $\widehat{a}_{yi}^L = \widehat{a}_{yi}^* + \frac{1 - \gamma d - c}{\gamma 3\widehat{\rho}_{yi}}$ , for  $i = 1, 2$ .*

The comparison between (6) and (9) shows that under RLAH, the wholesale roaming charges of home operators  $xi$  (resp. operators  $yi$ ) depend on the elasticity of the (non-discriminatory) retail price  $\widehat{p}$  (resp.  $p$ ) instead of the elasticity of roaming price  $\widehat{r}$  (resp.  $r$ ). This outcomes leads to the results stated in proposition 2 regarding roaming charges under RLAH and suggests two interesting results. First, under the RLAH obligation, wholesale roaming charges are higher, than in the regime without RLAH. For instance, if we consider wholesale roaming charges in the high-cost country  $x$ , we easily show that  $a_{xi}^L \geq a_{xi}^*$  because operators more accurately consider the market conditions in the foreign country  $y$  (i.e.  $\widehat{c}$  and  $\widehat{\gamma}$ ) when deciding the level of roaming charges. Therefore, the retail price is less sensitive to the roaming charge with RLAH than without it, i.e.,  $\eta_{\widehat{p}}(a) < \eta_{\widehat{r}}(a)$ ; thus, this outcome gives operators a greater incentive to increase their roaming charges. The second comment regards the impact that parameters  $\widehat{c}$  and  $\widehat{\gamma}$  produce on the roaming charge level. Let us consider the equilibrium roaming charge of home operators in the high-cost country  $x$ . Hence, the explicit expression for the roaming charge  $a_{xi}^L$  shows how market conditions in the low-cost country  $y$  affect the price decisions of operators  $xi$  in their home wholesale markets. More precisely, marginal cost  $\widehat{c}$  positively affects the equilibrium level of  $a_{xi}^L$ , while the exogenous parameter  $\widehat{\gamma}$  (roaming out of the low-cost country  $y$ ) negatively impacts the roaming charge. The roaming charge clearly acts like an instrument of "tacit collusion" because of a "raise-each-other's-cost" effect. In the

absence of roaming obligations, this effect impacts only the roaming retail prices (i.e.,  $r_x^*$  and  $\widehat{r}_y^*$ ), whereas it bears upon the non-discriminatory retail prices (i.e.,  $p_x^L$  and  $\widehat{p}_y^L$ ) under the RLAH obligation and thus also impacts the price that consumers pay for home access. Consequently, RLAH extends the "raise-each-other's-cost" effect to the domestic market in both countries.

Plugging (9) into (8), we obtain explicit expressions of the equilibrium retail prices, i.e.  $p_x^L = \frac{c - c\gamma + 2d + \widehat{c}\gamma}{3}$  and  $\widehat{p}_y^L = \frac{\widehat{c} - \widehat{c}\widehat{\gamma} + 2\widehat{d} + \widehat{c}\widehat{\gamma}}{3}$ . Comparisons with the equilibrium retail prices obtained in the benchmark case yield the following result:

**Proposition 3** . *Comparing the equilibrium usage prices under limited RLAH and without RLAH yield:*

(i) *RLAH makes domestic access more expensive for home consumers in the low cost country  $y$  whereas consumers living in the high cost country  $x$  might pay less if the cost difference between the two countries is sufficiently large, i.e.,  $\widehat{c} < c - \frac{2(d-c)}{\gamma}$ ; and*

(ii) *RLAH makes roaming access less expensive for home consumers in the low cost country  $y$ , whereas home consumers of the high-cost country  $x$  pay more for access when they are travelling.*

Compared with a scenario without RLAH, in the case where RLAH is imposed, domestic access is more expensive for consumers living in the low-cost country  $y$ , while these consumers pay less for access from abroad, i.e., when travelling in country  $x$ . Under RLAH, consumers living in the high-cost country  $x$  may pay less for domestic access if cost asymmetry between the two countries is sufficiently high. In this case, consumers in the high-cost country  $x$  benefit from the very low cost of operators  $yi$  through the retail price  $p_x^L$  that they pay for access. However, RLAH always makes roaming access more expensive for consumers living in the high-cost country  $x$ . For RLAH to be beneficial for consumers in country  $x$ , cost asymmetry between the two countries must be significantly high in comparison to the exogenous parameters of the roaming flows (i.e. the roaming out of country  $x$ ) and the market size in the high-cost country (i.e.,  $d$ ).

Plugging (9) into (3), we obtain the equilibrium wholesale profits of operators in the two countries when demand is linear, i.e.  $(\pi_x^w)^L = \frac{5}{54}(\widehat{\gamma}c - \widehat{c}\widehat{\gamma} + \widehat{c} - \widehat{d})^2$  and  $(\widehat{\pi}_y^w)^L = \frac{5}{54}(\gamma\widehat{c} - c\gamma + c - d)^2$  where  $q_x^L = \frac{d-c+c\gamma-\widehat{c}\gamma}{3}$  and  $\widehat{q}_y^L = \frac{\widehat{d}-\widehat{c}+\widehat{c}\widehat{\gamma}-c\widehat{\gamma}}{3}$ . Finally, the total profits

are obtained and combined with the retail profits,  $\pi_x^L$  and  $\widehat{\pi}_y^L$ , which we denote  $\Pi_x^L$  and  $\widehat{\Pi}_y^L$ .

## 5 Unlimited RLAH

In this section, we consider that RLAH is not accompanied by the fair use clause and then we allow an unlimited RLAH regime. This scenario is the so-called "permanent roaming" that can arise if operators are not allowed to apply roaming surcharges in cases of subscribers' "unusual" access usage when travelling abroad. The market is a more competitive market than that described in the previous section in the sense that every operator can now make offers to consumers regardless of the country in which they live. Then, in the following, we consider that operators are only subject to RLAH without any fair use safeguard. Hereafter, we denote by subscript "U" the equilibrium outcomes of this regulatory regime.

### 5.1 Market shares and profit functions

We still assume that each operator's network covers only its home country but now we consider that every operator provides access services in the two countries. Hence, all 4 of the operators  $x_i = \{x1, x2\}$  and  $y_i = \{y1, y2\}$  provide network access services to home consumers in the two countries. That is, in each country, the market is composed of a set of 4 spokes with a common core, and thus, all possible varieties of network access services are provided by operators located at the 4 extremities of the spoke network. Let us denote operator  $k \in \{x_i, y_i\}$  and its associated line  $l_k$  in country  $x$  and  $\widehat{l}_k$  in country  $y$ .

Every operator now participates in three related markets. First, each operator competes with all other operators (domestic and foreign) in the retail market for consumers in its home country, and second for consumers in the foreign country. Third, in the wholesale market, each operator offers roaming services to foreign operators and buys roaming services to resell to its home consumers.

**Market shares.** Consider country  $x$ . Since all varieties are now provided, all consumers located in the spoke model prefer two supplied varieties. The marginal consumer  $\alpha$  between operator  $k$  and any rival  $k'$  is thus given by  $w_k - t\alpha = w_{k'} - t(1 - \alpha)$ . Hence, considering all competitors, the market share  $\alpha_k$  for operator  $k$  in country  $x$  is:

$\alpha_k = \frac{1}{6} \sum_{k' \neq k} \left[ \frac{1}{2} + \sigma(w_k - w_{k'}) \right]$ . Rearranging terms, we obtain:

$$\alpha_k = \frac{1}{4} + \frac{\sigma}{6} (3w_k - \sum_{k' \neq k} w_{k'}) \quad (10)$$

similarly, the market share  $\hat{\alpha}_k$  for operator  $k$  in country  $y$  is:

$$\hat{\alpha}_k = \frac{1}{4} + \frac{\sigma}{6} (3\hat{w}_k - \sum_{k' \neq k} \hat{w}_{k'}) \quad (11)$$

where  $w_k = v + v(p_k) - F_k$  and  $\hat{w}_k = \hat{v} + v(\hat{p}_k) - \hat{F}_k$

**Profit functions.** For home operator  $xi$  in country  $x$ , the total profit is  $\Pi_{xi} = \pi_{xi}^r + \hat{\pi}_{xi}^r + \pi_{xi}^w$ , where  $\pi_{xi}^r$ ,  $\hat{\pi}_{xi}^r$  and  $\pi_{xi}^w$  are retail profit in the home market, retail profit abroad and wholesale roaming profit, respectively. Hence, the total profit  $\Pi_{xi}$  is obtained, considering the retail profit in the home market

$$\pi_{xi}^r = \alpha_{xi} [p_{xi} - (1 - \gamma)c - \gamma c_x] q(p_{xi}) + \alpha_{xi} F_{xi}, \quad (12)$$

its retail profit abroad

$$\hat{\pi}_{xi}^r = \hat{\alpha}_{xi} [\hat{p}_{xi} - \hat{\gamma}c - (1 - \hat{\gamma})c_x] \hat{q}(\hat{p}_{xi}) + \hat{\alpha}_{xi} \hat{F}_{xi} \quad (13)$$

and its wholesale profit

$$\begin{aligned} \pi_{xi}^w &= \rho_{xi} \hat{\gamma} (a_{xi} - c) [\hat{\alpha}_{y1} \hat{q}(\hat{p}_{y1}) + \hat{\alpha}_{y2} \hat{q}(\hat{p}_{y2})] \\ &\quad + \rho_{xi} (1 - \gamma) (a_{xi} - c) [\alpha_{y1} q(p_{y1}) + \alpha_{y2} q(p_{y2})], \end{aligned} \quad (14)$$

The total profit for home operators  $yi$  in country  $y$  is symmetrically given by  $\hat{\Pi}_{yi} = \hat{\pi}_{yi}^r + \pi_{yi}^r + \hat{\pi}_{yi}^w$ .

Note that each operator now obtains wholesale profit from two types of consumers: foreign consumers who seek access from abroad and home consumers who have purchased access to a foreign operator. While the wholesale roaming charge previously depended only on the foreign demand for roaming, it will now also depend on the demand for access by home consumers. More precisely and considering operator  $xi$ , the roaming charge  $a_{xi}$

depends on the demand in the foreign country  $\widehat{q}(\widehat{p}_{yi})$  and that in the home country  $q(p_{yi})$ . That is, the wholesale roaming charge  $a_{xi}$  set by operator  $xi$  will result from a combined effect between home and foreign retail competition.

Then, without a fair use safeguard, each operator  $k$  offers two sets of prices,  $(p_k, F_k)$  and  $(\widehat{p}_k, \widehat{F}_k)$ , where  $p_k$  and  $\widehat{p}_k$  are retail prices in country  $x$  and in country  $y$ , and  $F_k$  and  $\widehat{F}_k$  are the corresponding subscription fees, respectively. We consider the same two-stage game as described previously, with the difference that operators offer access services to consumers in both countries. In the following section, we start by determining the Nash equilibrium prices  $(p_k, F_k)$  and  $(\widehat{p}_k, \widehat{F}_k)$  for each operator  $k$  for a given set of wholesale roaming prices.

## 5.2 Retail equilibrium

For clarity, let us consider first operator  $xi$  and then deduce by symmetry equilibrium prices for operator  $yi$ .

The retail profits of operator  $xi$  in the home market (in country  $x$ ) and abroad (in country  $y$ ) are given by (12) and (13), respectively. Then, the first-order conditions for the profit maximization problem with respect to usage prices  $p_{xi}$  and  $\widehat{p}_{xi}$  give the following symmetric equilibrium prices:

$$p_x^U = (1 - \gamma)c + \gamma c_x \quad \text{and} \quad \widehat{p}_x^U = \widehat{\gamma}c + (1 - \widehat{\gamma})c_x \quad (15)$$

Expression (15) shows that usage prices reflect the weighted average of true marginal costs in each country. When setting usage price  $\widehat{p}_x^U$  in the foreign country  $y$ , operator  $xi$  considers the marginal cost that it bears for its foreign consumers according to whether they seek access in their home country  $((1 - \widehat{\gamma})c_x)$  or from abroad  $(\widehat{\gamma}c)$ . Note that, for each unit of domestic access from foreign consumers, operator  $xi$  pays a roaming cost  $c_x$  since it has no network coverage in country  $y$ .

Similarly, we obtain equilibrium usage prices  $p_y^U$  and  $\widehat{p}_y^U$  for operator  $yi$  in its home country  $y$  and in the foreign country  $x$ , respectively. Equilibrium is then given by  $p_y^U = \gamma\widehat{c} + (1 - \gamma)\widehat{c}_y$  and  $\widehat{p}_y^U = (1 - \widehat{\gamma})\widehat{c} + \widehat{\gamma}\widehat{c}_y$ .

Again, usage prices are according to their perceived marginal costs and each country's exogenous roaming flows, given by  $\gamma$  and  $\widehat{\gamma}$ , while, in the benchmark case (no regulation),

competition for home and roaming services is independent and the permanent roaming regime links both markets. Home competition is affected by unlimited RLAH for two reasons. First, this regime enables each operator to provide access services to consumers abroad, reinforcing retail competition in both countries because all service varieties are now supplied. Second, this regulatory regime does not allow operators to engage in price discrimination between access from the home country and abroad; thus, the choice of wholesale roaming charges by each operator directly affects competition for home access services.

We now determine the operators' choice of subscription fee in the two countries, i.e.,  $(F_{xi}, F_{yi})$  for country  $x$  and  $(\widehat{F}_{xi}, \widehat{F}_{yi})$  for country  $y$ . The first-order conditions for operator  $xi$ 's profit maximization are:

$$\begin{aligned} \frac{\partial \pi_{xi}^r}{\partial F_{xi}} &= \alpha_{xi} + \frac{\partial \alpha_{xi}}{\partial F_{xi}} F_{xi} = 0 \text{ for } i = 1, 2 \\ &\text{and} \\ \frac{\partial \widehat{\pi}_{xi}^r}{\partial \widehat{F}_{xi}} &= \widehat{\alpha}_{xi} + \frac{\partial \widehat{\alpha}_{xi}}{\partial \widehat{F}_{xi}} \widehat{F}_{xi} = 0 \text{ for } i = 1, 2 \end{aligned}$$

Solving the system of the first-order conditions, we obtain the subscription fees at equilibrium:

$$\begin{aligned} F_x^U = F_{xi}^U &= \frac{1}{2\sigma} + \frac{2}{7}(v(p_x^U) - v(p_y^U)) \\ F_y^U = F_{yi}^U &= \frac{1}{2\sigma} + \frac{2}{7}(v(p_y^U) - v(p_x^U)) \end{aligned} \quad (16)$$

Similarly, we obtain the subscription fees at equilibrium in country  $y$ , given by  $\widehat{F}_x^U = 1/2\sigma + (2/7)(\widehat{v}(\widehat{p}_x^U) - \widehat{v}(\widehat{p}_y^U))$  and  $\widehat{F}_y^U = 1/2\sigma + (2/7)(\widehat{v}(\widehat{p}_y^U) - \widehat{v}(\widehat{p}_x^U))$ , respectively, for operators  $xi$  and  $yi$ .

For clarity of exposition, the following lemma summarizes the results focusing only on country  $x$ .

**Lemma 3** . *Under unlimited RLAH, at equilibrium the retail prices in the high-cost country  $x$  are  $\mathbf{p}_x^U = (p_x^U, F_x^U)$  for home operators and  $\mathbf{p}_y^U = (p_y^U, F_y^U)$  for foreign operators. The usage prices are  $p_x^U = (1 - \gamma)c + \gamma c_x$  and  $p_y^U = \gamma \widehat{c} + (1 - \gamma)\widehat{c}_y$ , and subscription fees are  $F_x^U = 1/2\sigma + (2/7)(v(p_x^U) - v(p_y^U))$  and  $F_y^U = 1/2\sigma + (2/7)(v(p_y^U) - v(p_x^U))$ .*

Again, the usage prices are equal to their perceived marginal cost. Note that the usage price  $p_x^U$  for home operators in country  $x$  is unchanged compared to the limited RLAH regime because their perceived marginal cost is the same with and without the safeguard. The results show that the usage prices for foreign operators operating in country  $x$  are also equal to their corresponding costs. This outcome leads to two interesting comments. First, the domestic retail market for access services is now directly impacted by the cost efficiency parameter of foreign operators (i.e.,  $\hat{c}$ ), whereas this was not the case with the safeguard clause. This findings means that the absence of the fair use safeguard can be beneficial for home consumers in the high cost country  $x$ , i.e.,  $c > \hat{c}$ . Second, competition in the domestic market is directly affected by the wholesale roaming charges  $a_{xi}$  set by home operators because the usage price  $p_y^U$  is partially composed of foreign operators' roaming cost  $\hat{c}_y$ , which itself depends on the wholesale access competition in country  $x$ . This link between the domestic market and the wholesale market in each country is a new effect produced by the absence of the fair usage clause, i.e., permanent roaming, which introduces for operators choosing their wholesale roaming charge an interesting trade-off that did not appear in the two other regulatory regimes. Home operators might indeed have incentive to set a high roaming charge to disadvantage the foreign competitors in the domestic retail market for access services, which indicates that operators might be engaged in raising a rival's cost strategy. Finally, the results show that subscription fees now depend on the price difference between home and foreign operators in both countries. According to whether  $p_x^U$  is higher or lower than  $p_y^U$ , home operators set lower or higher subscription fees than foreign operators. Thus, a high usage price leads operators to attract consumers with a low subscription fee, i.e. the waterbed effect. This trade-off between usage prices and subscription fees depends not only on the market conditions (marginal cost of operators, roaming flows, and network signal quality, etc.) but also precisely on the level of roaming charges. The next section determines the equilibrium on the wholesale market for roaming access in the two countries.

### 5.3 Wholesale equilibrium

We now determine wholesale roaming charges for each operator. Since roaming regulation now does not impose a fair use safeguard, each operator can offer access services to both domestic and foreign consumers. The results stated in lemma 3 show that equilibrium retail prices are no longer symmetric. Thus, subscription fees and market shares

now depend on the difference between the retail price set by both domestic and foreign operators. Consequently, retail profits (in the home market and abroad) are now affected by operators' pricing decisions in the wholesale market in the two countries. That is, the wholesale equilibrium is more complex to analyse because, to maximize their total profit, operators must consider the impacts of wholesale charges on both their retail and wholesale profits.

Plugging equilibrium retail prices into (12), (13) and (14), we obtain retail profits in the home market and abroad and the wholesale profit of operator  $xi$  as functions of wholesale charges:

$$\pi_{xi}^r(a_{xi}, a_{yi}) = \alpha_{xi} F_{xi}^U \quad \text{and} \quad \widehat{\pi}_{xi}^r(a_{xi}, a_{yi}) = \widehat{\alpha}_{xi} \widehat{F}_{xi}^U \quad (17)$$

and,

$$\pi_{xi}^w(a_{xi}, a_{yi}) = (a_{xi} - c) \left[ \rho_{xi} \widehat{\gamma} (\widehat{\alpha}_{y1} + \widehat{\alpha}_{y2}) \widehat{q}(\widehat{p}_y^U) + \rho_{xi} (1 - \gamma) (\alpha_{y1} + \alpha_{y2}) q(p_y^U) \right], \quad (18)$$

where market shares of operator  $xi$  are  $\alpha_{xi} = \frac{1}{4} + \frac{\sigma}{7} (v(p_x^U) - v(p_y^U))$  and  $\widehat{\alpha}_{xi} = \frac{1}{4} + \frac{\sigma}{7} (\widehat{v}(\widehat{p}_x^U) - \widehat{v}(\widehat{p}_y^U))$ , and retail prices are given in the lemma 3.

Expression (17) shows that wholesale roaming charges affect retail profits through usage prices and subscription fees. Hence, a high wholesale charge, increases the usage price of foreign operator  $yi$  in country  $x$  and thus allows operator  $xi$  to obtain a high market share in its home country. This outcome leads operator  $yi$  to lower its subscription fees to attract consumers in country  $x$ . Finally, the combination of these two effects relaxes competition to attract consumers for operator  $xi$  in its home market and thus can increase its subscription fees.

Expression (18) clearly shows that the wholesale demand addressed to operator  $xi$  correspond to the sum of its roaming demand from visiting consumers, who are located in foreign country  $y$  (i.e.,  $Q_{xi}^y = \rho_{xi} \widehat{\gamma} (\widehat{\alpha}_{y1} + \widehat{\alpha}_{y2}) \widehat{q}(\widehat{p}_y^U)$ ) and from home consumers in country  $x$  who have subscribed to foreign operators  $yi$  (i.e.,  $Q_{xi}^x = \rho_{xi} (1 - \gamma) (\alpha_{y1} + \alpha_{y2}) q(p_y^U)$ ).

From (17) and (18), we can now deduce the marginal impact generated by an increase in the wholesale charge  $a_{xi}$  on the retail profits and the wholesale profit of operator  $xi$ . We therefore have the marginal impact for the retail profit in the home market



$$\frac{\partial \pi_{xi}^r}{\partial a_{xi}} = \frac{4}{7} \alpha_{xi} q(p_y^U) (1 - \gamma) \rho_{xi}, \quad (19)$$

for the retail profit abroad

$$\frac{\partial \widehat{\pi}_{xi}^r}{\partial a_{xi}} = \frac{4}{7} \widehat{\alpha}_{xi} \widehat{q}(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi}, \quad (20)$$

and for the wholesale profit

$$\frac{\partial \pi_{xi}^w}{\partial a_{xi}} = Q_{xi} \left( 1 - \frac{a_{xi} - c}{a_{xi}} \epsilon_{xi} \right), \quad (21)$$

where  $\epsilon_{xi} = -\frac{a_{xi} Q'_{xi}}{Q_{xi}}$  is the elasticity of the total roaming demand of operator  $xi$ . For operator  $xi$ , let us denote by  $s_{xi}^y = Q_{xi}^y / Q_{xi}$  and  $s_{xi}^x = Q_{xi}^x / Q_{xi}$  the share of the roaming demand from visiting consumers and home consumers who have subscribed to foreign operator  $yi$ , respectively. This elasticity of the total roaming demand can be rewritten as  $\epsilon_{xi} = s_{xi}^y (\eta_{\widehat{\alpha}_y} + \widehat{\epsilon} \cdot \eta_{\widehat{p}}) + s_{xi}^x (\eta_{\alpha_y} + \epsilon \cdot \eta_p)$ , where  $\eta_{\widehat{\alpha}_y}$  and  $\eta_{\alpha_y}$  are the elasticity of the total market share of operator  $yi$  in its home country and abroad, respectively. Note that the two first marginal effects (19 and 20) are positive, that is, the impact on retail profits from the effect of rivals' increased cost. The marginal impact on the wholesale profit depends on the elasticity of the total roaming demand addressed to operators  $xi$ , i.e.,  $\epsilon_{xi}$ .

Summing (19), (20) and (21) and rearranging the terms, we obtain the following pricing rule for the wholesale roaming charge of operator  $xi$ :

$$\frac{a_{xi}^U - c}{a_{xi}^U} = \frac{1}{\epsilon_{xi}} \left( 1 + \frac{\pi_{xi}^r}{a_{xi}^U Q_{xi}} (\eta_{F_{xi}} - \eta_{\alpha_{xi}}) + \frac{\widehat{\pi}_{xi}^r}{a_{xi}^U Q_{xi}} (\eta_{\widehat{F}_{xi}} - \eta_{\widehat{\alpha}_{xi}}) \right) \quad (22)$$

where:  $\eta_{F_{xi}} = \frac{\partial F_{xi}}{\partial a_{xi}} \frac{a_{xi}}{F_{xi}}$  is the elasticity of the subscription fee  $F_{xi}$  with respect to the wholesale charge  $a_{xi}$ ,  $\eta_{\alpha_{xi}} = -\frac{\partial \alpha_{xi}}{\partial a_{xi}} \frac{a_{xi}}{\alpha_{xi}}$  corresponding to the price elasticity of the equilibrium market share of operator  $xi$  in its home country,  $\frac{\pi_{xi}^r}{a_{xi}^U Q_{xi}}$  is the equilibrium retail profit (in the home market) per wholesale unit revenue of operator  $xi$  and  $\frac{\widehat{\pi}_{xi}^r}{a_{xi}^U Q_{xi}}$  represents the equilibrium retail profit (abroad) per wholesale unit revenue of operator  $xi$ .

The following lemma states the result.

**Lemma 4** . *Under unlimited RLAH, the equilibrium roaming charge  $a_{xi}^U$  of the operators in the high-cost country is given by the Lerner index as characterized by (22). The wholesale charge  $a_{xi}^U$  is undoubtedly different from the charge  $a_{xi}^L$  characterized by Lemma (9) because it now internalizes more complex effects on the retail market both at home and abroad.*

In the unlimited RLAH regime, operators can offer access services to foreign consumers abroad. Since the markets in the two countries and operators  $xi$  and  $yi$  are different (cost, demand and roaming flows asymmetries), foreign markets directly impact retail competition in the home market and then complicate the pricing decisions of operators  $xi$  in the wholesale market. As shown by (22), the equilibrium wholesale charge  $a_{xi}^U$  of operator  $xi$  is now defined by a complex relationship that depends on the price elasticities of different types of demand (retail/wholesale, domestic/foreign) and the elasticities of retail prices with respect to the roaming charges. More specifically, the equilibrium charge  $a_{xi}^U$  is defined by the share of retail profit of operator  $xi$  (home and abroad) relative to the revenues it obtains from the wholesale market, i.e.  $(\pi_{xi}^r/a_{xi}Q_{xi})$  and  $(\hat{\pi}_{xi}^r/a_{xi}Q_{xi})$ . This finding indicates how operator  $xi$  trades off between two contrasting effects when deciding the roaming charge: an effect on the wholesale market and an effect on the retail markets both at home and abroad. The direct effect is captured entirely by the elasticity of the total roaming demand  $\epsilon_{xi}$ , which is composed of two terms: the elasticity of the roaming demand from visiting consumers living abroad,  $\eta_{\hat{\alpha}_y} + \hat{\epsilon} \cdot \eta_{\hat{p}}$  and the elasticity of home consumers who have subscribed to a foreign operator,  $\eta_{\alpha_y} + \epsilon \cdot \eta_p$ . These two terms of elasticities are weighted by the relative shares of the corresponding wholesale demand into the total roaming demand of operator  $xi$ , i.e., respectively,  $s_{xi}^y$  and  $s_{xi}^x$ . The indirect effect is captured by the elasticities of retail profits at home and abroad, which are given, respectively, by  $(\partial\pi_{xi}^r/\partial a_{xi})/(a_{xi}/\pi_{xi}^r) = \eta_{F_{xi}} - \eta_{\alpha_{xi}} \geq 0$  and  $(\partial\hat{\pi}_{xi}^r/\partial a_{xi})/(a_{xi}/\hat{\pi}_{xi}^r) = \eta_{\hat{F}_{xi}} - \eta_{\hat{\alpha}_{xi}} \geq 0$ .

Comparing  $a_{xi}^L$  and  $a_{xi}^U$  is difficult because of the complexity of the expressions. However, when comparing the Lerner indices (9) and (22) in the two countries, the following lemma holds.

**Lemma 5** *There exists a unique and positive threshold of the price elasticity of demand for each country such that unlimited RLAH leaves the wholesale roaming charges unchanged compared with the limited regime.*

Comparison of the two Lerner indexes (9) and (22) shows that roaming charges are unchanged for  $\varepsilon^U = \varepsilon_1(\widehat{\varepsilon}^U)$  and  $\widehat{\varepsilon}^U = \widehat{\varepsilon}_2(\varepsilon^U)$ , respectively, for country  $x$  and  $y$ , where  $\varepsilon^U$  is the elasticity of demand at equilibrium. These thresholds are complex functions of all parameters, and they increase with the price elasticity of demand in the foreign country (see Appendix). Because we assume linear demand functions, the elasticities of demand in the two countries,  $\varepsilon$  and  $\widehat{\varepsilon}$ , depend on the demand parameters  $d$  and  $\widehat{d}$ . Hence, the thresholds expressed in the previous lemma also affect  $d$  and  $\widehat{d}$ . This result leaves a scope for lower wholesale roaming charges when permanent roaming is possible, as shown in the proposition below:

**Proposition 4** . *Compared to unlimited RLAH, the limited regime reduces the wholesale roaming charge (i) in the high cost country if  $\varepsilon^U \leq \varepsilon_1(\widehat{\varepsilon}^U)$ ; and (ii) in the low cost country if  $\widehat{\varepsilon}^U \leq \widehat{\varepsilon}_2(\varepsilon^U)$ . Otherwise, a fair use safeguard can increase the wholesale roaming charges, which leaves a scope for the unlimited RLAH regime to push wholesale roaming charges downwards..*

When the limited RLAH regime is applied, the wholesale roaming charge chosen by each operator affects only the roaming demand from visiting consumers and thus its wholesale profit. Consequently, wholesale charges depend on the demand parameters in the foreign country and especially on the elasticity of demand at equilibrium in the foreign country (see proposition 2). In the absence of a fair use safeguard, i.e., the unlimited regime, the impact from the roaming charge is more complex because it affects both the retail and wholesale profits of each operators. The effect on the retail profits (at home and abroad) is clearly positive since, by increasing its roaming charge, a home operator increases the costs of its foreign rivals not only in the domestic retail market but also in the retail market in the foreign country. The total effect on the retail profit of operator  $xi$  clearly depends on the demand parameters in the two countries, i.e., the elasticities of demand. The effect on the wholesale profit is more complex because, under the unlimited regulatory regime, wholesale profit depends on the roaming demand from visiting consumers and on the roaming demand from domestic consumers who have subscribed to foreign operators. That is, the wholesale profit is also sensitive to the elasticity of domestic demand, while it depends on the elasticity of demand in the foreign country only when the non-discrimination policy is accompanied by a fair use safeguard, i.e., limited RLAH. Therefore, for each operator, this outcome leads to a conflict of interest between

its retail and wholesale profits regarding the level of the roaming charge. Note that by reducing the retail demand of foreign operators in the home country, a higher roaming charge also decreases home operators' wholesale demand (from home consumers who are attached to foreign operators) for roaming. Then, when considering its retail profit, each operator has incentives to set relatively high roaming charges, while it has the opposite incentives when considering its wholesale profit.

Proposition 4 claims that, when the elasticity of demand in the home market is not too high, i.e.,  $\varepsilon^U \leq \varepsilon_1(\widehat{\varepsilon}^U)$  and/or  $\widehat{\varepsilon}^U \leq \widehat{\varepsilon}_2(\varepsilon^U)$ , each operator can increase its total retail profit by setting a relatively high wholesale charge preserving its wholesale profit. In reality, these conditions correspond to a sufficient level of demand parameters  $d$  and  $\widehat{d}$ . In this way, operators set higher wholesale roaming charges in the unlimited RLAH. In the opposite case, i.e., a sufficiently high level of elasticity, this regulatory policy intensifies competition in wholesale roaming and thus yields lower roaming charges than in the limited regime.

Recall that the main purpose of our analysis is to determine the impacts of limited RLAH and unlimited RLAH regimes on competition in domestic markets and, thus, on retail tariffs. Considering the perfect symmetric case, the following results hold:

**Proposition 5** . *Assume perfect symmetry between operators and countries. Compared to the unlimited RLAH, the limited RLAH might reduce the symmetric roaming charges, i.e.  $a^L \leq a^U$ , only if  $\varepsilon \leq \bar{\varepsilon}$ . In such a case, usage prices are lower under limited RLAH, i.e.  $p^L \leq p^U$ . In contrast, when the price elasticity of demand is sufficiently high, i.e.,  $\varepsilon > \bar{\varepsilon}$ , lower roaming charges are produced under the unlimited regime.*

Proposition 5 implies that a fair use safeguard is generally beneficial for all consumers if the price elasticity of demand is not too high. In this case, all usage prices for both domestic and roaming access are less than those in the unlimited RLAH regulation. Hence, when the price elasticity of demand increases over the threshold  $\bar{\varepsilon}$ , operators have incentives to set lower roaming charges in the absence of a fair use safeguard. In this case, raising the roaming charge, under unlimited RLAH becomes detrimental to operators because the potential positive impact of "raising a rival's costs" on retail profit is overwhelmed by the negative effects on wholesale profit. Thus, operators set a lower roaming charge than with the fair use safeguard. When this outcome occurs, it might be better

for consumers to ensure that all operators can freely offer access services to foreign consumers, i.e., unlimited RLAH. Finally, note that, when countries are perfectly symmetric, the unique equilibrium subscription fee is then given by  $F^L = \frac{5}{2\sigma}$  in the regime with the fair use safeguard, whereas it is  $F^U = \frac{1}{2\sigma} < F^L$  without any fair use clause. Hence, when  $\varepsilon \leq \bar{\varepsilon}$ , the lowering effect of the fair use clause on usage prices can be compensated for operators by setting a high subscription fee  $F^L (> F^U)$ , while when  $\varepsilon > \bar{\varepsilon}$ , both the usage prices and the subscription fees are lower, i.e.  $p^U < p^L$  and  $F^U < F^L$ . This outcome might be surprising because, in this latter case, the classical "waterbed effect" does not appear: usage prices and subscription fees decrease together when  $\varepsilon > \underline{\varepsilon}$ . This finding can be explained by retail market competition among four operators in each country in the absence of a fair use safeguard, whereas competition is reduced to a duopoly between the two home operators under limited RLAH.

## 6 Conclusion

We have examined competition in the retail and wholesale roaming markets under different regulatory regimes, considering the domestic market for access services in a model for two countries. The obtained results led to at least three general conclusions that could facilitate a better understanding of the potential impacts of international roaming regulations.

First, it is not clear that coupling RLAH with a (strict) fair use policy might be an optimal way to produce the lowest roaming charges and sustainable competition in retail markets. A less-restricted regulatory regime could be beneficial for both operators and social welfare because asymmetries between countries and operators could lead to opposite effects, which could fail to make the limited RLAH regime the better regulatory regime in the long-run. This first conclusion should be tempered for at least two reasons. First, our model should be more realistic in terms of how operators negotiate in the wholesale market for roaming services. Second, we restrict attention in our framework to a situation in which each operator offers a single service in retail and wholesale markets. Operators are multiproduct firms, so considering imperfect substitutability between services could greatly enhance the analysis. These interesting extensions are left to further research.

Second, the unlimited RLAH regime, i.e., the absence of a fair use safeguard when

operators are subjected to RLAH, could increase market competition depending on the importance of cost and demand asymmetries between countries.

Third, under an unlimited RLAH policy, wholesale caps might be unnecessary because wholesale market competition might be sufficient to limit the risk of exceedingly high roaming charges.

In conclusion, let us remark on the issue of wholesale regulation for roaming (wholesale caps). We address the question of whether the implementation of RLAH should lead to a large revision of wholesale caps, but the answer is not so simple because a more restricted retail regulation, i.e., no price discrimination between domestic and roaming access in the retail market, could increase or decrease wholesale roaming charges freely chosen by operators depending on the parameter sets. For instance, when the high-cost country is also the high-demand country and roaming is low and unbalanced between countries, a regulatory policy that allows for permanent roaming could significantly decrease roaming charges. In this case, one might question the desirability of a wholesale floor rather than focusing on a wholesale cap. In reality, and because European markets are very different in terms of access costs, demand sizes and/or price elasticities of demand, and the structure and/or level of roaming flows, one may make recommendations for soft wholesale regulation, defining both a lower and a high bound for roaming charges based on a case-by-case analysis. However, to offer more focused policy recommendations, the model must more precisely analyze competition on the wholesale market by allowing operators to negotiate both roaming charges and volumes with visited networks. We leave this extension for future research.

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## 7 Appendix

### 7.1 Lemma 1

The first order conditions for operator  $xi$  profit maximization with respect to  $F_{xi}$  are:

$$\frac{\partial \pi_{xi}^r}{\partial F_{xi}} = \alpha_{xi} + \frac{\partial \alpha_{xi}}{\partial F_{xi}} F_{xi} = 0 \text{ for } i = 1, 2.$$

$$\text{We have } \alpha_{x1} = \frac{5}{12} + \frac{\sigma(w_{x1} - w_{x2})}{6} \text{ and } \alpha_{x2} = \frac{5}{12} + \frac{\sigma(w_{x2} - w_{x1})}{6}$$

$$\text{with } w_{x1} = u + (1 - \gamma)v(p_x^*) + \gamma v(r_x^*) - F_{x1} \text{ and } w_{x2} = u + (1 - \gamma)v(p_x^*) + \gamma v(r_x^*) - F_{h2x}$$

Using equilibrium prices, we then have:

$$\begin{aligned} \alpha_{x1} &= \frac{5}{12} + \frac{\sigma}{6} ((1 - \gamma)v(p_x^*) + \gamma v(r_x^*) - F_{x1} - (1 - \gamma)v(p_x^*) - \gamma v(r_x^*) + F_{h2x}) \\ &= \frac{5}{12} + \frac{\sigma}{6} (F_{h2} - F_{h1}) \end{aligned}$$

and

$$\alpha_{x2} = \frac{5}{12} + \frac{\sigma}{6} (F_{x1} - F_{x2})$$

The FOC rewrite:

$$\begin{aligned} \frac{\partial \pi_{x1}^r}{\partial F_{x1}} &= \alpha_{x1} + \frac{\partial \alpha_{x1}}{\partial F_{x1}} F_{x1} = 0 \\ &\Leftrightarrow \frac{5}{12} + \frac{\sigma}{6} (F_{x1} - F_{x2}) - \frac{\sigma}{6} F_{x1} = 0 \\ &\Leftrightarrow \frac{5}{12} + \frac{\sigma}{6} F_{x2} - \frac{2\sigma}{6} F_{x1} = 0 \\ &\Leftrightarrow F_{x1}(F_{x2}) = \frac{5}{4\sigma} + \frac{F_{x2}}{2} \end{aligned}$$

and,

$$\begin{aligned} \frac{\partial \pi_{x2}^r}{\partial F_{x2}} &= \alpha_{x2} + \frac{\partial \alpha_{x2}}{\partial F_{x2}} F_{x2} = 0 \\ &\Leftrightarrow F_{x2}(F_{x1}) = \frac{5}{4\sigma} + \frac{F_{x1}}{2} \end{aligned}$$

Hence,

$$F_{x1} = \frac{5}{4\sigma} + \frac{F_{x2}}{2} \Leftrightarrow 4\sigma F_{x1} = 5 + 2\sigma \left( \frac{5}{4\sigma} + \frac{F_{x1}}{2} \right) \Leftrightarrow F_x^* = \frac{5}{2\sigma}$$

Equilibrium market shares are  $\alpha_{h1}^* = \alpha_{h2}^* = \frac{5}{12}$  and  $\hat{\alpha}_{f1}^* = \hat{\alpha}_{f2}^* = \frac{5}{12}$ .



### 7.1.1 Lemma 3

Let's consider the country  $x$ . The home profit of operator  $xi$ , i.e.  $\pi_{xi}^r = \alpha_{xi}F_{xi}$ . Hence, the first-order condition for operator  $xi$  profit maximization is:

$$\frac{\partial \pi_{xi}^r}{\partial F_{xi}} = \alpha_{xi} + \frac{\partial \alpha_{xi}}{\partial F_{xi}} F_{xi} = 0, \text{ for } i = 1, 2 \quad (23)$$

with  $\alpha_{xi} = \frac{1}{4} + \frac{\sigma}{6}(3w_{xi} - \sum_{k' \neq xi} w_{k'})$  and  $w_k = v(p_k) - F_k$ .

The F.O.C. (23) rewrites:

$$\begin{aligned} \frac{\partial \pi_{xi}^r}{\partial F_{xi}} &= \alpha_{xi} + \frac{\partial \alpha_{xi}}{\partial F_{xi}} F_{xi} \\ &= \left( \frac{1}{4} + \frac{\sigma}{6}(2v(p_x^U) - 2v(p_y^U) - 3F_{xi} + F_{xj} + F_{yi} + F_{yj}) \right) - 3\frac{\sigma}{6}F_{xi} = 0 \end{aligned}$$

and the reaction function of operator  $xi$  for  $F_{xi}$  is  $F_{xi} = \frac{1}{4\sigma} + \frac{2}{6}(v(p_x^U) - v(p_y^U)) + \frac{1}{6}(F_{xj} + F_{yi} + F_{yj})$ . Using symmetry, we can obtain reaction function of foreign operator  $yi$ , that is  $F_{yi} = \frac{1}{4\sigma} + \frac{2}{6}(v(p_y^U) - v(p_x^U)) + \frac{1}{6}(F_{xi} + F_{xj} + F_{yj})$ . Summing up, we finally have:  $F_x^U = F_{xi}^U = \frac{1}{2\sigma} + \frac{2}{7}v(p_x^U) - \frac{2}{7}v(p_y^U)$  and  $F_y^U = F_{yi}^U = \frac{1}{2\sigma} + \frac{2}{7}v(p_y^U) - \frac{2}{7}v(p_x^U)$  for  $i = 1, 2$ . Market shares in country  $x$  are respectively  $\alpha_x = \alpha_{xi} = \frac{1}{4} + \frac{\sigma}{7}(v(p_x^U) - v(p_y^U))$ , for home operators, and  $\alpha_y = \alpha_{yi} = \frac{1}{4} + \frac{\sigma}{7}(v(p_y^U) - v(p_x^U))$ , for foreign operators.

Similarly, we obtain subscription fees both for home and foreign operators in country  $y$ , i.e.  $\widehat{F}_x^U = 1/2\sigma + (2/7)(\widehat{v}(\widehat{p}_x^U) - \widehat{v}(\widehat{p}_y^U))$  and  $\widehat{F}_y^U = 1/2\sigma + (2/7)(\widehat{v}(\widehat{p}_y^U) - \widehat{v}(\widehat{p}_x^U))$ .

### 7.1.2 Proposition 3

**Price difference for domestic prices:**

- in country  $y$ :  $\widehat{p}_y^* - \widehat{p}_y^L = \frac{2(\widehat{c}-\widehat{d})+(\widehat{c}-c)\widehat{\gamma}}{3} < 0$

- in country  $x$ :  $p_x^* - p_x^L = \frac{2(c-d)+(c-\widehat{c})\gamma}{3} > 0$  iff  $\widehat{c} < c - \frac{2(d-c)}{\gamma}$ , that is cost difference is high enough.

**Price difference for retail roaming:**

- in country  $y$ :  $\widehat{r}_y^* - \widehat{p}_y^L = \frac{(c-\widehat{c})(1-\widehat{\gamma})}{3} > 0$

- in country  $x$ :  $\widehat{r}_x^* < p_x^L$

### 7.1.3 Lemma 5 and Proposition 4

(1) Let's consider country  $x$ . Using all equilibrium outcomes given in Lemma 3 and substituting into 22, we obtain the equilibrium value of the Lerner index taking into account:

- equilibrium retail profits for home operators:

$$\pi_{xi}^r = \alpha_{xi} F_{xi} = \frac{2}{\sigma} \alpha_{xi}^2 = \frac{2}{\sigma} \left( \frac{1}{4} + \frac{\sigma}{7} v(p_x^U) - \frac{\sigma}{7} v(p_y^U) \right)^2$$

$$\widehat{\pi}_{xi}^r = \frac{2}{\sigma} \widehat{\alpha}_{xi}^2 = \frac{2}{\sigma} \left( \frac{1}{4} + \frac{\sigma}{7} v(\widehat{p}_x^U) - \frac{\sigma}{7} v(\widehat{p}_y^U) \right)^2$$

- the total roaming demand from visiting consumers in country  $x$ :

$$Q_{xi} = \rho_{xi} (1 - \gamma) (\alpha_{y1} + \alpha_{y2}) q(p_y^U) + \rho_{xi} \widehat{\gamma} (\widehat{\alpha}_{y1} + \widehat{\alpha}_{y2}) \widehat{q}(\widehat{p}_y^U)$$

- elasticities of the subscription fees and market shares in country  $x$ :

$$\eta_{F_{xi}} = \frac{2}{7} q(p_y^U) (1 - \gamma) \rho_{xi} \frac{a_{xi}}{2} = \frac{\sigma}{7} q(p_y^U) (1 - \gamma) \rho_{xi} \frac{a_{xi}}{\alpha_{xi}}$$

$$\eta_{\widehat{F}_{xi}} = \frac{2}{7} \widehat{q}(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi} \frac{a_{xi}}{2} = \frac{\sigma}{7} \widehat{q}(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi} \frac{a_{xi}}{\widehat{\alpha}_{xi}}$$

$$\eta_{\alpha_{xi}} = - \left( -\frac{\sigma}{7} v'(p_y^U) (1 - \gamma) \rho_{xi} \right) \frac{a_{xi}}{\alpha_{xi}} = -\frac{\sigma}{7} q(p_y^U) (1 - \gamma) \rho_{xi} \frac{a_{xi}}{\alpha_{xi}}$$

$$\eta_{\widehat{\alpha}_{xi}} = - \left( -\frac{\sigma}{7} \widehat{v}'(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi} \right) \frac{a_{xi}}{\widehat{\alpha}_{xi}} = -\frac{\sigma}{7} \widehat{q}(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi} \frac{a_{xi}}{\widehat{\alpha}_{xi}}$$

We then have:

$$\begin{aligned} \frac{a_{xi} - c}{a_{xi}} &= \frac{1}{\epsilon_{xi}} \left[ 1 + \frac{\pi_{xi}^r}{a_{xi} Q_{xi}} (\eta_{F_{xi}} - \eta_{\alpha_{xi}}) + \frac{\widehat{\pi}_{xi}^r}{a_{xi} Q_{xi}} (\eta_{\widehat{F}_{xi}} - \eta_{\widehat{\alpha}_{xi}}) \right] \\ \frac{a_{xi} - c}{a_{xi}} &= \frac{1}{\epsilon_{xi}} \left[ 1 + \frac{2}{7} \frac{\alpha_{xi}^2}{Q_{xi} \alpha_{xi}} \rho_{xi} (q(p_y^U) (1 - \gamma) + q(p_y^U) (1 - \gamma)) + \frac{2}{7} \frac{\widehat{\alpha}_{xi}^2}{Q_{xi} \widehat{\alpha}_{xi}} \rho_{xi} (\widehat{q}(\widehat{p}_y^U) \widehat{\gamma} + q(p_y^U) \widehat{\gamma}) \right] \\ \frac{a_{xi} - c}{a_{xi}} &= \frac{1}{\epsilon_{xi}} + \frac{1}{\epsilon_{xi}} \frac{2}{7} \frac{(1 - \gamma) \alpha_x q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_x \widehat{q}(\widehat{p}_y^U)}{(1 - \gamma) \alpha_y q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)} \end{aligned} \quad (24)$$

Evaluating the equilibrium values of the shares of roaming demand  $s_{xi}^x$  and  $s_{xi}^y$ , price elasticities  $\eta_p$  and  $\eta_{\widehat{p}}$  and market share elasticities  $\eta_{\alpha_y}$  and  $\eta_{\widehat{\alpha}_y}$  in the foreign country, we have:

$$\begin{aligned}
s_{xi}^y &= Q_{xi}^y / Q_{xi} = \frac{\widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)}{(1-\gamma)\alpha_y q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)} \\
s_{xi}^x &= Q_{xi}^x / Q_{xi} = \frac{(1-\gamma)\alpha_y q(p_y^U)}{(1-\gamma)\alpha_y q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)} \\
\eta_p &= (1-\gamma)\rho_{xi} \frac{a_{xi}}{p_y^U} \\
\eta_{\widehat{p}} &= \widehat{\gamma} \rho_{xi} \frac{a_{xi}}{\widehat{p}_y^U} \\
\eta_{\alpha_y} &= \left(-\frac{\sigma}{7} v'(p_y^U) (1-\gamma)\rho_{xi}\right) \frac{a_{xi}}{\alpha_{yi}} = \frac{\sigma}{7} q(p_y^U) (1-\gamma)\rho_{xi} \frac{a_{xi}}{\alpha_{yi}} \\
\eta_{\widehat{\alpha}_y} &= \left(-\frac{\sigma}{7} \widehat{v}'(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi}\right) \frac{a_{xi}}{\widehat{\alpha}_{yi}} = \frac{\sigma}{7} \widehat{q}(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi} \frac{a_{xi}}{\widehat{\alpha}_{yi}}
\end{aligned}$$

Then, the elasticity of the total roaming demand at the equilibrium is:

$$\epsilon_{xi} = s_{xi}^y (\eta_{\widehat{\alpha}_y} + \widehat{\varepsilon} \cdot \eta_{\widehat{p}}) + s_{xi}^x (\eta_{\alpha_y} + \varepsilon \cdot \eta_p) \quad (25)$$

$$\begin{aligned}
\epsilon_{xi} &= \frac{\widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)}{(1-\gamma)\alpha_y q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)} \left[ \frac{\sigma}{7} \widehat{q}(\widehat{p}_y^U) \widehat{\gamma} \rho_{xi} \frac{a_{xi}}{\widehat{\alpha}_{yi}} + \widehat{\varepsilon}^U \widehat{\gamma} \rho_{xi} \frac{a_{xi}}{\widehat{p}_y^U} \right] \\
&\quad + \frac{(1-\gamma)\alpha_y q(p_y^U)}{(1-\gamma)\alpha_y q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)} \left[ \frac{\sigma}{7} q(p_y^U) (1-\gamma)\rho_{xi} \frac{a_{xi}}{\alpha_{yi}} + \varepsilon^U (1-\gamma)\rho_{xi} \frac{a_{xi}}{p_y^U} \right] \quad (26) \\
\epsilon_{xi} &= \frac{\rho_{xi} a_{xi}}{(1-\gamma)\alpha_y q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)} \left[ \widehat{\gamma}^2 \widehat{q}^2(\widehat{p}_y^U) \frac{\sigma}{7} + (1-\gamma)^2 q^2(p_y^U) \frac{\sigma}{7} + \widehat{\varepsilon} \frac{\widehat{\gamma}^2 \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)}{\widehat{p}_y^U} + \varepsilon \frac{(1-\gamma)^2 \alpha_y q(p_y^U)}{p_y^U} \right]
\end{aligned}$$

Substituting (25) into (24) gives implicit value of the equilibrium roaming charge of operator  $xi$

$$\begin{aligned}
\frac{a_{xi} - c}{a_{xi}} &= \frac{1}{\epsilon_{xi}} + \frac{1}{\epsilon_{xi}} \frac{2(1-\gamma)\alpha_x q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_x \widehat{q}(\widehat{p}_y^U)}{7(1-\gamma)\alpha_y q(p_y^U) + \widehat{\gamma} \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)} \quad (27) \\
\frac{a_{xi} - c}{a_{xi}} &= \frac{1}{7\rho_{xi} a_{xi}} \frac{(1-\gamma)q(p_y^U) [5\alpha_y + (2\alpha_y + 2\alpha_x)] + \widehat{\gamma} \widehat{q}(\widehat{p}_y^U) [5\widehat{\alpha}_y + (2\widehat{\alpha}_y + 2\widehat{\alpha}_x)]}{\widehat{\gamma}^2 \widehat{q}^2(\widehat{p}_y^U) \frac{\sigma}{7} + (1-\gamma)^2 q^2(p_y^U) \frac{\sigma}{7} + \widehat{\varepsilon} \frac{\widehat{\gamma}^2 \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)}{\widehat{p}_y^U} + \varepsilon \frac{(1-\gamma)^2 \alpha_y q(p_y^U)}{p_y^U}} \\
\frac{a_{xi} - c}{a_{xi}} &= \frac{1}{\rho_{xi} a_{xi}} \frac{(1-\gamma)q(p_y^U) 5\alpha_y + \widehat{\gamma} \widehat{q}(\widehat{p}_y^U) 5\widehat{\alpha}_y + (1-\gamma)q(p_y^U) + \widehat{\gamma} \widehat{q}(\widehat{p}_y^U)}{\widehat{\gamma}^2 \widehat{q}^2(\widehat{p}_y^U) \sigma + (1-\gamma)^2 q^2(p_y^U) \sigma + 7\widehat{\varepsilon} \frac{\widehat{\gamma}^2 \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U)}{\widehat{p}_y^U} + 7\varepsilon \frac{(1-\gamma)^2 \alpha_y q(p_y^U)}{p_y^U}}
\end{aligned}$$

(2) In the following, we will make comparison between the two equilibrium roaming charges  $a_x^U$  and  $a_x^L$  giving condition on price elasticities at the equilibrium in the regime in which RLAH is accompanied with a fair use clause, i.e.  $\varepsilon^U$  and  $\widehat{\varepsilon}^U$ .

- Let's first rewrite the Lerner index of the roaming charge (9) substituting all elasticity terms in function of price equilibrium and considering the linear demand function. Then, we can easily show that  $\widehat{\varepsilon} = \frac{\widehat{p}_y^L}{\widehat{d} - \widehat{p}_y^L}$  and  $\eta_{\widehat{p}} = \widehat{\gamma}\rho_{xi} \frac{3a_{xi}}{\widehat{c} - \widehat{c}\widehat{\gamma} + 2\widehat{d} + c\widehat{\gamma}}$ . Finally, the roaming charge in the RLAH regulatory regime at the equilibrium is implicitly given by  $\frac{a_{xi}^L - c}{a_{xi}^L} = E$ , where  $E = \frac{\widehat{d} - \widehat{p}_y^L}{\widehat{p}_y^L} \frac{\widehat{c} - \widehat{c}\widehat{\gamma} + 2\widehat{d} + c\widehat{\gamma}}{3a_{xi}^L \widehat{\gamma} \rho_{xi}}$ .

- We now make the following comparison:  $\frac{a_x^U - c}{a_x^U} > \frac{a_x^L - c}{a_x^L}$ .

Then, considering (27) we have:  $\frac{a_x^U - c}{a_x^U} > \frac{a_x^L - c}{a_x^L}$  iff

$$E > \frac{\widehat{p}_y^U \widehat{p}_y^U [(1 - \gamma)q(p_y^U)5\alpha_y + \widehat{\gamma}\widehat{q}(\widehat{p}_y^U)5\widehat{\alpha}_y + (1 - \gamma)q(p_y^U) + \widehat{\gamma}\widehat{q}(\widehat{p}_y^U)]}{\widehat{\gamma}^2 \widehat{q}^2(\widehat{p}_y^U) \sigma \widehat{p}_y^U p_y^U + 7\varepsilon^U \widehat{\gamma}^2 \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U) p_y^U + (1 - \gamma)^2 q^2(p_y^U) \sigma \widehat{p}_y^U p_y^U + 7\varepsilon^U (1 - \gamma)^2 \alpha_y q(p_y^U) \widehat{p}_y^U}$$

Rearranging terms, this condition can be expressed as a condition on price elasticities and we obtain:

$$\frac{a_x^U - c}{a_x^U} > \frac{a_x^L - c}{a_x^L} \iff \varepsilon^U < \varepsilon_1(\widehat{\varepsilon}^U) = A_1 - \widehat{\varepsilon}^U H_1 \quad (28)$$

where:

$$A_1 = \frac{1}{E} \frac{\widehat{p}_y^U \widehat{p}_y^U}{7(1 - \gamma)^2 \alpha_y q(p_y^U) \widehat{p}_y^U} [(1 - \gamma)q(p_y^U)5\alpha_y + (1 - \gamma)q(p_y^U) + \widehat{\gamma}\widehat{q}(\widehat{p}_y^U)5\widehat{\alpha}_y + \widehat{\gamma}\widehat{q}(\widehat{p}_y^U)] - \frac{\sigma \widehat{p}_y^U p_y^U}{7(1 - \gamma)^2 \alpha_y q(p_y^U) \widehat{p}_y^U} [\widehat{\gamma}^2 \widehat{q}^2(\widehat{p}_y^U) + (1 - \gamma)^2 q^2(p_y^U)]$$

$$\text{and } H_1 = \frac{\widehat{\gamma}^2 \widehat{\alpha}_y \widehat{q}(\widehat{p}_y^U) p_y^U}{(1 - \gamma)^2 \alpha_y q(p_y^U) \widehat{p}_y^U}$$

- Using symmetry, the comparison for the roaming charge of home operators in country  $y$  is:

$$\frac{\widehat{a}_y^U - \widehat{c}}{\widehat{a}_y^U} > \frac{\widehat{a}_y^L - \widehat{c}}{\widehat{a}_y^L} \iff \widehat{\varepsilon}^U < \widehat{\varepsilon}_2(\varepsilon^U) = A_2 - \varepsilon^U H_2 \quad (29)$$

where

$$A_2 = \frac{\widehat{p}_x^U \widehat{p}_x^U}{7(1 - \widehat{\gamma})^2 \widehat{\alpha}_x \widehat{q}(\widehat{p}_x^U) \widehat{p}_x^U E} [(1 - \widehat{\gamma})\widehat{q}(\widehat{p}_x^U)5\widehat{\alpha}_x + (1 - \widehat{\gamma})\widehat{q}(\widehat{p}_x^U) + \gamma q(p_x^U)5\alpha_x + \gamma q(p_x^U)] - \frac{\sigma \widehat{p}_x^U \widehat{p}_x^U}{7(1 - \widehat{\gamma})^2 \widehat{\alpha}_x \widehat{q}(\widehat{p}_x^U) \widehat{p}_x^U} [\gamma^2 q^2(p_x^U) + (1 - \widehat{\gamma})^2 \widehat{q}^2(\widehat{p}_x^U)]$$

$$\text{and } H_2 = \frac{\gamma^2 \alpha_x q(p_x^U) \widehat{p}_x^U}{(1 - \widehat{\gamma})^2 \widehat{\alpha}_x \widehat{q}(\widehat{p}_x^U) p_x^U}$$

#### 7.1.4 Proposition 5

Directly from previous results and considering that  $\gamma = \widehat{\gamma}$  ;  $\alpha_x = \alpha_y = \widehat{\alpha}_x = \widehat{\alpha}_y = 1/4$  ;  
 $p^U = p_x^U = p_y^U = \widehat{p}_x^U = \widehat{p}_y^U$  ;  $\varepsilon^U = \widehat{\varepsilon}^U$ .