DOCUMENTO DE TRABAJO. E2009/ 08

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Abstract

This paper compares different licensing contracts defined by the type of payment (fees or royalties) and contract duration (short- or long-term) in a setting in which an outside patent holder that owns a patented innovation lasting for two periods licenses it to downstream Cournot firms; further, there is asymmetric information about firms' costs emerged from the use of innovation, but they are signaled through the output produced in period 1. In this context, if we concentrate on fee contracts, the patent holder prefers short-term (revealing) contracts rather than long-term contracts. From a social perspective, however, short-term fee contracts only dominate long-term contracts under certain conditions. Further, when comparing fee contracts, royalty contracts and contracts formed by royalties in period 1 and fees in period 2, the dominance (to the patent holder) of short-term fee contracts survives. Moreover, (short- or long-term) fee contracts are socially superior to any other form of licensing arrangement since they imply a lower distortion in the users' behavior. Thus the dominance of fees that emerges under perfect and complete information is robust to the presence of asymmetric information and signaling.

JEL Classification Number: D45

Keywords: Licensing, signaling, fees, royalties, short- and long-term contracts, welfare

[*] I wish to thank an anonymous referee for helpful comments and suggestions. Thanks are also due to Antonio R. Sampayo for his assistance. Financial support from the Xunta de Galicia through Grant INCITE09201042PR is gratefully acknowledged.

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1. Introduction

Literature on licensing shows that, in a context of perfect and complete information with Cournot competition, a non-producing patent holder prefers fee rather than royalty contracts to license an innovation[1] (Kamien and Tauman 1986, Katz and Shapiro 1986, Kamien et al. 1992). However, asymmetric information problems, where someone owns more information than another (the patent holder since it has made the discovery, or the licensee because it has more information about the technical production environment),[2] are common in technology transfer. Our interest is to investigate whether the dominance of fee payments in licensing arrangements is robust or not to the presence of asymmetric information and signaling as a way to solve the asymmetric information problem.

To analyze how the combination of an outside patent holder, asymmetric information and signaling may affect the optimal form of payments and duration of licensing contracts, we consider a two-period signaling model in which there is an outside patent holder that owns a patented innovation lasting for two production periods. Since the patent holder is unable to exploit the innovation, so it should be licensed to several downstream firms, which compete à la Cournot in the product market; the production cost of each licensee is unknown to everyone until after contracting, at which point each particular user gets private information about its own cost, whereas the other players –the competitors and the patent holder– only have a prior assessment of such cost (it may adopt a low or a high value with a certain probability); these players can infer, however, the true cost after observing the licensee's output of the first period (in the separating equilibrium of the signaling game induced by successive short-term contracts), or remain ignorant about it (in a long-term contract). In the first case, information is complete in period 2; in the second, it remains incomplete.

[1] Contrariwise, a producing patent holder that transfers its innovation to some or all of its competitors prefers royalty contracts.
[2] Also, potential licensees may face market uncertainty that affects only some firms, the control of the production level or the non-contractual use of the technology may be difficult, etc.

In this setting, we examine the outcome of different licensing schemes that may differ in the type of payments (fixed fees, royalties, or royalties in period 1 and fees in period 2) and in the duration of contracts (short-term contracts renewed periodically versus long-term contracts for the entire lifetime of innovation). The presence of asymmetric information may induce opportunistic behavior, since the possibility of the contracts' period-by-period design allows each licensee to use signaling strategies to influence other players' beliefs concerning its private information. Thus, both scheduled payments and contract duration are likely designed to mitigate these problems of opportunism.

The paper explores three issues. First, does the dominance of fees over royalties that exists in a perfect and complete information context survive under asymmetric information and signaling? Second, does the patent holder find it more profitable to offer short- or long-term licensing contracts? Third, in evaluating the social performance of the optimal contracting to the patent holder, to what extent are private and social interests aligned or in conflict?

Findings show that if we concentrate on fee contracts, the patent holder always prefers to offer short-term (revealing) contracts rather than long-term (non-revealing) contracts. With short-term contracts there is indeed a separating equilibrium of the signaling game induced by a series of short-term contracts and it is always the patent holder's preferred strategy because signaling in period 1 increases the firms' profits in that period. In addition, after period 1, complete information is recovered, and the patent holder can reap the maximum profit of each firm by charging the low-cost producer a higher fee than the high-cost one. This difference in payment can tempt each efficient user to misrepresent itself by under-producing in such a period, but the patent holder can profitably remove this temptation by increasing the upfront fee imposed in period 1. This makes the period 1's optimal output for any high-cost firm too low for it to be profitable for a low-cost user of the innovation to mislead, restoring the separating equilibrium.

Since the patent holder increases the first-period payment of each licensee in order to screen for its cost, it is better off in this period than it would be under a long-term contract. Screening for costs implies a deviation of firms' production (compared to production levels that would exist in the absence of screening), which benefits the patent holder, whereas signaling is harmless for producers because their expected profits are always harvested by the patent holder. As a result, the patent holder's preferred licensing agreement is unequivocally a sequence of short-term fee contracts, because it increases licensing income in both production periods as compared to long-term fee contracts.

Short-term fee contracts dominate not only long-term fee contracts, but also royalty contracts, and even those contracts formed by royalties in (incomplete information) period 1 and fees in (complete information) period 2. This means that such contracts are the optimal licensing arrangement for a non-producing patent holder in a dynamic setting where each licensee acquires informational advantage and may behave opportunistically. Hence, the dominance of fees over royalties that prevails under perfect and complete information is robust to the presence of asymmetric information and signaling, with the particularity that, in this case, the (outside) patent holder prefers a sequence of short-term (revealing) contracts rather than a long-term (non-revealing) contract. In other words, interaction of an outside patent holder (that favors the use of fees) and the presence of asymmetric information (that indicates the use of royalties) leads fees to be better than royalties as licensing scheme when signaling emerges.

Finally, fee contracts are socially superior to any other form of licensing arrangement, because they induce lower distortion on firms' choice. However, short-term fee contracts lead to greater social welfare than long-term fee contracts only when both the a priori probability of a firm being an efficient user of the innovation and the bad realization of production cost are sufficiently high. Otherwise, long-term fee contracts are more advantageous for society as a whole. Distortion on firms' production in period 1 due to signaling induced by a sequence of short-term fee contracts leads to a decrease on total expected output of that period. Thus, consumers become worse off in period 1 compared to a scenario of long-term fee contracts. Moreover, this reduction on consumer surplus is so large that it outweighs the increase on patent holder's income in period 1 so that total welfare in period 1 under short-term fee contracts is lower than under long-term fee contracts. Taking into account that the opposite holds in period 2, when the patent holder and consumers are better off under short-term than under long-term fee contracts, the result whereby short-term (revealing) fee contracts may be socially superior or inferior to long-term (non-revealing) fee contracts holds. That is, a conflict between private and social interests may arise since consumers are better off, under some circumstances, if the innovation were diffused via long-term contracts.

Information problems such as incomplete information, when the absence of information affects both parts equally, and asymmetric information, when one party is better informed than the other, introduce new issues in licensing analysis with respect to a context of perfect and complete information. Incomplete information adds risk to the licensing relationship and favors royalty payments because they allow shared risk of success or failure (in the new production process or the commercialization of the new product) between the seller and the buyer.[3] Asymmetric information, on the other hand, may give rise to adverse selection problems largely examined by licensing literature (Gallini and Wright 1990, Macho-Stadler and Pérez-Castrillo 1991, Beggs 1992).

In a two-period signaling model, Antelo (2009) addressed the question of the optimal duration of royalty-only contracts under asymmetric information and signaling. The finding is that if both the probability of becoming a low-cost licensee and the value adopted by the bad realization of cost are sufficiently large, the patent holder imposes a series of short-term royalty contracts rather than a long-term royalty contract. Under such circumstances, short-term contracts allow the patent holder to recover complete information in period 2 at little or no signaling cost in period 1.

[3] For instance, the case of new hybrid seeds from former products, where results are not easily forecast.

Hence, cumulative royalty revenues are higher than under long-term contracts, with no signaling and the permanence of incomplete information in period 2. However, a long-term contract is preferred whenever signaling is very costly, because the extra income by the acquisition of complete information exceeds the cost of collecting such information. The current paper extends this framework to one in which the patent holder may choose both the duration and payments of licensing contracts.

The remainder of the article is organized as follows. Section 2 describes the model. Section 3 examines the outcome of long-term and short-term fee contracts. Both types of contracts are compared in Section 4. Fee contracts and other licensing arrangements (royalty contracts and contracts formed by royalties in period 1 and fees in period 2) are compared in Section 5. Section 6 analyzes the best licensing policy for the society as a whole. Section 7 concludes.

2. The model

Consider an upstream licensor that owns a patented innovation lasting for two periods, t=1,2. The patent holder is unable to exploit the innovation, so it should be licensed to downstream users. These users produce a homogeneous product for a market whose demand is given by

$$p_t(Q_t) = 1 - Q_t\,, \tag{1}$$

in each production period t, where Q_t represents total output. For simplicity, we assume only two licensees, A and B; so, $Q_t = q_t^{\mathrm{A}} + q_t^{\mathrm{B}}$. The demand given in (1) remains unchanged across periods.

The production cost of each licensee i, i=A,B, is a random variable that adopts one of two possible values, $\tilde{c}^i \in \{0, c\}$, with $c > 0$. Only firm i knows for sure the realization of its cost derived from using the innovation; the rest of the players –firm j, $j \neq i$, and the patent holder– only know the distribution of $\tilde{c}^i$, given by $\mathrm{Prob}(\tilde{c}^i = 0) = \mu$ and $\mathrm{Prob}(\tilde{c}^i = c) = 1 - \mu$, with $0 < \mu < 1$.

All players acting in the game are risk neutral and the discount factor between periods is one. The patent holder has all the bargaining power. Finally, the following property is assumed.

Assumption 1. Marginal cost of production *c* is such that $0 < c < 1/2$.

Given that parameter *c* measures not only the marginal cost of each licensee derived from a bad realization of the innovation but also the cost difference that may exist between (cost heterogeneous) licensees, this assumption ensures that any user *i* of the innovation will produce positive output, regardless of the realization of its marginal cost, that of the rival *j*, and the belief of third parties –firm *j* and the patent holder– about the firm *i*'s realization.

3. Fee contracts

3.1 Long-term contracts

This section examines the equilibrium of the following three-stage game. In the first stage, the patent holder simultaneously proposes a licensing contract to firms, whereby each one can use the innovation for its entire lifetime in exchange of an upfront fee. In the second stage, firms simultaneously decide whether to purchase a license. In the third stage, licensees produce with the cost structure assumed in the second stage and with incomplete information. Competition between users of the innovation in the market product is à la Cournot.

A long-term licensing contract has an upfront fee paid by each firm for the entire lifetime of the patent. This is equivalent to equal payments in each period. Such fee is given by each firm's expected profit per period under incomplete information, because incomplete information exists (in period 1), when the patent holder designs the licensing contract covering all production periods. Thus each firm faces the problem

$$\max \pi^i = \mu(1-c^i-q^i-q^j_{L,\mathrm{II}})q^i + (1-\mu)(1-c^i-q^i-q^j_{H,\mathrm{II}})q^i, \quad i,j=\mathrm{A,B};\ j\neq i, \qquad (2)$$

where subscripts L and H denote, respectively, low- and high-cost licensee, and subscript II stands for incomplete information. The resolution of (2) yields

$$q^i_{L,\mathrm{II}}(q^j_{H,\mathrm{II}}) = \frac{1-(1-\mu)q^j_{H,\mathrm{II}}}{2+\mu} \tag{3}$$

as the best-reply function for each low-cost firm, and

$$q^i_{H,\mathrm{II}}(q^j_{L,\mathrm{II}}) = \frac{1-c-\mu\, q^j_{L,\mathrm{II}}}{3-\mu} \tag{4}$$

as the best-reply for each high-cost firm. From (3) and (4), we have

$$q^i_{L,\mathrm{II}} = \frac{2+(1-\mu)c}{6}\text{, } i\text{=A,B,} \tag{5}$$

and

$$q^i_{H,\mathrm{II}} = \frac{2(1-c)-\mu c}{6} \tag{6}$$

as the equilibrium output of the low- and high-cost licensee, respectively, in each production period. Description of the equilibrium is completed with the values of Table 1, where superscript *PH* denotes patent holder.

Table 1. Equilibrium values in each (II) period of the licensing game induced by long-term fee contracts

$(\tilde{c}^i, \tilde{c}^j)$	Q_{II}	π^{PH}_{II}	π^i_{II}
$(0,0)$	$[2+(1-\mu)c]/3$	$\frac{1}{9}-\frac{(1-\mu)c[8-(4+5\mu)c]}{36}$	$\frac{(1-\mu)c[4-(1+2\mu)c]}{12}$
$(0,c)$	$[4-(1+2\mu)c]/6$		
$(c,0)$	$[4-(1+2\mu)c]/6$		$-\frac{\mu c[4-(1+2\mu)c]}{12}$
(c,c)	$[2(1-c)-\mu c]/3$		

In sum, the (long-term) licensing contract covering the entire expected lifetime of the innovation is defined by upfront fee

$$F_{\mathrm{II}}^{i} \equiv 2\pi_{\mathrm{II}}^{PH} = \frac{1}{18}[4-(1-\mu)c(8-(4+5\mu)c)] \tag{7}$$

to be paid by each firm i in the first production period. The fact that the patent holder cannot distinguish a low- from a high-cost licensee either in the first or in the second period means that both types of firm pay the same fee for using the innovation; an amount that equals expected profit of each firm through the two production periods. The firm i's expected net profit throughout the two production periods is then

$$\pi_{L,\mathrm{II}}^{i} = \frac{1}{6}(1-\mu)c[4-(1+2\mu)c] \tag{8}$$

in the case of an efficient licensee, and

$$\pi_{H,\mathrm{II}}^{i} = -\frac{1}{6}\mu c[4-(1+2\mu)c] \tag{9}$$

for an inefficient licensee. That is, each low-cost user gets positive net profits, $\pi_{L,\mathrm{II}}^{i} > 0$, whereas each high-cost firm suffers losses, $\pi_{H,\mathrm{II}}^{i} < 0$. On average, however, each firm i obtains a zero net profit, $\pi_{\mathrm{II}}^{i} = 0$, since all gross profit goes to the patent holder.

3.2 Period-by-period contracts

In this case, the patent holder offers a contract to each firm for the first production period. Licensees produce in this period under incomplete information, but each firm i's production is observed by competitor j and the patent holder. In a Bayesian separating equilibrium, the observation of this output allows third parties to infer, in period 2, the firm i's true cost. Knowing the licensees' costs, the patent holder offers another fee contract for the second period. If accepted, licensees produce in this period under conditions of complete information.

Clearly, the first-period contract designed for each firm will be the same for both types of firm because of the patent holder's inability to distinguish between them. In the second period, however, the patent holder can discriminate, in a Bayesian separating equilibrium, one type from another due to the recovery of complete information from the observation of first period output. As usual, a Bayesian separating equilibrium is calculated by backwards induction.

Period 2

In a separating equilibrium, the period 2 game becomes a complete information game, where information about each licensee's value of the innovation is public. The equilibrium values of such a game are collected in Table 2, where subscript CI denotes complete information.

Table 2. Equilibrium values of the (CI) second period of the game induced by short-term fee contracts

$(\tilde{c}^i, \tilde{c}^j)$	q^i_{CI}	Q_{CI}	π^{PH}_{CI}	π^i_{CI}
$(0,0)$	$1/3$	$2/3$	$1/9$	0
$(0,c)$	$(1+c)/3$	$(2-c)/3$	$(1+c)^2/9$	0
$(c,0)$	$(1-2c)/3$	$(2-c)/3$	$(1-2c)^2/9$	0
(c,c)	$(1-c)/3$	$2(1-c)/3$	$(1-c)^2/9$	0

The values of the fourth column of Table 2 define the contracts offered to each firm *i* in period 2 according to its cost realization and that of firm *j*. In turn, the values of the last column show that each type of licensee obtains a zero net profit, namely that $\pi^i_{L,\mathrm{CI}} = \pi^i_{H,\mathrm{CI}} = 0$. Thus, comparing $\pi^i_{L,\mathrm{CI}}$ with (8) and $\pi^i_{H,\mathrm{CI}}$ with (9) affords $\pi^i_{L,\mathrm{CI}} < \pi^i_{L,\mathrm{II}}$, but $\pi^i_{H,\mathrm{CI}} > \pi^i_{H,\mathrm{II}}$, i.e. whereas each efficient licensee obtains less profits in a CI game than in an II scenario, the contrary holds for each inefficient user of the innovation.

The following lemma describes the net profits of each licensee in period 2 when it misrepresents its costs as compared to those reporting them truthfully.

Lemma 1. *Let* $\pi_2^i(x|y;\tilde{c}^j)$ *denote the firm i's net profit in period* 2 *when it has cost x, but it revealed cost y in period* 1. *Then:*

(i) $\pi_2^i(0|c;0) = (4-5c)c/12$, $\pi_2^i(0|c;c) = (4-c)c/12$, $\pi_2^i(c|0;0) = -(4-3c)c/12$ *and* $\pi_2^i(c|0;c) = -(4+c)c/12$.

(ii) $\pi_2^i(c|c;\tilde{c}^j) > \pi_2^i(c|0;\tilde{c}^j)$ *and* $\pi_2^i(0|0;\tilde{c}^j) < \pi_2^i(0|c;\tilde{c}^j)$.

Proof. See the Appendix.

Each firm *i* has a horizontal incentive to be understood as a low-cost firm by its rival *j*, because this reduces *j*'s output and profit in period 2 and, consequently, increases *i*'s output and profit in that period. At the same time, each firm has a vertical incentive to report to the patent holder that it is a high-cost producer in order to pay a lower fee in period 2. What Lemma 1 states is that the latter incentive outweighs the former. Overall, then, each firm *i* has an interest in being perceived as a high-cost firm, regardless its true costs.

Period 1

In period 1, the patent holder is unable to distinguish between efficient and inefficient firms, so each firm *i* pays the same fee, irrespective of its type. It also produces output level q_1^{is} under incomplete information; and output that will be observed to other players, from which they infer (in the separating equilibrium of the game) the firm *i*'s true cost. The separating equilibrium of minimum cost for the entire game induced by a series of short-term fee contracts may be described in the following lemma, where superscript *s* denotes signaling in period 1.

Lemma 2. *In the separating equilibrium of minimum cost of the licensing game induced by successive short-term fee contracts the following holds.*

(i) *In period 1, each firm i, i=A,B, produces* $q_{1H}^{is} = 1/3 - (2+\mu)\sqrt{3(4-(1+4\mu)c)\,c}\,/18$, *if it is a high-cost licensee, and* $q_{1L}^{is} = 1/3 + (1-\mu)\sqrt{3(4-(1+4\mu)c)\,c}\,/18$, *if it is a low-cost licensee.*

(ii) *Posterior beliefs about firm i's type are* $Prob(\tilde{c}^{\,i} = c \mid q_1^i = q_{1H}^{is}) = 1$ *and* $Prob(\tilde{c}^{\,i} = c \mid q_1^i = q_{1L}^{is}) = 0$.

(iii) *In period 2, output levels of each firm i,* q_{CI}^{i}, *are as given in Table 1.*

Proof. See the Appendix.

The basic point of the separating equilibrium stated in Lemma 2 is that, in period 1, $q_{1H}^{is} < q_{1H,\mathrm{II}}^{i}$; that is, each inefficient user of the innovation, in order to be distinguished as such in period 2, is forced to produce in period 1 less than the profit-maximizing output it would produce as a simple monopolist under II with no signaling activity. In other words, signaling is costly in the entire (μ,c)-parameters space defined by $0 < \mu < 1$ and $0 < c < 1/2$. The intuition behind this result is simple. According to Lemma 1, each low-cost firm has a strong incentive to misrepresent itself as being a high-cost producer since this allows it to have a positive net profit: $(4-5c)c/12$, if the rival firm is a low-cost producer, and $(4-c)c/12$, if the rival is a high-cost producer. Consequently, high-cost firms need to under-produce in period 1 to avoid the low-cost firms mimic their production levels. As a reaction, the low-cost licensees produce in period 1 a higher output than the profit-maximizing output under II with no signaling, $q_{1L}^{is} > q_{1L,\mathrm{II}}^{i}$. Nevertheless, given that under-production of high-cost firms is a first-order deviation, whereas over-production of low-cost firms is a second-order deviation induced by under-production of high-cost licensees, total output of period 1 is lower than it would be under II with no signaling (or, alternatively, if signaling were costless). In a sense, signaling is anticompetitive.[4]

4. The optimal duration of upfront fee contracts

In this section, the outcome for the patent holder of long-term and short-term fee contracts are compared. According to (7), with long-term fee arrangements the patent holder's revenue is

$$\pi_{\mathrm{LT}}^{PH} \equiv 2F_{\mathrm{II}}^{i} = \frac{1}{9}[4-(1-\mu)c(8-(4+5\mu)c)], \qquad (10)$$

where subscript LT stands for a long-term contract covering the entire expected lifetime of the innovation. On the other hand, when licensing policy consists of a succession of short-term contracts, the patent holder's revenue amounts to

$$\pi_{\mathrm{ST}}^{PH} \equiv 2\left[\mu\left(\frac{1}{3}+\frac{(1-\mu)\sqrt{3(4-(1+4\mu)c)\,c}}{18}\right)^{2}+(1-\mu)\left(\frac{1}{3}-c+\frac{(4-\mu)\sqrt{3(4-(1+4\mu)c)\,c}}{18}\right)\right.$$

$$\left.\left(\frac{1}{3}-\frac{(2+\mu)\sqrt{3(4-(1+4\mu)c)\,c}}{18}\right)\right]+\frac{1}{3}[1-(1-\mu)c(2-(1+4\mu)c)], \qquad (11)$$

where subscript ST denotes short-term contracts. Comparison of revenues given in (10) and (11) yields the following proposition.

Proposition 1. *When licensing is made through fees, the patent holder prefers short-term (revealing) contracts rather than long-term (non-revealing) contracts.*

In such a series of short-term fee contracts, what each firm pays in the first-period is

[4] This will reduce the level of expected consumer surplus achieved in period 1 compared to the level that would exist if signaling were costless. See Lemma 4 later on.

$$F_{1,\mathrm{II}}^{is} = \mu\left(\frac{1}{3} + \frac{(1-\mu)\sqrt{3(4-(1+4\mu)c)\,c}}{18}\right)^2 + (1-\mu)\left(\frac{1}{3} - c + \frac{(4-\mu)\sqrt{3(4-(1+4\mu)c)\,c}}{18}\right)\left(\frac{1}{3} - \frac{(2+\mu)\sqrt{3(4-(1+4\mu)c)\,c}}{18}\right), \quad (12)$$

irrespective of its type, because the patent holder cannot distinguish a low-cost from a high-cost type. In the second period, however, each type of firm pays a different fee depending on the cost realizations observed by the patent holder. In particular, the second period licensing contract is defined by fee

$$F_{\mathrm{CI}}^{i} = \begin{cases} \left(\frac{1}{3}\right)^2, \text{ if } (\tilde{c}^i, \tilde{c}^j) = (0,0) \\ \left(\frac{1+c}{3}\right)^2, \text{ if } (\tilde{c}^i, \tilde{c}^j) = (0,c) \\ \left(\frac{1-2c}{3}\right)^2, \text{ if } (\tilde{c}^i, \tilde{c}^j) = (c,0) \\ \left(\frac{1-c}{3}\right)^2, \text{ if } (\tilde{c}^i, \tilde{c}^j) = (c,c). \end{cases} \quad (13)$$

The fact that signaling is costly in period 1 leads to an increase on firms' expected profits for that period compared to those they would obtain if signaling were costless (or, similarly, if the licensing game were induced by long-term fee contracts). This is because the firms that increase their production in period 1 are the low-cost firms, whereas those that decrease their production are the high-cost firms; a kind of productive deviation that obviously improves profit. Indeed, the increase on firm *i*'s expected profits during period 1 due to signaling amounts to

$$\Delta\pi_1^i \equiv \pi_{1,\mathrm{II}}^{is} - \pi_{1,\mathrm{II}}^{i}$$

$$= \frac{1}{54}(1-\mu)[(2+3(2+\mu)c)\sqrt{3(4-(1+4\mu)c)\,c} - 2(11+\mu)\,c - (2-9\mu-2\mu^2)\,c^2]\,. \quad (14)$$

In addition, a series of short-term contracts allows complete information to be restated in period 2, yielding more profits to firms in that period than those obtained in the II context induced by long-term contracts. Such increase on firm *i*'s expected profits in period 2 amounts to

$$\Delta\pi_2^i \equiv \pi_{\text{CI}}^i - \pi_{\text{II}}^i = \frac{11}{36}\mu(1-\mu)c^2 . \qquad (15)$$

Consideration of (14) and (15) then directly leads to the result of Proposition 1. Likewise, from (12), net profits (denoted by superscript *N*) in period 1 for each low-cost licensee are positive and amount to

$$\pi_{1L,\text{II}}^{Nis} = \frac{1}{36}(1-\mu)c[24 - 3(1+4\mu)c - 2(2+\mu)\sqrt{3(4-(1+4\mu)c)c}\,], \qquad (16)$$

whereas those of each high-cost licensee,

$$\pi_{1H,\text{II}}^{Nis} = -\frac{1}{36}\mu c[24 - 3(1+4\mu)c - 2(2+\mu)\sqrt{3(4-(1+4\mu)c)c}\,], \qquad (17)$$

are negative. The following lemma establishes that fees $F_{1,\text{II}}^{is}$ and F_{CI}^{i}, defining the short-term contract, allow the patent holder to obtain the whole expected profit of licensees. This may be stated in the following lemma, where superscript *N* denotes net profits and superscript *s* stands for signaling.

Lemma 3. *Each firm i gets, on average, zero net profits both in each period of the short-term licensing game,* $\pi_{1,\text{II}}^{Nis} = 0$, $\pi_{\text{CI}}^{Ni} = 0$.[5]

Proof. See the Appendix.

[5] The same holds in each period of the long-term fee licensing game, $\pi_{\text{II}}^{Ni} = 0$.

Payments given in (12) and (13) allow the patent holder to obtain all expected profits of licensees in both production periods. Despite the fee payments, signaling in period 1 distorts the licensees' behavior in that period, where II exists. This effect –that fee contracts distort firms' behavior– is novel with respect to a context of perfect and complete information in which fees do not distort licensees' behavior at all.

Finally, from (12) and (13) the following corollary can be obtained.

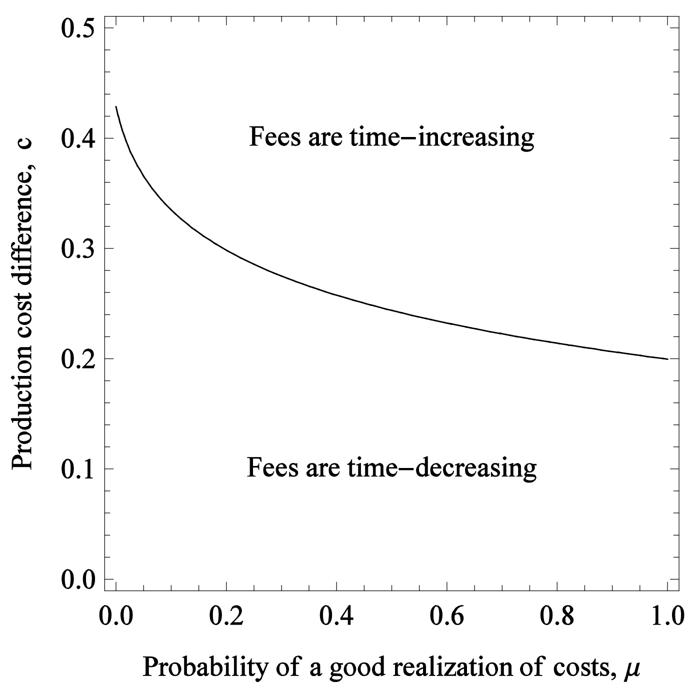
Corollary 1. *If parameters μ and c satisfy*

$$2(2+3(2+\mu)c)\sqrt{3(4-(1+4\mu)c)\,c}-(4(11+\mu)+(4-\mu)(1+4\mu)c)\,c>0\,,$$

then fees of successive short-term contracts are time-decreasing, namely $F_{1,\mathrm{II}}^{is}>F_{2,\mathrm{CI}}^{i}$. *Otherwise, they are time-increasing,* $F_{1,\mathrm{II}}^{is}<F_{2,\mathrm{CI}}^{i}$.

This result may be illustrated in Figure 1.

Fig. 1. Time-pattern of expected fees in a series of short-term contracts



In words, if one or both licensees are sufficiently efficient as such that $c < 1/5$, fees are time-decreasing, regardless of the degree of uncertainty. This is because in this circumstance, signaling in period 1 leads firms to produce an output level very different than the output they would produce under II with no signaling (each efficient firm over-produces and each inefficient firm under-produces); this leads the licensees to obtain substantial excess profits, which allow the patent holder to charge a high fixed payment. In addition, in period 2 market competition is fierce whenever c is sufficiently low, reducing the profits obtained by each user of the innovation. Consequently, the payment the patent holder can set in period 2 diminishes. Similarly, when c is sufficiently high, $c > 3/7$, fees are time-increasing, irrespective of the value of μ, the probability of a good realization of the innovation. In this case, signaling is slightly costly and firms' outputs are close to their output levels under II without signaling; so profits are low (and close to profits under II without signaling) and the payment that the patent holder can charge to each firm decreases. Moreover, market competition in period 2 is soft, which allows the patent holder to charge high fees in such a period. Finally, for intermediate values of the efficiency gap, $1/5 < c < 3/7$, fees are likely to be time-decreasing (time-increasing) as μ is sufficiently low (high).

5. Fee vs. other licensing contracts

If the patent holder can simultaneously choose both the duration of licensing contracts and their payment form (fee contracts, royalty contracts, or contracts based on royalties in the first period and then fees in the second period), the following result emerges.

Proposition 2. *When the patent holder can choose both the duration of contracts and their payment form, the optimal licensing policy consists of short-term fee contracts. Namely, short-term fee contracts are better than:*

(i) *Long-term fee contracts.*

(ii) *Short- and long-term royalty contracts.*

(iii) *(Short-term) contracts based on royalties in period 1 and fees in period 2.*

Proof. See the Appendix.

It is a well-known fact that, under perfect and complete information, fee licensing is a better mechanism than royalty licensing for a non-producing patent holder (Kamien and Tauman 1986; Katz and Shapiro 1986; Kamien et al. 1992). What Proposition 2 shows is that this finding survives in a dynamic context in which the patent holder lacks information about the value of the innovation, although it can infer such information from observing the licensees' output. The shading that asymmetric information and signaling adds to this finding is that fees are charged period-by-period rather than in the first period for the expected lifetime of the innovation. Given that signaling is costly and leads to an increase in firms' expected profits, the duration of the contract for one period is better than for two periods.

Part (i) of the proposition refers to the result of Proposition 1. Part (ii) indicates that royalties distort the licensees' behavior and reduce the revenue of the patent holder compared to when (short-term) fees are used. Finally, Part (iii) indicates that the superiority of short-term fee contracts remains even when considering the potential for the patent holder to design mixed contracts using royalties in the first period and fees in the second period.[6] The explanation is that signaling induced in a royalty situation implies a more pronounced distortion of firms' behavior of period 1 (even when fees are charged in period 2) than it does when fees are used.

In sum, the underlying idea of Proposition 2 is that in the "conflict" between the presence of an outside patent holder –that encourages the use of fees to license the innovation– and the presence

[6] Due to the fact that complete information exists in period 2, the patent holder will never resort to royalty licensing in that period.

of asymmetric information –a fact that induces the use of royalty licensing–, the effect of the presence of the outside patent holder dominates, when signaling emerges.

6. Welfare

In this subsection, the social performance of the fee-licensing policy is examined. To this end, expected welfare is defined as the expected consumer surplus plus the licensees' expected (net) profits and the patent holder's licensing income, $W = CS + \sum_{i=\mathrm{A,B}} \pi^{i} + \pi^{PH}$. From (1), consumer surplus can be derived as $CS = (1/2)[1-(1-Q)^2]$, where Q denotes total output. Given that the patent holder accrues all the firms' expected gross profits regardless of the informational context (see Lemma 3), expected welfare simply reduces to the sum of expected consumer surplus and the patent holder's expected income, $W = CS + \pi^{PH}$.

When long-term fee contracts are used to license the innovation and incomplete information remains throughout the entire expected lifetime of the innovation, expected consumer surplus in period *t*, *t*=1,2, amounts to

$$CS_{t,\mathrm{II}} = \frac{1}{36}[16-(1-\mu)c(8+(8+\mu)c)] \tag{18}$$

and the patentee's expected revenue to

$$\pi_{t,\mathrm{II}}^{PH} = \frac{1}{18}[4-(1-\mu)c(8-(4+5\mu)c)]. \tag{19}$$

From (18) and (19), expected social welfare in each period *t* is then

$$W_{t,\mathrm{II}} = \frac{1}{12}[8-(1-\mu)c(8-3\mu c)]. \tag{20}$$

On the other hand, a licensing game induced by successive short-term fee contracts, each one lasting one period, yields expected consumer surplus

$$CS^{s}_{1,\mathrm{II}} = \frac{1}{108}[48-(1-\mu)(8\sqrt{3(4-(1+4\mu)c)c}+4(8+\mu)c-(8+\mu)(1+4\mu)c^{2})] \qquad (21)$$

in period 1 and the income $\pi^{PHs}_{1,\mathrm{II}} = 2F^{is}_{1,\mathrm{II}}$ to the patent holder.[7] Hence, the level of total welfare in period 1 is

$$W^{s}_{1,\mathrm{II}} = \frac{1}{36}[24-(1-\mu)c(4(2+\mu)\sqrt{3(4-(1+4\mu)c)c}+4(14+\mu)-(8+\mu)(1+4\mu)c)]. \qquad (22)$$

It follows immediately from (12) and (19) that, in period 1, the patent holder is better off with signaling (induced by short-term fee contracts) than in the absence of signaling (in a context of long-term fee contracts). However, consumers are unequivocally worse off in this period when signaling exists as the following lemma states from checking (18) and (21).

Lemma 4. *In period 1, the following holds:*

(i) $CS^{s}_{1,\mathrm{II}} < CS_{1,\mathrm{II}}$.

(ii) $\nabla CS_1 \equiv CS^{s}_{1,\mathrm{II}} - CS_{1,\mathrm{II}} = -\frac{1}{27}(1-\mu)[2\sqrt{3(4-(1+4\mu)c)c}+(2+\mu)c-(8+\mu)(1+\mu)c^{2}]$.

That is, if licensing is done through a series of short-term fee contracts, expected consumer surplus in period 1 is lower than it would be when long-term contracts are used. The explanation of this result is quite simple. Signaling induced by successive short-term fee contracts forces each high-cost licensee to under-produce compared to a non-signaling context and, as a reaction, each low-cost licensee over-produces. However, the former distortion is of first-order, whereas the latter is a second-order effect and thus its magnitude is lower. Thus, on average, licensees reduce output level, i.e. $Q^{s}_{1,\mathrm{II}} < Q_{1,\mathrm{II}}$, which decreases expected consumer surplus in period 1 when signaling exists as compared to the expected consumer surplus that would emerge in an

[7] See expression (12).

incomplete information (and no signaling) context. This reduction is indeed so large that it outweighs the increase on patent holder profits due to signaling, so overall $W_{1,\text{II}}^{s} < W_{1,\text{II}}$ in the entire (μ,c)-parameter space. Indeed, from (20) and (22), we obtain

$$W_{1,\text{II}}^{s} - W_{1,\text{II}} = \frac{1}{9}(1-\mu)c[(2+\mu)\sqrt{3(4-(1+4\mu)c)c} - 8 - \mu + (2+6\mu+\mu^2)c], \tag{23}$$

which is negative. That is, short-term fee contracts imply lower expected welfare in period 1 than long-term contracts. In period 2, however, short-term contracts lead to higher welfare than long-term contracts. Indeed, expected consumer surplus in period 2 derived from short-term licensing contracts amounts to

$$CS_{\text{CI}} = \frac{1}{9}[4-(1-\mu)c(2+(2-\mu)c)] \tag{24}$$

and the patent holder's revenue to

$$\pi_{\text{CI}}^{PH} = \frac{1}{3}[1-(1-\mu)c(2-(1+4\mu)c)] \tag{25}$$

whereby expected welfare in such period is

$$W_{\text{CI}} = \frac{1}{3}[2-(1-\mu)c(2-3\mu c)] \tag{26}$$

and both consumers and the patent holder are better off with short-term rather than with long-term fee contracts, which leads to $W_{\text{CI}} > W_{2,\text{II}}$. In particular, the increase in expected welfare due to use of short-term fee rather than long-term fee contracts is

$$\Delta W_2 \equiv W_{\text{CI}} - W_{2,\text{II}} = \frac{3}{4}\mu(1-\mu)c^2 . \tag{27}$$

Overall, social welfare generated throughout the two periods by a series of short-term fee contracts, $W_{\mathrm{ST}f} = W_{1,\mathrm{II}}^{s} + W_{\mathrm{CI}}$, where subscript ST*f* indicates short-term fee contracts

$$W_{\mathrm{ST}f} = \frac{1}{36}[48-(1-\mu)c(12(2-3\mu c)-4(2+\mu)\sqrt{3(4-(1+4\mu)c)c}-4(14+\mu)+(8+\mu)(1+4\mu)c)] \quad (28)$$

and comparing (28) with $W_{\mathrm{LT}f} \equiv 2W_{1,\mathrm{II}}$, where subscript LT*f* stands for long-term fee contracts, allows to obtain the following result.

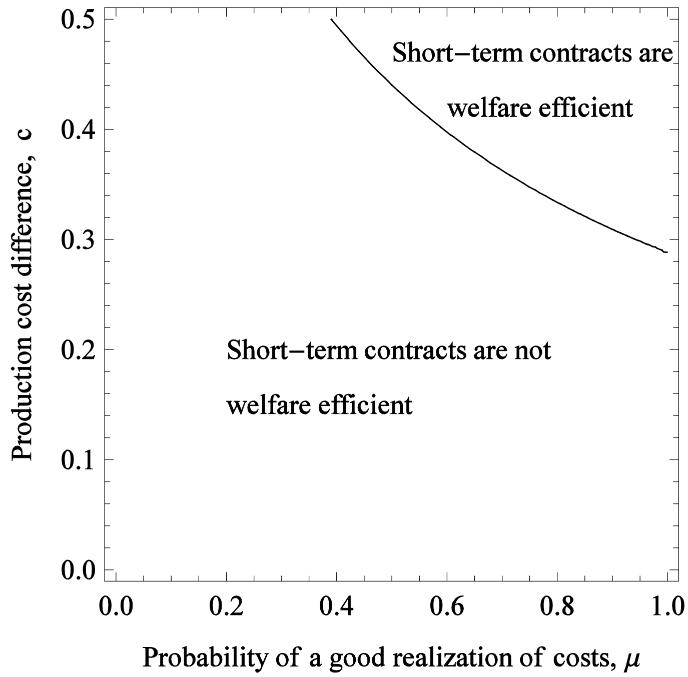
Proposition 3. *If parameters* μ *and* c *satisfy* $4(8+\mu)-(8+51\mu+4\mu^2)c - 4(2+\mu)\sqrt{3(4-(1+4\mu)c)c} < 0$, *short-term fee contracts are socially efficient. Otherwise, they are socially inferior to long-term fee contracts.*

Proof. See the Appendix.

Short-term (revealing) fee contracts leads to higher social welfare than long-term fee contracts only when both μ, the probability of a good realization of production cost, and *c*, the magnitude of the bad realization of production cost[8] are sufficiently high. In such a case, reduction on consumer surplus in period 1 when signaling exists is minimal as compared to consumer surplus in that period under long-term (non-revealing) fee contracts. In turn, this implies little reduction on welfare level in period 1, and this reduction is offset by the increase on welfare in period 2 due to a sequence of short-term fee contracts (and the recovering of complete information it leads to). In any other circumstance, long-term fee contracts are socially superior to short-term fee contracts. The result of Proposition 3 is graphically illustrated in Figure 2 below.

[8] That is, the efficiency gap between licensees if their production costs differ or the firms' cost level if both of them become inefficient when using the innovation.

Fig. 2. Short-term fee contracts and social welfare



Expressions (16) and (22) denote, respectively, the total expected welfare of a long-term fee contract and of a series of short-term fee contracts. On the other hand, the level of social welfare achieved when the patent holder resorts to a sequence of short-term royalty contracts is given by[9]

$$W_{\mathrm{ST}r} = 1-(1-\mu)\left[\frac{2(20+7\mu)c+(3-2\mu)(2+7\mu)c^2+12(1-(1+2\mu)c)\sqrt{(2+(3-2\mu)c)c}}{108}\right.$$

$$\left.+\frac{(8-(2+5\mu)c)c}{12}\right], \tag{29}$$

where subscript STr denotes short-term royalty contracts. Similarly, if the patent holder licenses the innovation through long-term royalty contracts, expected social welfare is

$$W_{\mathrm{ST}r} = 1-(1-\mu)\frac{(8-(2+\mu)c)c}{6}. \tag{30}$$

[9] See Antelo (2009).

When comparing the social outcome of short- and long-term fee contracts to short- and long-term royalty contracts, the result is unambiguous: fee contracts are socially superior to royalty contracts due to the fact that royalties distort the licensees' behavior more than fees. Thus, the result of Proposition 3 remains valid in a context in which the patent holder can simultaneously choose the fee or royalty form of the contracts (including royalties in period 1 and fees in period 2) and their duration.

7. Conclusions

With perfect and complete information, an outside patent holder prefers fee to royalty licensing. This result persists in an asymmetric information context, where each licensee acquires private information about its production cost emerged from the use of the innovation that may be then signaled to third parties (in a succession of short-term contracts) or not (in a long-term contract). In this case, the patent holder continues to prefer upfront fees instead of royalties. Indeed, a succession of short-term fee contracts (rather than a long-term fee contract) is the best dynamic licensing scheme for the patent holder, but socially efficient only when both the a priori probability of a firm being an efficient user of the innovation and the difference in licensees' production costs are sufficiently high; otherwise, long-term fee contracts are social superior to short-term fee contracts, in which case a conflict between private and social interests arises.

Comparison of short-term fee contracts, short-term and long-term royalty contracts, and even those (short-term) contracts formed by royalties in period 1 and fees in period 2 affirms these findings. Hence, interaction between and outside patent holder (that motivates the use of fee licensing contracts) and asymmetric information (that encourages royalty based contracts) leads (short-term) fee contracts to be better off than royalty contracts. More precisely, the possibility of licensees' signaling confirms the superiority of fees over royalties and, within the fee contracts, of short-term over long-term fee contracts.

Appendix A

Proof of Lemma 1.

(i) The result follows from the fact that $\pi_2^i(0|c;0) = ((2-c)/6)^2 - ((1-2c)/3)^2$, $\pi_2^i(0|c;c) = ((2+c)/6)^2 - ((1-c)/3)^2$, $\pi_2^i(c|0;0) = ((2-3c)/6)^2 - (1/3)^2$, and $\pi_2^i(c|0;c) = ((2-c)/6)^2 - ((1+c)/3)^2$.

(ii) Immediate. □

Proof of Lemma 2. The conditions to be met by a separating equilibrium are

$$q_{1L}^{is} = \frac{1-(1-\mu)q_{1H}^{is}}{2+\mu}\ ,\ i\text{=A,B,} \tag{A1}$$

$$q_{1H}^{i*} = \frac{2(1-c)-\mu c-2(1-\mu)q_{1H}^{is}}{2(2+\mu)}, \tag{A2}$$

$$\begin{aligned}\mu(1-2q_{1L}^{is})q_{1L}^{is} + (1-\mu)(1-q_{1L}^{is}-q_{1H}^{js})q_{1L}^{is} - F_1^{is} \geq \mu\left[(1-q_{1H}^{is}-q_{1L}^{js})q_{1H}^{is} + \left(\frac{2-c}{6}\right)^2 - \left(\frac{1-2c}{3}\right)^2\right] \\ + (1-\mu)\left[(1-2q_{1H}^{is})q_{1H}^{is} + \left(\frac{2+c}{6}\right)^2 - \left(\frac{1-c}{3}\right)^2\right] - F_1^{is},\quad i,j\text{=A,B; } i\neq j,\end{aligned} \tag{A3}$$

and

$$\begin{aligned}\mu(1-c-q_{1H}^{is}-q_{1L}^{js})q_{1H}^{is} + (1-\mu)(1-c-2q_{1H}^{is})q_{1H}^{is} - F_1^{is} \geq \mu\left[(1-c-q_{1H}^{i*}-q_{1L}^{js})q_{1H}^{i*} + \left(\frac{2-3c}{6}\right)^2\right. \\ \left. -\left(\frac{1}{3}\right)^2\right] + (1-\mu)\left[(1-c-q_{1H}^{i*}-q_{1H}^{js})q_{1H}^{i*} + \left(\frac{2-c}{6}\right)^2 - \left(\frac{1+c}{3}\right)^2\right] - F_1^{is},\end{aligned} \tag{A4}$$

where superscript *s* denotes signaling and superscript * denotes the best reaction in period 1 of each high-cost licensee provided that, in period 2, it will be recognized as such. Condition (A1) represents the first-period output of a low-cost licensee *i* in the equilibrium of the two-period game: a low-cost licensee that signals its costs faithfully in period 1 forgoes the possibility of the "illicit" period 2 gains held out by Lemma 1; therefore it has no reason not to maximize its expected period 1 profit, without regard to period 2. On the other hand, a high-cost licensee producing any but the equilibrium quantity q_{1H}^{i} in period 1 would be seen as a low-cost licensee by the other players in period 2. Taking this into account in determining its optimal behavior in period 2, it would behave as in Lemma 1. Since its expected period 2 profit is not affected by its period 1 output (so long as the latter differs from q_{1H}^{i}), in period 1 it would produce the quantity maximizing its single-period profit in that period as Condition (A2) states. In view of Lemma 1, a low-cost licensee will indeed be tempted to misrepresent itself if its gains in period 2 (as the result of its deception) are more than its losses in period 1 (as the result of producing output q_{1H}^{i} instead of $q_{L,\mathrm{II}}^{i}$). By contrast, a high-cost firm, for whom such behavior by a low-cost licensee would be highly detrimental in period 2, might find it to its overall advantage to set period 1 output q_{1H}^{i} so low that deception is not profitable for a low-cost licensee. This coercion requires satisfaction of the self-selection Condition (A3). Finally, (A4) is the incentive-compatibility condition corresponding to each high-cost licensee, whereby its expected gains in the equilibrium exceed the expected value of the period 2 profit given by Lemma 1 plus the expected value of the period 1 profit obtained by producing output q_{1H}^{i*}. By solving the incentive-compatibility conditions (A3)-(A4) as equalities, the continuum of separating equilibria is given by the interval of outputs $q_{1H}^{is} \in [r^{-}, z^{-}]$, where

$$r^{-} = \frac{1-c}{3} - \frac{\mu c}{6} - \frac{(2+\mu)\sqrt{3(4+(1-4\mu)c)c}}{18} \tag{A5}$$

and

$$z^{-} = \frac{1}{3} - \frac{(2+\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}. \quad \text{(A6)}$$

The fact that $r^{-} < z^{-}$ in the entire (μ,c)-parameter space implies that the interval $[r^{-}, z^{-}]$ is non-degenerated. Hence, the output of each high-cost licensee forming part of the separating equilibrium of minimum cost is

$$q_{1H}^{is} \equiv z^{-} = \frac{1}{3} - \frac{(2+\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}. \quad \text{(A7)}$$

On the other hand, denoting the profit-maximizing output of each high- and low-cost licensee in an II context by $q_{1H,\text{II}}^{i} = \frac{1}{3} - \frac{(2+\mu)c}{6}$ and $q_{1L,\text{II}}^{i} = \frac{1}{3} + \frac{(1-\mu)c}{6}$, respectively (see Equations (5) and (6) in the text), it immediately follows that $q_{1H}^{is} < q_{1H,\text{II}}^{i}$ for every admissible values of parameters μ and c. That is, the separating equilibrium is always costly. □

Proof of Lemma 3. When the patent holder offers a long-term contract (and II exists), the gross profit in each period of a low-cost firm, $\mu(1-q_{L,\text{II}}^{i}-q_{L,\text{II}}^{j})q_{L,\text{II}}^{i}+(1-\mu)(1-q_{L,\text{II}}^{i}-q_{H,\text{II}}^{j})q_{L,\text{II}}^{i}$, i,j=A,B; i≠j, is

$$\pi_{L,\text{II}}^{Gi} = \left(\frac{2+(1-\mu)c}{6}\right)^{2}, \quad \text{(A8)}$$

where superscript G denotes gross profit. Thus, net profit (denoted by superscript N), $\pi_{L,\text{II}}^{Ni} = \left(\frac{2+(1-\mu)c}{6}\right)^{2} - \frac{1}{36}(4-8(1-\mu)c+(4+\mu-5\mu^{2})c^{2})$, is as reflected in Table 1. Similarly, the gross profit of each high-cost licensee, $\mu(1-c-q^{i}_{H,\text{II}}-q^{j}_{L,\text{II}})q^{i}_{H,\text{II}}+(1-\mu)(1-c-q^{i}_{H,\text{II}}-q^{j}_{H,\text{II}})q^{i}_{H,\text{II}}$, i,j=A,B; $i\neq j$, amounts to

$$\pi^{Gi}_{H,\text{II}}=\left(\frac{2(1-c)-\mu c}{6}\right)^{2} \tag{A9}$$

and its net profit is that stated in Table 1. It is evident that net profit of each firm, $E\pi^{i}_{\text{II}}$, is zero, $\pi^{i}_{\text{II}}=\mu\pi^{Ni}_{L,\text{II}}+(1-\mu)\pi^{Ni}_{H,\text{II}}=0$. On the other hand, if a short-term contract is offered to licensees and they signal their cost realizations, the gross profit in period 1 of each low-cost licensee, $\pi^{Gis}_{1L,\text{II}}=\mu(1-q^{is}_{1L}-q^{js}_{1L})q^{is}_{1L}+(1-\mu)(1-q^{is}_{1L}-q^{js}_{1HI})q^{is}_{1L}$, is

$$\pi^{Gis}_{1L,\text{II}}=\frac{1}{108}[12+4(1-\mu)^{2}c-(1-\mu)^{2}c^{2}+4(1-\mu)\sqrt{3(4-(1+4\mu)c)c}] \tag{A10}$$

and its net profit, $\pi^{Nis}_{1L,\text{II}}=\pi^{Gis}_{1L,II}-F^{is}_{1,\text{II}}$, is as given in (16). Likewise, $\pi^{Gis}_{1H,\text{II}}=\mu(1-c-q^{is}_{1H}-q^{js}_{1L})q^{is}_{1H}+(1-\mu)(1-c-q^{is}_{1H}-q^{js}_{1HI})q^{is}_{1H}$, i,j=A,B; $i\neq j$, amounts to

$$\pi^{Gis}_{1H,\text{II}}=\frac{1}{108}\{12-2[34-6\sqrt{3(4-(1+4\mu)c)c}+\mu(4-2\mu-3\sqrt{3(4-(1+4\mu)c)c})]c$$
$$+(4-\mu)(2+\mu)(1+4\mu)c^{2}+(4-\mu)\sqrt{3(4-(1+4\mu)c)c}\} \tag{A11}$$

and the net profit, $\pi^{Nis}_{1H,\text{II}}=\pi^{Gis}_{1H,\text{II}}-F^{is}_{1,\text{II}}$, is as given in (17). Once more, the net profit to each firm *i* is zero; namely, $\pi^{Nis}_{1,\text{II}}=\mu\pi^{Nis}_{1L,\text{II}}+(1-\mu)\pi^{Nis}_{1H,\text{II}}=0$. The same result of zero net profit for each licensee in period 2 when complete information is recovered can be derived. □

Proof of Proposition 2.

(i) Immediate from comparing (10) and (11).

(ii) When licensing is made through a long-term royalty contract covering the entire expected lifetime of the innovation, the patent holder obtains (see Antelo, 2009)

$$\pi_{\mathrm{LT}r}^{PH} = \frac{1}{3}[1-(1-\mu)c]^2 , \tag{A12}$$

and comparison of (11) and (A12) shows the result stated in the first part of (ii).

On the other hand, when the innovation is licensed by means of short-term royalty contracts (denoted by subscript ST*r*), the patent holder's income is

$$\pi_{\mathrm{ST}rc}^{PH} = \frac{1}{3}\left[1-\frac{(1-\mu)\sqrt{(2+(3-2\mu)c)c}}{3}\right]^2 + \frac{1}{6}[1-2(1-\mu)c+(1-\mu^2)c^2] , \tag{A13}$$

if signaling in period 1 is costly (which is denoted by subscript *c*), and

$$\pi_{\mathrm{ST}rnc}^{PH} = \frac{1}{6}[1-(1-\mu)c]^2 + \frac{1}{6}[1-2(1-\mu)c+(1-\mu^2)c^2] , \tag{A14}$$

if signaling in period 1 is not costly (which is denoted by subscript *nc*). By comparing (11) with (A13) and (A14), the result presented in (ii) holds.

(iii) If contracts of period 1 are based on royalty payments (and those of period 2 on fee payments), the conditions defining a separating equilibrium of the resulting game are

$$q_{1L}^{is} = \frac{1-r_1^i-(1-\mu)q_{1H}^{is}}{2+\mu} \ , \ i\text{=A,B}, \tag{A15}$$

where r_1^i denotes the per-unit royalty to be paid by each licensee *i* in period 1, regardless of its type,

$$q_{1H}^{i*} = \frac{2(1-c-r_1^i)-\mu c-2(1-\mu)q_{1H}^{is}}{2(2+\mu)} , \tag{A16}$$

$$\mu(1-r_1^i-2q_{1L}^{is})q_{1L}^{is}+(1-\mu)(1-r_1^i-q_{1L}^{is}-q_{1H}^{js})q_{1L}^{is}\geq\mu\left[(1-r_1^i-q_{1H}^{is}-q_{1L}^{js})q_{1H}^{is}+\left(\frac{2-c}{6}\right)^2-\left(\frac{1-2c}{3}\right)^2\right]$$

$$+(1-\mu)\left[(1-r_1^i-2q_{1H}^{is})q_{1H}^{is}+\left(\frac{2+c}{6}\right)^2-\left(\frac{1-c}{3}\right)^2\right],\ i,j\text{=A,B; } i\neq j, \quad \text{(A17)}$$

and

$$\mu(1-c-r_1^i-q_{1H}^{is}-q_{1L}^{js})q_{1H}^{is}+(1-\mu)(1-c-r_1^i-2q_{1H}^{is})q_{1H}^{is}$$

$$\geq\mu\left[(1-c-r_1^i-q_{1H}^{i*}-q_{1L}^{js})q_{1H}^{i*}+\left(\frac{2-3c}{6}\right)^2-\left(\frac{1}{3}\right)^2\right]$$

$$+(1-\mu)\left[(1-c-r_1^i-q_{1H}^{i*}-q_{1H}^{js})q_{1H}^{i*}+\left(\frac{2-c}{6}\right)^2-\left(\frac{1+c}{3}\right)^2\right]. \quad \text{(A18)}$$

The content of conditions (A17)-(A18) is similar to that of conditions (A1)-(A4). By solving (A17)-(A18) as equalities, once (A15) and (A16) are taken into account, the output of high-cost licensees that allow themselves to separate at minimum cost from low-cost licensees is

$$q_{1H}^{is}(r_1^i)=\frac{1-r_1^i}{3}-\frac{(2+\mu)\sqrt{3(4-(1+4\mu)c)c}}{18},\ i\text{=A,B,} \quad \text{(A19)}$$

and satisfies $q_{1H}^{is}<\frac{1}{3}-\frac{(2+\mu)c}{6}=q_{1H,\text{II}}^{i}$, being $q_{1H,\text{II}}^{i}$ the profit-maximizing output in period 1 of each high-cost licensee under incomplete information. That is, the separating equilibrium is costly for all admissible values of parameters μ and c. Consideration of (A15) yields

$$q_{1L}^{is}(r_1^i)=\frac{1-r_1^i}{3}+\frac{(1-\mu)\sqrt{3(4+(1-4\mu)c)c}}{18},\ i\text{=A,B.} \quad \text{(A20)}$$

On the other hand, from (A19) and (A20), the resolution of the patent holder's problem,

$$\max_{r_1^i}\ 2r_1^i[\mu\cdot q_{1L}^{is}(r_1^i)+(1-\mu)\cdot q_{1H}^{is}(r_1^i)], \quad \text{(A21)}$$

affords

$$r_1^{is} = \frac{1}{2} - \frac{(1-\mu)\sqrt{3(4+(1-4\mu)c)c}}{6}\,,\ \ i\text{=A,B,} \tag{A22}$$

as the optimal royalty rate in period 1. Finally, substitution of (A22) into (A19) and (A20) yields $q_{1H}^{is} = 1/6 - (1+2\mu)\sqrt{3(4-(1+4\mu)c)c}/18$ and $q_{1L}^{is} = 1/6 + (1-\mu)\sqrt{3(4+(1-4\mu)c)c}/9$ as the equilibrium outputs of period 1 for high-cost and low-cost licensees, respectively. Thus, the patent holder's expected income in period 1 amounts to

$$\pi_{rf}^{PH} = \frac{1}{54}[3-(1-\mu)\sqrt{3(4-(1+4\mu)c)c}]^2\,, \tag{A23}$$

where subscript *rf* indicates that licensing is done by means of royalties in period 1 and upfront fees in period 2. Finally, comparing (A23) with

$$2F_{1,\mathrm{II}}^{is} = 2\left[\mu\left(\frac{1}{3}+\frac{(1-\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}\right)^2 + (1-\mu)\left(\frac{1}{3}-c+\frac{(4-\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}\right)\left(\frac{1}{3}-\frac{(2+\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}\right)\right],\ i\text{=A,B} \tag{A24}$$

completes the result. □

Proof of Proposition 3. Taking into account the values of the second column of Table 1 and the fact that $CS_{\mathrm{II},(\tilde{c}^i,\tilde{c}^j)} = (1/2)[1-(1-Q_{\mathrm{II},(\tilde{c}^i,\tilde{c}^j)})^2]$, the expected consumer surplus per period in a regime of long-term fee contracts is

$$CS_{\mathrm{II}} = \frac{1}{36}[16-(1-\mu)(8+(8+\mu)c)c]\,. \tag{A25}$$

In turn, the net profit of each licensee i is zero (by virtue of Lemma 3), whereas the per period income of the patent holder amounts to

$$\pi_{\text{II}}^{PH} = \frac{1}{18}[4-(1-\mu)(8-(4+5\mu)c)c]. \tag{A26}$$

From (A25) and (A26), the level of expected welfare through the entire lifetime of the innovation is

$$W_{\text{II}} = 2(CS_{\text{II}} + \pi_{\text{II}}^{PH}) = \frac{1}{6}[8-(1-\mu)(8-3\mu c)c]. \tag{A27}$$

On the other hand, a series of (two) short-term fee contracts leads to consumer surplus

$$CS = CS_{1,\text{II}}^{s} + CS_{\text{CI}} = \frac{1}{108}[48-(1-\mu)(8\sqrt{3(4-(1+4\mu)c)c} + 4(8+\mu)c-(8+\mu)(1+4\mu)c^2)]$$

$$+\frac{1}{9}[4-2(1-\mu)c+(1-\mu)(1+4\mu)c^2] \tag{A28}$$

and the patent holder's licensing income

$$\pi^{PH} = 2(F_{1,\text{II}}^{is} + F_{\text{CI}}^{i})$$

$$= 2\left[\mu\left(\frac{1}{3}+\frac{(1-\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}\right)^2 + (1-\mu)\left(\frac{1}{3}-c+\frac{(4-\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}\right)\right.$$

$$\left.\left(\frac{1}{3}-\frac{(2+\mu)\sqrt{3(4-(1+4\mu)c)c}}{18}\right)\right]+\frac{1}{3}[1-2(1-\mu)c+(1-\mu)(1+4\mu)c^2]. \tag{A29}$$

Hence, social welfare is as given in (28). From here, the result of Proposition 3 follows immediately. □

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