INNOVATION INCENTIVES IN TECHNICAL STANDARDS

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ABSTRACT. I study the incentives to develop complementary technologies and include them in a technical standard. I find standardization may lead to insufficient or excessive innovation. Patent pools increase innovation incentives, while price caps may increase or decrease them. Although both policies increase user surplus and welfare, I find price caps dominate (are dominated by) patent pools if the incremental value of technologies is small (large). From innovators' perspective, patent pools are more profitable than price caps. This finding helps explain why patent pools are more prevalent than price caps, even though price caps may imply higher welfare. I also find cooperation in R&D decreases welfare if the incremental value of technologies is small. The paper's results contribute to the discussion of the effects of recent policy changes in the VITA and IEEE standard-setting organizations.

KEYWORDS: Technical Standards, Innovation, Complementary Technologies, Technology Choice, Adoption, Standard-Setting Organizations, Licensing, Hold-up, Ex Ante Agreements, Price Caps, Patent Pools, Cooperation in R&D (JEL: O31, O34, L15, L40).

1. INTRODUCTION

Complex innovative technologies—such as the ones behind autonomous driving vehicles, the internet of things, deep-space exploration, electric and hydrogen cars, and artificial intelligence—are typically composed by a myriad of complementary inventions developed by multiple firms. Technical standards are an essential tool for the combination, integration, and interoperability of such complementary technologies.

Recent works have shown that the characteristics of the standard-setting process may result in the inefficient development and adoption of standards (Llanes and Poblete, 2014, forthcoming; Lerner and Tirole, 2015). The relation between the standard-setting process and the *incentives to innovate*, on the other hand, is less understood from a conceptual point of view and is the main focus of this paper.

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Understanding the relation between innovation and standardization is important because many technologies are developed with the objective of being included in a standard, which implies the characteristics of the standard-setting process are an essential determinant of the incentives to develop standard-related technologies.

For example, when developing the 802.11n (Wi-Fi) standard, a technical group inside the Institute of Electrical and Electronics Engineers (IEEE) investigated ways to increase transmission rates, which required significant investments from Intel and other firms, and such investments were affected by the likelihood of inclusion in the standard and the rules of the standard-setting process (DeLacey, Herman, Kiron, and Lerner, 2006).

Likewise, in the case of fifth-generation (5G) telecommunication technologies, firms like Samsung, Huawei, ZTE, Ericson, and Qualcomm are currently involved in an innovation race with the aim of controlling future standards, and such competition is complicated by the fact that firms do not only compete to develop technologies, but also negotiate to determine which technologies are included in standards.[1]

These issues have sparked an intense policy debate within standard-setting organizations. In particular, VITA changed its IPR policy in 2006 to require firms to commit to a maximum royalty fee for the use of their standard-essential patents, and IEEE changed its policy in 2015 in a way which allegedly reduces patent holders' price-setting power. Both policy changes have generated significant controversy over their effects on innovation activity and standardization.[2]

[1]In the case of 5G, the negotiation of the standard is further complicated by the US government's distrust of Chinese firms and their potential ability to control the data generated through 5G devices, which has lead the US to promote a number of political and regulatory measures against these firms (mainly Huawei).

[2]In a nutshell, IEEE's policy change compels firms to base royalty rates on their patents' contribution to the smallest saleable component (e.g., a microchip), instead of basing them on their proportional contribution to the value of the final product (e.g., a cellphone), and induces firms not to seek injunctions over alleged patent infringers until they win a first-level appellate review. See Alderman (2014) for VITA's Executive Director's view of the rationale behind their policy change, and Katznelson (2015), Pohlmann (2017, 2018), and Gupta and Effraimidis (2018) for differing practitioners' views on the effects of IEEE's policy change.

In this paper, I study the interaction between innovation, standardization, pricing, and adoption of technologies. To the best of my knowledge, this is the first paper to jointly address these closely related but separate aspects of the standard-setting process.[3] My main objective is to determine how different types of cooperative agreements and non-cooperative commitments shape the relation between innovation and standardization. Understanding the effects of these policies is important because standard-setting organizations and antitrust agencies—in particular, the Federal Trade Commission and the Department of Justice in the US and the European Commission in the EU—are currently debating whether different types of agreements between firms involved in the standard-setting process benefit or harm competitors and consumers.

I consider a four-stage non-cooperative game. In the first stage, each firm chooses its investment in R&D, which determines the probability of developing a new technology. In the second stage, after innovation outcomes are realized, successful innovators and users negotiate which technologies to include in the standard. In the third stage, firms with technologies in the standard choose a license fee for the use of their standard-essential patents. Finally, each user decides whether to adopt the standard.

I find the equilibrium may be inefficient for three reasons: inefficient adoption of the standard by users, inefficient (either insufficient or excessive) investments in R&D, and inefficient inclusion of technologies in the standard. The adoption inefficiency is caused by market power, which allows patent holders to price above marginal cost. In this model with complementary components and ex post licensing, the pricing inefficiency is exacerbated

[3]Ganglmair, Froeb, and Werden (2012) study the effects on hold-up on innovation but do not consider competition in R&D and do not model the standard-setting process. Baron, Ménière, and Pohlmann (2014) study the effects of spillovers on standardization but do not consider the incentives to innovate or license technologies (they assume patent holders' revenues are exogenously given). Layne-Farrar, Llobet, and Padilla (2014) consider the effects of price caps on the incentives to innovate, but do not allow for the endogenous determination of licensing fees (in their model, a standard-setting organization determines license fees according to an incremental value rule). Rey and Tirole (forthcoming) study the welfare effects of coordinated commitments to set maximum prices, but do not explicitly model competition in R&D and standardization. More importantly, Rey and Tirole assume price commitments are negotiated collectively. I assume price commitments are determined individually, which better reflects the way real-world price caps operate. Finally, it is important to note none of the above papers compares the effects of price caps and patent pools on innovation and welfare, which is one of the main objectives of the present paper.

by patent hold-up and Cournot's (1838) complementary monopoly problem.[4] Hold-up and complementary monopoly, in turn, affect patent holders' profits and user surplus, which affect the incentives to develop technologies and to include them in the standard.

I then consider two policies which have been proposed in the literature to address the problems caused by hold-up and complementary monopoly: price caps and patent pools. Price caps allow firms to *individually* commit to a maximum license fee for the use of their standard-essential patents *before* the standard is defined. Patent pools allow firms to *coordinate* their license fees *after* the standard is defined. Thus, although both policies can potentially address hold-up and complementary monopoly, they differ in their level of coordination and their timing within the standard-setting process.

Price caps induce firms to compete ex ante to have their technologies included in the standard, which increases user surplus and welfare. In equilibrium, firms set smaller license fees which allows them to (partially) overcome the complementary monopoly problem. The decrease in license fees increases firms' revenues if it is relatively small, but it decreases revenues if it is large. Thus, investments in R&D may increase or decrease with price caps.

Patent pools, on the other hand, allow innovators to coordinate prices ex post, and therefore always increase licensing revenues and innovation investments.[5] However, patent pools eliminate the incentives to compete ex ante, and may thus imply a smaller user surplus and welfare than price caps.

Although both policies increase user surplus and welfare, I show price caps dominate (are dominated by) patent pools in welfare terms if the incremental value of technologies is small (large). The comparison between the two policies depends on a trade off between price coordination and competition: patent pools are a better instrument for price coordination, but they eliminate price competition. If the technological impact of having more technologies

[4]The complementary monopoly problem is also known as the Cournot effect or royalty stacking, and is similar to the double-marginalization effect of vertical structures. Complementary technologies may also give rise to transaction costs (Aoki and Schiff, 2010; Llanes and Poblete, 2014). Spulber (2016, 2017) shows the pricing inefficiency disappears if input providers negotiate individually with downstream producers. I focus on settings with many patent holders and users, in which case transaction costs render individual negotiations unfeasible.

[5]This result is consistent with the findings of Baron and Pohlmann (2015), who document significant increases in patenting rates following patent-pool creation announcements.

in the standard is large, coordination is more important than competition, and patent pools generate larger welfare than price caps. The inverse result holds when the technological impact of having more technologies in the standard is small.

From the point of view of firms, patent pools are always more desirable than price caps, because they imply higher individual revenues. Thus, firms will attempt to avoid price caps if they believe the formation of a patent pool is likely after the standard is set. This result helps explain why patent pools have been more prevalent than price caps in the development of technical standards, even though price caps may provide higher welfare.[6]

I also study the welfare effects of the coordination of R&D investments, and whether this policy should be used in conjunction with price caps or patent pools. I find cooperation in R&D increases (decreases) equilibrium investments if investments are complements (substitutes) from firms' point of view. The nature of complementarity, in turn, depends on the specific pricing game under consideration. I find cooperation in R&D is optimal if the incremental value of technologies is large. Thus, cooperation in both prices and R&D becomes more desirable the larger the value component technologies bring to the standard.

This paper has three main contributions. First, I show both price caps and patent pools increase user surplus and welfare, and are thus desirable policies from a social point of view. These policies have the advantage of being straightforward to implement, as they do not require complex ex ante negotiations or transfers between agents. Second, I show price caps imply higher welfare than patent pools when the incremental value of technologies is small. To the best of my knowledge, this is the first paper to compare both policies while taking into account innovation and standardization incentives. Finally, I show cooperation in R&D and prices are complementary policies if the value of technologies is large. This result extends previous analyses of research joint ventures and R&D cartels (D'Aspremont and Jacquemin, 1988; Kamien, Muller, and Zang, 1992) to the case of complementary goods.

[6]Baron and Pohlmann (2015) identify fifty patent pools arising out of standard-setting efforts. In contrast, only one standard-setting organization has made price caps compulsory (VITA) and other two have allowed for voluntary price caps commitments (IEEE and ETSI).

In addition to these results, in Section 8 I discuss the robustness of the paper's results to alternative standards' negotiation frameworks, and in Section 9 I study innovation and standardization when firms have different bargaining abilities at the standard-setting stage. In Section 11, I present the main conclusions and limitations of the paper and discuss potential directions for future research.

2. The model

Two firms, $i = A, B$, may develop technologies that may be used in a standard. A continuum of users of mass one indexed by $\theta \in [0, 1]$ may adopt a standard based on the firms' technologies. Users represent final consumers or downstream firms that use the standard to produce goods for final consumers.

Each firm may develop a technology by investing in R&D. The outcome of the R&D process is probabilistic. In particular, firm i develops technology i with probability $x_i \in [0, 1]$ by incurring in an R&D cost of $\alpha x_i^2/2$, where $\alpha > 0$ is a parameter measuring the cost of innovation. If a firm is successful at developing a technology, it obtains a patent allowing it to charge a license fee for the use of that technology. R&D costs are sunk after development and firms have no other fixed or variable costs.

A standard is a set of technologies, and its value depends on the technologies it includes. If the standard does not include any technology, it has a value of zero. Let v_n be the value of a standard based on the technologies of $n \in \{1, 2\}$ firms. Assume $0 \leq v_1 \leq v_2$, which implies both technologies are valuable, and α is sufficiently large relative to v_2, which implies the profit and welfare maximization problems have interior solutions.

User θ's utility from using a standard with value v is

$$v - P - \theta,$$

where $\theta \sim U[0, 1]$ represents an idiosyncratic adoption cost and P is the sum of licensing fees paid to the owners of the standard's technologies. A user's utility from not adopting any standard is normalized to zero.

Developing a standard generally requires consensus between agents with different stakes in the standard. The Joint Electron Devices Engineering Council (JEDEC), for instance, is formed by manufacturers and suppliers of microelectronics that participate in more than 50 technical committees and subcommittees and determine standards through negotiation.

The real-world negotiation of standards is a complex and relatively unstructured process.[7] For simplicity, I assume each firm proposes a standard, and then users and firms vote over which proposal to accept. In Section 8, I study alternative bargaining procedures and show the main results of the paper are robust to changes in the standard's bargaining protocol.

In particular, I assume users have a collective voting weight of $\omega \in (0, 1)$, and each firm has a voting weight of $(1 - \omega)/2$. If a proposal obtains a sum of voting weights larger than $1/2$, then it is approved and implemented. If no proposal obtains a sum of votes larger than $1/2$, a standard based on zero technologies—representing an alternative or status quo standard that does not employ the firms' technologies—is implemented.

Given that users' idiosyncratic valuations enter additively into utility, all users agree on which standard is best. Therefore, users vote on standards to maximize the net value of the standard $v - P$. If users are indifferent between two proposals, they choose each proposal with equal probability.[8] If a firm is indifferent between proposing a standard with one or two technologies, it proposes a standard with two technologies.

Standardization generally requires specific investments from users, which are sunk after the standard is developed (Farrell, Hayes, Shapiro, and Sullivan, 2007). These investments may include the acquisition or development of complementary goods and the costs of coordinating to adopt the same standard. Specific investments create switching costs that make

[7]See DeLacey, Herman, Kiron, and Lerner (2006) for details on the negotiation of Wi-Fi and DSL standards and Baron and Gupta (2018) for the negotiation of 3GPP standards.
[8]To test the robustness of the results, in Section 9 I assume users choose the proposal of firm A with probability one when they are indifferent between the two proposals.

it difficult for adopters to change to a different standard. For simplicity, I assume the technical characteristics of the standard cannot be altered after it is approved, but it would be straightforward to extend the model to include a cost of reverting technology choices.[9]

I consider the following four-stage non-cooperative game. First, firms choose their investments in R&D. Second, users and firms negotiate which standard to implement. Third, firms with technologies in the standard choose a licensing fee p_i for the use of their technologies. Fourth, users choose whether to adopt the standard. The solution concept is subgame-perfect equilibrium.

The assumption that firms choose prices after the standard is defined reflects the fact that *licensing fees are negotiated ex post*, and is commonly employed in the standard-setting literature (see, e.g., Llanes and Poblete, 2014, forthcoming; Lerner and Tirole, 2015). In Section 5, I study a model in which firms can commit to a maximum licensing fee (price cap) before the standard is defined, in which case firms effectively compete in prices ex ante.

3. Solution of the model

In the fourth stage, given a standard with value v and total price P, user θ adopts the standard if $v - P - \theta \geq 0$ and the total demand for the standard is

$$\Pr(v - P - \theta \geq 0) = v - P.$$

In the third stage, owners of standard-essential patents choose a price. If the standard includes one technology, its owner chooses p to maximize $(v_1 - p)\,p$. It follows that the optimal price is $v_1/2$, firm revenue is $v_1^2/4$, and users' net value is $v_1/2$. If the standard includes two technologies, firm i chooses p_i to maximize $(v_2 - p_i - p_{-i})\,p_i$, where $-i$ is the

[9]The main results of the paper would hold as long as this cost is sufficiently large. If the technical characteristics of the standard are easy to change ex post, hold-up is not a significant problem and technology choices are second-best efficient (that is, they are efficient subject to the restriction of monopolistic pricing). Therefore, in this case, standardization does not impose significant constraints on innovation and technology choice. Given that the main objective of the paper is to study how standardization affects innovation incentives, I concentrate on the case of high technology-reversion costs.

firm other than i. In this case, equilibrium price is $v_2/3$, individual firm revenue is $v_2^2/9$, and users' net value is $v_2/3$.

In the second stage, if only one technology has been developed, its owner proposes a standard with one technology and users vote to accept the standard (the only alternative is to select the status quo standard, which yields no value).

If two technologies have been developed, the equilibrium number of technologies in the standard depends on the resolution of a trade off between technical efficiency and royalty stacking. If $v_2 \geq \frac{3}{2}v_1$, technical efficiency is more important than royalty stacking and users' and firms' interests are aligned. In equilibrium, at least one of the firms proposes a standard with two technologies and this standard is approved. If $v_2 < \frac{3}{2}v_1$, on the other hand, users' net value is maximized when the standard includes only one technology. Thus, if one firm proposes a standard with $n = 1$ and the other proposes a standard with $n = 2$, users vote for the standard with $n = 1$. In equilibrium, each firm proposes a standard based on its own technology, and users select each standard with equal probability.

In the first stage, firm $i = A, B$ chooses x_i to maximize

$$\pi_i = x_i\, x_{-i}\, R_2 + x_i\,(1 - x_{-i})\, R_1 - \alpha\, x_i^2/2, \tag{1}$$

where x_{-i} is the innovation probability of firm $-i$, R_1 is the firm's licensing revenue if it is the only one to develop a technology, and R_2 is a firm's licensing revenue if two firms develop a technology.

From the above developments, it follows that $R_1 = v_1^2/4$ and $R_2 = v_2^2/9$ if $v_2 \geq \frac{3}{2}v_1$, and that $R_1 = v_1^2/4$ and $R_2 = v_1^2/8$ if $v_2 < \frac{3}{2}v_1$. An important difference between the $v_2 \geq \frac{3}{2}v_1$ and $v_2 < \frac{3}{2}v_1$ cases is that in the first case a firm benefits when the other firm innovates, and in the second case a firm loses when the other firm innovates.

The equilibrium probability of innovation is

$$x^* = \frac{R_1}{\alpha + R_1 - R_2},$$

which is less than one as long as $\alpha > R_2$. The following lemma summarizes the result of the standard-setting stage.

Lemma 1 (Equilibrium standardization)**.** *If $v_2 \geq \frac{3}{2} v_1$, any technology that is successfully developed is included in the standard. If $v_2 < \frac{3}{2} v_1$, at most one technology is included in the standard. Therefore, in this case, if two technologies are developed only one of them is included in the standard.*

Lemma 1 shows some technologies may not be included in the standard in equilibrium. The reason is that firms and users anticipate a complementary monopoly problem in the subsequent pricing game. If the marginal value of the second technology is small, the negative effects of royalty stacking more than compensate the increase in surplus from using a better technology, in which case firms and users prefer to limit the number of technologies in the standard.

Before moving to the next section, it is worth to reflect on the nature of complementarity and substitution of firms' technologies and actions. Technologies are complementary from a technical point of view, given that $v_2 > v_1$. If two technologies are included in a standard, they become perfect complements from the point of view of users' demands, and in the ensuing price competition prices are strategic substitutes. Finally, from the point of view of innovation incentives, investments are gross and strategic complements if $v_2 > \frac{3}{2} v_1$ and they are gross and strategic substitutes if $v_2 < \frac{3}{2} v_1$.[10] As I explain in Section 10, the nature of complementarity/substitution of R&D investments depends on firms' licensing revenues, which in turn depend on the pricing game under consideration.

[10] Investments are gross complements (substitutes) if $\partial \pi_i / \partial x_{-i} > (<)\ 0$, and strategic complements (substitutes) if $\partial^2 \pi_i / (\partial x_i \partial x_{-i}) > (<)\ 0$. See Bulow, Geanakoplos, and Klemperer (1985) for similar definitions.

4. Welfare

Social welfare is equal to the sum of expected user surplus and expected licensing revenues net of R&D investment costs. In what follows, I show the equilibrium may be inefficient for three reasons: inefficient adoption of the standard by users, inefficient investments in R&D, and inefficient inclusion of technologies in the standard.

The inefficiency in the adoption by users is a consequence of monopoly power. In this model with complementary components, the inefficiency stemming from monopoly power is compounded by Cournot's (1838) complementary monopoly problem. To understand the investment and standardization inefficiencies and how they interact with pricing and adoption decisions, I first study first-best choices, and then discuss second-best choices assuming monopolistic pricing. As I show below, both analyses yield similar qualitative results.

I define *ex post welfare* as the realized welfare in the downstream market after the standard is implemented, excluding R&D costs. In the first best, it is optimal to have all users adopt the standard and to include all technologies that are developed in the standard. Thus, ex post welfare is equal to total user surplus. It follows that the ex post welfare if n technologies are developed is $W_n = v_n^2/2$.

The optimal probabilities of innovation maximize

$$x_A\, x_B\, W_2 + x_A\,(1 - x_B)\, W_1 + x_B\,(1 - x_A)\, W_1 - \alpha\, x_A^2/2 - \alpha\, x_B^2/2. \tag{2}$$

The following lemma compares first-best and equilibrium choices. All proofs not included in the main text are in the appendix.

Lemma 2 (First-best welfare analysis)**.** *If $v_2 \geq \frac{3}{2}\, v_1$, standardization decisions are optimal given innovation outcomes, and investments in R&D are bellow the optimal level. If $v_2 < \frac{3}{2}\, v_1$, the equilibrium number of technologies included in the standard is weakly less than optimal and investments in R&D may be bellow or above the optimal level.*

If the incremental value of the second technology ($v_2 - v_1$) is large, firms have incentives to include all technologies in the standard, which is efficient. When the incremental value is small, a firm's individual expected profit is larger when only one technology is included in the standard, and thus firms have incentives to exclude other technologies from the standard. Such exclusion of technologies is inefficient from a first-best point of view.

A more surprising result is that equilibrium investments in R&D may be too large from a first-best point of view. Comparing the first-order conditions arising from equations (1) and (2), it follows there are two differences between the equilibrium and first-best probabilities of innovation. First, the social value of a successful innovation is larger than the private value ($W_k > R_k$), which tends to make socially-optimal investments larger than equilibrium investments. Second, when a firm chooses its investment in R&D, it does not internalize the "business-stealing" effect it imposes on the other firm, which tends to make equilibrium investments larger than socially-optimal investments. If the incremental value of the second innovation is small, the second effect dominates the first, and equilibrium investments are larger than optimal.

Consider next second-best standardization incentives. Let W_n^* be the equilibrium ex post welfare it the standard includes n technologies. If $n = 2$, user surplus is $v_2^2/18$ and total licensing revenues are $2\,v_2^2/9$, which implies ex post welfare is $W_2^* = \frac{5}{18}\,v_2^2$. If $n = 1$, user surplus is $v_1^2/8$ and licensing revenue is $v_1^2/4$, which implies ex post welfare is $W_1^* = \frac{3}{8}\,v_1^2$.

If only one technology is developed, it is optimal to include it in the standard. If two technologies are developed, it is second-best optimal to include both in the standard only if $v_2 \geq \phi\, v_1$, where $\phi = (27/20)^{1/2} \approx 1.16$. From Lemma 1, in equilibrium, two technologies are included in the standard only if $v_2 > \frac{3}{2}\,v_1$. Thus, if $\phi\, v_1 \leq v_2 \leq \frac{3}{2}\,v_1$, the equilibrium has insufficient standardization from a second-best point of view.

The above result shows it may be second-best optimal to exclude a successfully-developed technology from a standard, even though all technologies are valuable from a technical point of view. This result is due to the complementary monopoly problem: the welfare loss from monopolistic pricing increases as the number of firms with claims on the standard increases, which may more than compensate the positive technological effect of having a better technology.

The second-best probabilities of innovation maximize equation (2), after replacing W_n for W_n^*. The following lemma compares second-best and equilibrium choices.

Lemma 3 (Second-best welfare analysis)**.** *From a second-best perspective, if $\phi\, v_1 < v_2 < \frac{3}{2}\, v_1$, the number of technologies included in the standard is weakly suboptimal. If $v_2 \geq \frac{3}{2}\, v_1$, equilibrium investments in R&D are bellow the second-best optimal level. If $v_2 < \frac{3}{2}\, v_1$, equilibrium investments in R&D may be bellow or above the second-best optimal level.*

Lemmas 2 and 3 show the first-best and second-best analyses yield similar qualitative results: the equilibrium may provide either insufficient or excessive innovation incentives, and even if innovation incentives are adequate, the number of technologies included in the standard may be below the socially-desirable level.

In the following sections, I study whether two policies commonly proposed to address the inefficiencies of the standard-setting process (price caps and patent pools) can increase user surplus and welfare.

5. Price caps

Ex ante agreements—in the form of price caps—have been proposed as a way to overcome hold-up problems in standard setting (Swanson and Baumol, 2005; Farrell, Hayes, Shapiro, and Sullivan, 2007; Boone, Schuett, and Tarantino, 2019). Following this advise, some standard-setting organizations have incorporated price caps into their rules and regulations. VITA (2015), for example, requires members to declare a maximum royalty rate for the use of their essential patents, and IEEE (2010) and ETSI (2013) encourage such declarations, although they are not compulsory. In this section, I study the effects of price caps on innovation incentives and standardization.

As I explain in the introduction, most analyses to date have focused on the effects of price caps on adoption and on the incentives to include technologies in standards when technologies are substitutes (i.e., when two or more technologies compete to be included in a standard). A contribution of this paper is to study the effects of price caps when technologies are complementary. In this case, I show case price caps have additional welfare effects that have not been recognized before.

I consider a four-stage game similar to the one in Section 2. The only difference is that in the second stage, firms' proposals over which standard to implement also include a commitment to a maximum license fee or price cap $\bar{p}_i$, which constraints the license fees they may choose in the third stage (note firms may choose a non-binding price cap by choosing a sufficiently large $\bar{p}_i$).

The solution of the fourth stage is the same as that of the base model. In the third stage, firms with stakes in the standard choose prices $p_i \leq \bar{p}_i$. If the standard includes one technology, its owner solves

$$\max_{p \leq \bar{p}_i} (v_1 - p)\, p,$$

the optimal price is $p^* = \min\{v_1/2, \bar{p}_i\}$, revenue is p^{*2}, and the net value for users is $\max\{v_1/2, v_1 - \bar{p}_i\}$. If the standard includes two technologies, firm i solves

$$\max_{p_i \leq \bar{p}_i} (v_2 - p_i - p_{-i})\, p_i.$$

Consider now the second stage. If only one technology is developed, the firm has no incentives to restrict its licensing fees. Thus the firm chooses a non-binding price cap and the equilibrium of the continuation game is the same as before.

If $v_2 \geq \frac{3}{2}v_1$ and two technologies have been developed, in the absence of a price cap both technologies are included in the standard. Thus, firms have no incentives to set a price cap below $v_2/3$ (committing to a lower price cap decreases revenue and does not affect the inclusion of the technology in the standard) and the equilibrium of the continuation game is the same as before.

If $v_2 < \frac{3}{2}v_1$ and two technologies have been developed, in the absence of a price cap each firm proposes a standard with one technology and users choose either proposal with equal probability. With price caps, if users are offered two standards with one technology, they will choose the proposal of the firm with the smallest price cap. Thus, firms compete a la Bertrand and have incentives to undercut their rival's price cap until price caps are so low that firms find it optimal to propose a standard with two technologies. In equilibrium, $\bar{p}_i = v_2 - v_1$ and at least one firm offers a standard with $n = 2$, which is approved.

The above analysis implies that, in the first stage, if $v_2 > \frac{3}{2}v_1$ innovation incentives are not affected and the equilibrium is the same as the equilibrium of the unrestricted-pricing game. If $v_2 < \frac{3}{2}v_1$, on the other hand, a firm obtains $v_1^2/4$ if it is the only one to develop a technology and $\left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1)$ if two technologies are developed. Thus, in this case firm i chooses x_i to maximize

$$x_i \left(x_{-i}\left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1) + (1 - x_{-i})\, v_1^2/4\right) - \alpha\, x_i^2/2.$$

Comparing the equilibrium with the one of Section 3, I obtain the following proposition.

Proposition 1 (Equilibrium and welfare effects of price caps)**.** *If $v_2 \geq \frac{3}{2}\, v_1$, price caps have no effect on equilibrium outcomes. If $v_2 < \frac{3}{2}\, v_1$, price caps weakly increase adoption and the number of technologies included in the standard, may increase or decrease R&D investments, and strictly increase expected user surplus and welfare.*

Proposition 1 shows price caps may increase or decrease innovation incentives. The result that price caps may enhance innovation incentives arises because technologies are complementary. Price caps induce firms to set lower prices, and thus allow them to partially overcome the complementary monopoly problem, which in some cases increases their profits and improves innovation incentives.

In other cases, the decrease in prices with price caps is so large that firms' profits decrease, and as a result investments in R&D are lower. However, even in this case, social welfare increases as a result of price caps because user surplus and ex post welfare increase, and because equilibrium investments may actually be larger than socially optimal in the equilibrium without price caps (thus, lowering investments brings them closer to their socially optimal level).

6. Patent pools

Patent pools have been proposed as a solution to alleviate the complementary monopoly problem (Shapiro, 2001; Lerner and Tirole, 2004; Llanes and Trento, 2012; Llanes and Poblete, 2014). In this section, I study the effect of patent pools on innovation and standardization incentives.

I assume firms may decide to form a patent pool if both of them develop technologies and both technologies are included in the standard. If a patent pool is formed, a patent-pool administrator sets a price for the bundle of licenses in the pool and distributes licensing proceeds equally among pool members.

There exist two key differences between price caps and patent pools. First, price caps are chosen individually by firms, while patent pools imply price coordination. Second, price caps are chosen ex ante (before the standard is defined), while patent pools are formed ex post. In the next section, I compare both policies, and also discuss what would be the effect of allowing price coordination ex ante.

In the fourth stage, adoption decisions given prices are the same as in the base model. In the third stage, if only one technology is included in the standard, the optimal price is $v_1/2$, revenue is $v_1^2/4$, and users' net value is $v_1/2$. If two technologies are included in the standard, it is optimal for the firms to form a patent pool (because the patent pool increases the firm's joint profit), the equilibrium price for the bundle of patents is $v_2^2/4$, individual licensing revenue is $v_2^2/8$, and users' net value is $v_2/2$.[11]

In the second stage, if one technology has been developed, a standard based on that technology is implemented. If two technologies are developed, at least one firm proposes a standard based on both technologies and firms and users vote to implement this standard (expected licensing revenues and net user value are strictly smaller when only one technology is included in the standard).

[11] With more than two firms, a complete patent pool may fail to form because some firms may have incentives to remain outside the pool. See Brenner (2009), Choi (2010), Llanes and Trento (2012), Llanes and Poblete (2014), and Tesoriere (2019) for detailed analyses on the incentives to join patent pools.

In the first stage, firm i chooses its investment to maximize

$$x_i \left(x_{-i}\, v_2^2/8 + (1 - x_{-i})\; v_1^2/4\right) - \alpha\, x_i^2/2.$$

Proposition 2 (Equilibrium and welfare effects of a patent pool)**.** *In comparison with the unrestricted-pricing equilibrium of Lemma 1, the formation of a patent pool weakly increases users' adoption and the number of technologies included in the standard, and strictly increases R&D investments, expected user surplus, and welfare.*

A somewhat unexpected result of Proposition 2 is that pools weakly increase welfare. Patent pools allow innovators to coordinate when choosing their prices, and thus weakly improve innovation incentives. In principle, patent pools could in some cases exacerbate the problem of excessive innovation studied in Lemmas 1, 2, and 3. However, the increase in R&D investments is desirable once we take into account that the patent pool increases ex post welfare and improves standardization incentives. Thus, patent pools weakly improve expected user surplus and welfare, and are a socially desirable policy tool.

7. Comparison of price caps and patent pools

In this section, I compare the welfare properties of price caps and patent pools. I begin by noting that coordinating on prices before or after the standard is negotiated yields the same results, as long as prices are determined after the innovation outcome is realized (that is, after technologies are developed). The reason is that, if coordination is performed ex ante and two technologies are developed, firms have incentives to agree on the prices that maximize their joint profits, which are the same than the prices obtained in Section 6.

The following proposition follows from a direct comparison of the expected welfare with price caps and with a patent pool, which are given in the proofs of Propositions 1 and 2.

Proposition 3 (Comparison of price caps and patent pools)**.** *Price caps lead to higher welfare than patent pools if $v_2 < \frac{4}{3}v_1$, and patent pools lead to higher welfare if $v_2 > \frac{4}{3}v_1$.*

Price caps force firms to compete in prices ex ante, inducing them to set smaller prices. Although technologies are perfectly complementary from an ex post perspective, and thus patent pools also induce firms to set smaller prices, they eliminate ex ante price competition. As a result, either policy may lead to lower prices and greater welfare. In addition, either policy may induce a larger investment in R&D and probability of innovation. The proposition shows price caps dominate patent pools in welfare terms when the incremental value of the second technology is small.

To conclude with this section, it is interesting to note that if firms can choose between price caps and patent pools after they innovate, they will always prefer patent pools. The reason is that patent pools allow firms to maximize industry profits. Thus, firms and regulators may disagree on the best way to overcome pricing inefficiencies.

8. Alternative bargaining procedures

In this section, I study how alternative bargaining procedures for negotiating standards affect the paper's results. I start by noting that in the three variants of the model studied so far (unrestricted pricing, price caps, and patent pools) agents cannot make transfers among each other when discussing the standard. Thus, firms and users negotiate standards in a non-transferable utility (NTU) framework.

The NTU assumption is reasonable in the case of standards, given that in the real world firms face important institutional *bargaining restrictions*. Precisely, one of the main concerns of firms involved in standard setting is that more complex ex ante negotiations may expose them to antitrust litigation. Thus, in practice, standard-setting organizations have only considered ex ante agreements in the form of individually-chosen price caps, which is a restricted way of conducting ex ante negotiations.

In particular, the standard-setting organization that has gone further in their regulation of ex ante agreements is VITA, which requires firms to (individually) commit ex ante to a maximum licensing fee for the use of their standard-related patents. More complex ex ante agreements have not been observed in practice.

For completeness, nevertheless, consider what would happen if firms (but not users) could make transfers among themselves at the standard setting stage, thereby negotiating in a partial transferable utility (TU) setting. If firms cannot commit to the prices they will set after the standard is defined, previous results still hold. If firms can propose price caps, they can implement the joint-profit maximizing ex post license fees in the following way: one firm can set a price cap of zero, and the other firm can choose a non-binding price cap and make a transfer equal to half the downstream monopoly profits to the other firm. Thus, firms can implement the same outcome as a patent pool in an NTU framework. A patent pool in the TU framework would lead to the same results as a patent pool in an NTU framework. Thus, in this case, both policies lead to equivalent results.[12]

Consider next what happens if firms and users can make transfers among themselves, in which case they negotiate in a full TU setting. If firms cannot commit to a licensing fee, there are two possible outcomes: if $v_2 \geq \frac{3}{2}v_1$, then the outcome is the same as that of the previous sections. If $v_2 < \frac{3}{2}v_1$ and only one technology is developed, results are as those of the previous section. If $v_2 < \frac{3}{2}v_1$ and two technologies are developed, users can extract all surplus from firms by pitting one firm against the other. Thus, in this case, firms' incentives to invest in R&D decrease with respect to the case of NTU. Given the results of Section 4, expected welfare can increase or decrease as a result of the lower investments in R&D.

If firms can propose price caps in the full TU case, they can commit to a zero price cap ex post, which maximizes total surplus. The division of surplus between firms and users will then depend on their relative bargaining abilities. For example, if firms and users negotiate a la Nash, the profit captured by firms would depend on their bargaining coefficients. Thus, firms' investments in R&D may increase or decrease, depending on the portion of surplus captured by firms. Finally, if firms can form a patent pool (but cannot commit to prices ex ante), then the results are the same as in the previous sections.

[12]See Llanes and Poblete (2014, forthcoming) for detailed analyses of standard-formation in the transferable utility case.

Returning now to the NTU bargaining framework, we can model bargaining in several alternative ways. For example, Lerner and Tirole (2006) study a simple bargaining framework in which a committee in the standard-setting organization chooses the standard to maximize a linear combination of patent holders' profits and users' surplus. This alternative bargaining procedure would yield the same results as the voting algorithm of Section 2 as long as, when indifferent between two standards, the committee choses each standard with equal probability.

Another alternative would be to employ a sequential bargaining protocol as Larouche and Schuett (forthcoming). For example, suppose one of the firms is selected at random to make a first offer, and that firm proposes a standard based on a subset of invented technologies. Users and firms then vote to approve the standard or not. If the standard is approved, it is implemented. If the standard is not approved, the other firm proposes a standard. If the standard proposed by the second firm is not approved, then a standard based on zero technologies is implemented. Once again, results would be the same as the model of Section 2 as long as both firms have the same probability of making the first offer.

In particular, it is straightforward to see that any NTU bargaining framework can only yield one of two results. If firms are treated symmetrically (e.g., in the model of Section 2, when users are indifferent between two proposals, they pick each proposal with equal probability, or in the sequential bargaining protocol, both firms are chosen to make the first proposal with equal probability), results are those presented in the previous sections. If, on the other hand, firms are treated non-symmetrically (e.g., in the model of Section 2, when users are indifferent between two proposals, they pick the proposal of one of the firms with probability one, or in the sequential bargaining protocol, one of the firms is chosen to make the first proposal with probability one), results may differ because one of the firms may capture more value when two technologies are developed. In the next section, I study innovation and standardization in the second case (that is, when one of the firms has a negotiation advantage at the standard-setting stage).

9. Negotiation asymmetries at the standard-setting stage

In this section, I study innovation and standardization when one firm has a negotiation advantage at the standard-setting stage. I assume that when users are indifferent between the proposals of two firms, they choose the proposal of firm A with probability one.

If firms can commit to a price cap or can form a patent pool, results are the same as in the symmetric model of Sections 5 and 6. The reason is that in these cases, asymmetries do not have any effect on equilibrium prices, and therefore, they have no effect on innovation and standardization decisions.

Consider next the model with ex post pricing. The solutions of the fourth and third stages are the same as those of the base model. In the second stage, if only one technology has been developed, the solution is the same as in the base model. If two technologies have been developed and $v_2 \geq \frac{3}{2}v_1$, the solution is the same as in the base model. If $v_2 < \frac{3}{2}v_1$, firm A proposes a standard with its technology, and this standard is approved.

In the first stage, $v_2 \geq \frac{3}{2}v_1$, the solution is the same as in the base model. If $v_2 < \frac{3}{2}v_1$, firm A chooses x_A to maximize

$$x_A\, v_1^2/4 - \alpha\, x_A^2/2$$

and firm B chooses x_B to maximize

$$x_B\,(1 - x_A)\, v_1^2/4 - \alpha\, x_B^2/2.$$

The equilibrium probabilities of innovation are

$$\hat{x}_A = \frac{v_1^2}{4c}, \quad \hat{x}_B = \left(1 - \frac{v_1^2}{4c}\right)\frac{v_1^2}{4c}.$$

It is straightforward to see that previous results on the welfare effects of price caps and patent pools carry over to this model with negotiation asymmetries. The following lemma compares expected welfare and innovation incentives in the symmetric and asymmetric negotiation models.

Lemma 4 (Negotiation asymmetries). *If $v_2 \geq \frac{3}{2}v_1$, the symmetric and asymmetric negotiation models yield the same probabilities of innovation and welfare. If $v_2 < \frac{3}{2}v_1$, there exists a constant $\psi \in (0, 1/2)$ such that the model with negotiation asymmetries yields higher expected welfare and overall probability of innovation than the model with symmetric negotiation if $\alpha < \psi\, v_1^2$ and the model with symmetric negotiation yields higher welfare if $\alpha > \psi\, v_1^2$.*

10. Cooperation in R&D

In Section 6, I considered firms' incentives to cooperate by coordinating their prices. In this section, I study another way in which firms may cooperate: by coordinating their investments in R&D. The main objective of this section is to determine whether cooperation in R&D reinforces or hinders price coordination and ex ante price commitments, in order to know if these policies should be used in conjunction or not.

Knowing the welfare effects of different types of cooperation is important because antitrust agencies are concerned about whether different types of agreements between firms involved in the standard-setting process benefit or harm consumers.

To determine the effects of cooperation in R&D, I return to the models of Sections 2, 5, and 6, and assume firms choose their investments in R&D to maximize joint profits in the first stage. Proposition 4 characterizes the welfare effects of the coordination of R&D investments.

Proposition 4 (Cooperation in R&D). *When firms commit to price caps, the coordination of R&D investments decreases welfare if $v_2 < \frac{3}{2}\, v_1$, and increases welfare otherwise. There exists a constant $\lambda \in (0, \sqrt{2})$ such that when firms form a patent pool, the coordination of R&D investments decreases welfare if $\lambda\, v_1 < v_2 < \sqrt{2}\, v_1$, and increases welfare otherwise. Price caps without cooperation in R&D are optimal for $v_2 < \frac{4}{3}\, v_1$, a patent pool without cooperation in R&D is optimal for $\frac{4}{3}\, v_1 \leq v_2 < \sqrt{2}\, v_1$, and a patent pool with cooperation in R&D is optimal for $v_2 \geq \sqrt{2}\, v_1$.*

The proof of Proposition 4 shows coordination of R&D investments may increase or decrease equilibrium investments, depending on whether investments are complements of substitutes. The nature of the strategic relation between investments, in turn, depends on the particular pricing game under consideration.

With price caps, investments are complementary if $v_2 > \frac{3}{2}\,v_1$, in which case equilibrium investments and expected welfare increase with coordination. If $v_2 < \frac{3}{2}\,v_1$, on the other hand, investments are substitutes, and coordination implies a decrease of equilibrium investments and welfare.

With patent pools, investments are complements if $v_2 > \sqrt{2}\,v_1$, in which case they increase with coordination, and are substitutes if $v_2 < \sqrt{2}\,v_1$, in which case they decrease with coordination. The decrease in equilibrium investment increases welfare only if the value of the second innovation is small. Thus, cooperation in R&D is socially beneficial if v_2 is large (in which case cooperation increases equilibrium investments) or if v_2 is small (in which case cooperation decreases equilibrium investments). For intermediate values of v_2, welfare is larger when firms do not coordinate their investments in R&D.

Considering all these intermediate results, it holds that cooperation in R&D is socially desirable only if the value of the second technology is large enough. If v_2 is small, the socially-optimal policy is to favor competition over cooperation, both in terms of prices and investments in R&D. Thus, it is optimal to have price caps and competition in R&D. If v_2 is large, the optimal policy is to favor cooperation, both in terms of prices and investments in R&D. Thus, it is optimal to have patent pools and cooperation in R&D. For intermediate values of v_2, the optimal policy is to favor cooperation in prices but not in R&D.

Finally, from a private perspective, firms' expected profits are maximized when they cooperate in prices and R&D, so the finding that society and firms' interests may not be aligned still holds in the model in which cooperation in R&D is possible.

11. Conclusion

I study the incentives to develop complementary technologies and include them in a technical standard. I show standardization may give rise to three inefficiencies: inefficient adoption of the standard by users, inefficient incentives to develop technologies, and inefficient inclusion of technologies in the standard.

The most important result of the paper is to show price caps and patent pools mitigate such inefficiencies and weakly increase consumer surplus and welfare. Therefore, both policies are desirable from a social point of view. I also show price caps dominate (are dominated by) patent pools if the incremental value of technologies is small (large), in which case competition is more (less) important than coordination.

Throughout the paper, I have assumed firms and users know all relevant patents when negotiating the inclusion of technologies in the standard. Opportunism is more problematic when it is difficult to determine if relevant technologies are patented or not. In this case, patent-holders may try to hide standard-related patents until after the standard is defined. Such behavior is called *patent ambush*, and is exemplified by Rambus's alleged behavior in the development of the SDRAM memory standard. See Ganglmair and Tarantino (2014) for a detailed analysis of the incentives to disclose patents in standard-setting organizations. Studying the incentives to innovate when firms can hide relevant patents when discussing standards is an interesting direction for further research.

I have also abstracted from downstream competition. Llobet and Padilla (2016) show ad valorem license fees lead to smaller prices and higher welfare than per unit royalty fees if there is downstream market power and Reisinger and Tarantino (2019) show patent pools may decrease welfare when upstream licensors are integrated with downstream manufacturers. Modeling downstream markets in more detail is another venue for future work.

The papers' results can be tested using recent data on standards and pools (Baron and Spulber, 2018; Baron and Pohlmann, 2018). Baron, Li, and Nasirov (2018), for example, show firms with higher R&D expenditure are more likely to participate in standard-setting organizations and Baron and Pohlmann (2015) document significant increases in patenting rates following patent-pool creation announcements. These works are important precedents for future empirical research but more work is needed to understand the effects of standardization on R&D incentives and innovation.

Appendix: Proofs

Proof of Lemma 2. That the equilibrium has insufficient adoption (for any value of the parameters) follows from the fact that equilibrium prices are higher than marginal cost. That the equilibrium has efficient standardization if $v_2 \geq \frac{3}{2}\, v_1$ and insufficient standardization if $v_2 < \frac{3}{2}\, v_1$ follows from a comparison of first-best standardization decisions with those in Lemma 1. The first-best probability of innovation is

$$x^{fb} = \frac{v_1^2/2}{\alpha + v_1^2 - v_2^2/2}.$$

If $v_2 \geq \frac{3}{2}\, v_1$, the equilibrium probability of innovation is

$$x^* = \frac{v_1^2/4}{\alpha + v_1^2/4 - v_2^2/9}.$$

Comparing these expressions, it is straightforward to show $x^{fb} > x^*$ for all parameter values such that $v_2 \geq \frac{3}{2}\, v_1$. If $v_2 < \frac{3}{2}\, v_1$, on the other hand, the equilibrium probability of innovation is

$$x^* = \frac{v_1^2/4}{\alpha + v_1^2/4 - v_1^2/8}.$$

With some work, it can be shown that $x^* > x^{fb}$ if $2\, v_2^2 < 3\, v_1^2 - 4\, \alpha$, and that $x^{fb} > x^*$ otherwise. Thus, if $v_2 < \frac{3}{2}\, v_1$, the equilibrium can have an insufficient or excessive investment in R&D. ■

Proof of Lemma 3. That the equilibrium has insufficient standardization if $\phi\, v_1 < v_2 < \frac{3}{2}\, v_1$ follows from the analysis in the main text. If $v_2 \geq \phi\, v_1$, the second-best probability of innovation is

$$x^{sb} = \frac{\frac{3}{8}\, v_1^2}{\alpha + \frac{3}{4}\, v_1^2 - \frac{5}{18}\, v_2^2},$$

and if $v_2 < \phi\, v_1$, this probability is

$$x^{sb} = \frac{\frac{3}{8}\, v_1^2}{\alpha + \frac{3}{8}\, v_1^2}.$$

If $v_2 \geq \frac{3}{2}\, v_1$, the equilibrium probability of innovation is

$$x^* = \frac{v_1^2/4}{\alpha + v_1^2/4 - v_2^2/9}.$$

Comparing innovation probabilities, I obtain that $x^{sb} > x^*$ for all parameter values such that $v_2 \geq \frac{3}{2}\, v_1$. If $v_2 < \frac{3}{2}\, v_1$, on the other hand, the equilibrium probability of innovation is

$$x^* = \frac{v_1^2/4}{\alpha + v_1^2/4 - v_1^2/8}.$$

For the result, it suffices to compare innovation probabilities for $v_2 < \phi\, v_1$. From the comparison, it follows that $x^* > x^{fb}$ if $\alpha < \frac{3}{8}\, v1^2$, and that $x^{fb} > x^*$ otherwise. Thus, if $v_2 < \frac{3}{2}\, v_1$, the equilibrium can have insufficient or excessive innovation. ■

Proof of Proposition 1. The result that if $v_2 \geq \frac{3}{2}\, v_1$, price caps have no effect on equilibrium outcomes follows from the analysis in the main text. Suppose $v_2 < \frac{3}{2}\, v_1$. That price caps weakly increase the number of technologies in the standard follows from the analysis in the main text.

Solving the profit maximization problem, I obtain the equilibrium probability of innovation:

$$x^{pc} = \frac{\frac{1}{4} v_1^2}{\alpha + \frac{1}{4} v_1^2 - \left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1)}.$$

With some work, it is possible to show the probability of innovation is larger with price caps if $v_1 > \frac{2}{17}\left(\sqrt{2} + 6\right)\, v_2$, and is smaller otherwise.

Let W_n^{pc} be the ex post welfare if n technologies are included in a standard with price caps. If two technologies are developed, user surplus is $\left(v_2 - 2(v_2 - v_1)\right)^2/2$, total licensing revenues are $2\left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1)$, and ex post welfare is

$$W_2^{pc} = \frac{1}{2}\left(v_2 - 2(v_2 - v_1)\right)^2 + 2\left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1).$$

Without price caps consumers obtain a net value of $v_1/2$, and with price caps, they obtain a net value of $v_2 - 2(v_2 - v_1)$, which is always larger. If one technology is developed, user surplus, licensing revenues, and ex post welfare are as in Section 3. Thus, $W_1^{pc} = W_1^*$ and user's adoption and surplus weakly increase with price caps.

Finally, expected welfare at the beginning of the game is

$$x^{pc2}\, W_2^{pc} + 2\, x^{pc}\,(1 - x^{pc})\, W_1^{pc} - \alpha\, x^{pc2}.$$

Working with this expression, I obtain that the expected welfare with price caps is

$$\frac{v_1^4\left(4\alpha + 8v_1^2 - 10v_1v_2 + 3v_2^2\right)}{2\left(4\alpha + (3v_1 - 2v_2)^2\right)^2}. \tag{3}$$

Without price caps, on the other hand, expected welfare is

$$\frac{8\alpha v_1^4}{\left(8\alpha + v_1^2\right)^2}, \tag{4}$$

which is smaller than the welfare with price caps. ■

Proof of Proposition 2. The formation of the patent pool weakly decreases prices, and thus, weakly increases adoption and expected user surplus for any value of the parameters. The pool weakly increases the number of technologies in the standard, and thus weakly improves standardization incentives. The equilibrium probability of innovation with a patent pool is

$$x^{pp} = \frac{v_1^2/4}{\alpha + v_1^2/4 - v_2^2/8}.$$

Comparing innovation probabilities, it is straightforward to show that the patent pool increases the probability for any value of the parameters. Finally, expected welfare with the patent pool is

$$\frac{8\alpha v_1^4}{\left(8\alpha + 2v_1^2 - v_2^2\right)^2}, \tag{5}$$

which is larger than expected welfare with unrestricted pricing for all values of the parameters. ■

Proof of Lemma 4. In the text, I have shown negotiation asymmetries have no effect on the equilibrium when $v_2 \geq \frac{3}{2} v_1$. When $v_2 < \frac{3}{2} v_1$ ex post welfare is $\frac{3}{8} v_1^2$, when one or two technologies are developed, both with symmetric or asymmetric negotiation. With symmetric negotiation, the probability at least one technology is developed is

$$X_S = 1 - (1 - x^*)^2 = \frac{32\,\alpha\,v_1^2}{\left(8\,\alpha + v_1^2\right)^2}$$

and expected welfare is

$$W_S = \frac{8\,\alpha\,v_1^4}{\left(8\,\alpha + v_1^2\right)^2}.$$

With asymmetric negotiation, the probability at least one technology is developed is

$$X_A = 1 - (1 - x_A)\,(1 - x_B) = \frac{32\,\alpha^2\,v_1^2 - 8\,\alpha\,v_1^4 + v_1^6}{64\,\alpha^3}.$$

and expected welfare is

$$W_A = \frac{32\,\alpha^2\,v_1^4 - 8\,\alpha\,v_1^6 + v_1^8}{256\,\alpha^3}.$$

Comparing these expressions, I obtain the results in the lemma. ■

Proof of Proposition 4. The welfare of the unrestricted pricing, price caps, and patent pool models without coordination of R&D investments is given by expressions (4), (3), and (5) in Propositions 1 and 2. Let R_n be the individual expected licensing revenue of a firm when n innovations have been obtained (such revenues depend on the particular pricing game under consideration). With cooperation in R&D, firms choose symmetric innovation probabilities x to maximize

$$x^2\,2\,R_2 + 2\,x\,(1-x)\,R_1 - \alpha\,x^2,$$

which yields an optimal probability of innovation of

$$\tilde{x} = \frac{R_1}{\alpha + 2(R_1 - R_2)}.$$

Without cooperation in R&D, the probability of innovation is

$$\bar{x} = \frac{R_1}{\alpha + R_1 - R_2}.$$

It is straightforward to see that with cooperation in R&D, investments in R&D increase if $R_1 > R_2$, and decrease if $R_2 > R_1$. Consider now welfare with cooperation in R&D, and assume first $v_2 < \frac{3}{2} v_1$. After some straightforward calculations, I obtain that equilibrium welfare with unrestricted pricing is

$$\frac{16\alpha v_1^4 + 3v_1^6}{8\left(4\alpha + v_1^2\right)^2},$$

with price caps, it is

$$\frac{v_1^4\left(8\alpha + 43v_1^2 - 56v_1v_2 + 18v_2^2\right)}{16\left(2\alpha + (3v_1 - 2v_2)^2\right)^2},$$

and with a patent pool, it is

$$\frac{v_1^4\left(16\alpha + 6v_1^2 - 3v_2^2\right)}{8\left(-4\alpha - 2v_1^2 + v_2^2\right)^2}.$$

If $v_2 > \frac{3}{2} v_1$, on the other hand, welfare with unrestricted pricing or with price caps is

$$\frac{9v_1^4\left(72\alpha + 27v_1^2 - 14v_2^2\right)}{16\left(18\alpha + 9v_1^2 - 4v_2^2\right)^2},$$

and with a patent pool, it is

$$\frac{v_1^4\left(16\alpha + 6v_1^2 - 3v_2^2\right)}{8\left(-4\alpha - 2v_1^2 + v_2^2\right)^2}.$$

Comparing these expressions, I obtain the results described in the Proposition. ■

References

Alderman, R. (2014): "Fear And Loathing In The Standards Process," *Electronic Design.*

Aoki, R., and A. Schiff (2010): "Intellectual Property Clearinghouses: the Effects of Reduced Transaction Costs in Licensing," *Information, Economics and Policy*, 22(3), 218–227.

Baron, J., and K. Gupta (2018): "Unpacking 3GPP standards," *Journal of Economics & Management Strategy*, 27(3), 433–461.

Baron, J., C. Li, and S. Nasirov (2018): "Joining Standards Organizations: The Role of R&D Expenditures, Patents, and Product-Market Position," Working paper.

Baron, J., Y. Ménière, and T. Pohlmann (2014): "Standards, consortia, and innovation," *International Journal of Industrial Organization*, 36, 22–35.

Baron, J., and T. Pohlmann (2015): "The Effect of Patent Pools on Patenting and Innovation - Evidence from Contemporary Technology Standards," Working paper.

——— (2018): "Mapping standards to patents using declarations of standard-essential patents," *Journal of Economics & Management Strategy*, 27(3), 504–534.

Baron, J., and D. F. Spulber (2018): "Technology Standards and Standard Setting Organizations: Introduction to the Searle Center Database," *Journal of Economics & Management Strategy*, 27(3), 462–503.

Boone, J., F. Schuett, and E. Tarantino (2019): "Price commitments in standard setting under asymmetric information," Working paper.

Brenner, S. (2009): "Optimal Formation Rules for Patent Pools," *Economic Theory*, 40(3), 373–388.

Bulow, J. I., J. D. Geanakoplos, and P. D. Klemperer (1985): "Multimarket Oligopoly: Strategic Substitutes and Complements," *Journal of Political Economy*, 93(3), 488–511.

Choi, J. (2010): "Patent Pools and Cross-Licensing in the Shadow of Patent Litigation," *International Economic Review*, 51(2), 441–460.

Cournot, A. (1838): *Researches Into the Mathematical Principles of the Theory of Wealth.* Irwin (1963).

D'Aspremont, C., and A. Jacquemin (1988): "Cooperative and noncooperative R & D in duopoly with spillovers," *American Economic Review*, 78(5), 1133–1137.

DeLacey, B. J., K. Herman, D. Kiron, and J. Lerner (2006): "Strategic behavior in standard-setting organizations," Working paper, Harvard Business School.

ETSI (2013): "ETSI guide on Intellectual Property Rights," Version adopted by Board #94 on 19 September 2013. Available at http://www.etsi.org/images/files/IPR/etsi-guide-on-ipr.pdf, accessed May 30, 2019.

Farrell, J., J. Hayes, C. Shapiro, and T. Sullivan (2007): "Standard setting, patents, and hold-up," *Antitrust Law Journal*, 74, 603.

Ganglmair, B., L. M. Froeb, and G. J. Werden (2012): "Patent Hold-Up and Antitrust: How A Well-Intentioned Rule Could Retard Innovation," *The Journal of Industrial Economics*, 60(2), 249–273.

Ganglmair, B., and E. Tarantino (2014): "Conversation with secrets," *RAND Journal of Economics*, 45(2), 273–302.

Gupta, K., and G. Effraimidis (2018): "IEEE Patent Policy Revisions: An Empirical Examination of Impact," Working paper.

IEEE (2010): "Promoting competition and innovation: what you need to know about the IEEE Standards Association's antitrust and competition policy," Approved 22 March 2007, updated 24 August 2010. Available at http://standards.ieee.org/develop/policies/antitrust.pdf, accessed May 30, 2019.

Kamien, M. I., E. Muller, and I. Zang (1992): "Research Joint Ventures and R&D Cartels," *American Economic Review*, 82(5), 1293–1306.

Katznelson, R. D. (2015): "Perilous Deviations from FRAND Harmony – Operational Pitfalls of the 2015 IEEE Patent Policy," IEEE SIIT 2015, 9th International Conference on Standardization and Innovation in Information Technology, Sunnyvale, CA.

Larouche, P., and F. Schuett (forthcoming): "Repeated interaction in standard setting," *Journal of Economics & Management Strategy*.

Layne-Farrar, A., G. Llobet, and J. Padilla (2014): "Payments and participation: the incentives to join cooperative standard setting efforts," *Journal of Economics and Management Strategy*, 23(1), 24–29.

Lerner, J., and J. Tirole (2004): "Efficient Patent Pools," *American Economic Review*, 94(3), 691–711.

——— (2006): "A model of forum shopping," *American Economic Review*, 96(4), 1091–1113.

——— (2015): "Standard-essential patents," *Journal of Political Economy*, 123(3), 547–586.

Llanes, G., and J. Poblete (2014): "Ex-ante agreements in standard setting and patent-pool formation," *Journal of Economics and Management Strategy*, 23(1), 50–67.

——— (forthcoming): "Technology choice and coalition formation in standards wars," *Journal of Industrial Economics*.

Llanes, G., and S. Trento (2012): "Patent Policy, Patent Pools, and the Accumulation of Claims in Sequential Innovation," *Economic Theory*, 50(3), 703–725.

Llobet, G., and J. Padilla (2016): "The Optimal Scope of the Royalty Base in Patent Licensing," *The Journal of Law and Economics*, 59(1), 45–73.

Pohlmann, T. (2017): "Empirical study on patenting and standardization activities at IEEE," Working paper.

——— (2018): "IEEE's Empirical Record of Success and Innovation Following Patent Policy Updates," Working paper.

Reisinger, M., and E. Tarantino (2019): "Patent pools, vertical integration, and downstream competition," *The RAND Journal of Economics*, 50(1), 168–200.

Rey, P., and J. Tirole (forthcoming): "Price Caps as Welfare-Enhancing Coopetition," *Journal of Political Economy*.

Shapiro, C. (2001): "Navigating the Patent Thicket: Cross Licenses, Patent Pools, and Standard Setting," in *Innovation policy and the economy*, ed. by A. B. Jaffe, J. Lerner, and S. Stern, vol. 1, pp. 119–150. MIT Press, Cambridge.

Spulber, D. F. (2016): "Patent licensing and bargaining with innovative complements and substitutes," *Research in Economics*, 70(4), 693–713.

——— (2017): "Complementary Monopolies and Bargaining," *The Journal of Law and Economics*, 60(1), 29–74.

Swanson, D., and W. Baumol (2005): "Reasonable and nondiscriminatory (RAND) royalties, standards selection, and control of market power," *Antitrust Law Journal*, 73, 1.

Tesoriere, A. (2019): "Stable sharing rules for pools of essential patents," Working paper.

VITA (2015): "VSO Policies and procedures," Revision 2.8, September 1st. Available at https://www.vita.com/resources/Documents/Policies/vso-pp-r2d8.pdf, accessed May 30, 2019.