TECHNOLOGY CHOICE AND COALITION FORMATION IN STANDARDS WARS*

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Abstract. We study technology choice when standards result from competition between groups of firms sponsoring different technologies. We show that ex-ante licensing commitments increase industry profits but have an ambiguous effect on welfare, and find sufficient conditions which restore the efficiency of ex-ante agreements. We also provide existence and characterization results relevant to the literatures of coalition formation and equal-sharing partnerships.

Keywords: Standards Wars, Technology Choice, Standard-Setting Organizations, Ex-Ante Agreements, Coalition Formation, Cooperative Game Theory, Externalities, Equal-Sharing Partnerships (JEL: C71, L15, O34).

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1. Introduction

Technical standards –like the compact disk or the protocols that run the Internet– are essential for the development and adoption of new technologies. Standards often result from competition between groups of firms sponsoring different technologies. In the high-definition optical-disc standards war, for example, the Blu-ray standard –sponsored by Sony, Hitachi, LG, Panasonic, Pioneer, Philips, Samsung, Sharp, and Thomson– competed for adoption against the HD DVD standard –sponsored by Toshiba, NEC, Sanyo, Memory-Tech, Intel, and Microsoft. Standards wars such as this are the case rather than the exception. Chiao et al. (2007) show there is an average of fifteen standard-setting organizations (SSOs) per technology subfield, often proposing competing standards.

Recent works have argued that the prospect of hold up from standard-essential patents may lead to inefficient standards (Farrell et al., 2007; Schmalensee, 2009).[1] Allowing firms to sign licensing contracts before standards are defined (ex-ante agreements) may solve this problem, but most SSOs have traditionally forbidden or discouraged licensing discussions out of concern for potential antitrust exposure.[2] More recently, some SSOs have reconsidered this position and have received encouraging support from the Federal Trade Commission, the Department of Justice (DOJ and FTC, 2007), and the European Commission (2004). Llanes and Poblete (2014) and Lerner and Tirole (2015) show that ex-ante agreements lead to better standards when firms can only join one standard (monopoly-standards case). However, the effects of ex-ante agreements in standards wars are largely unknown.

In a standards war, the profits of the sponsors of a standard depend on the characteristics of competing standards: holding everything else equal, the likelihood that a standard is adopted decreases as the quality of competing standards increases, and even when a standard is adopted, the rents its sponsors can capture may be constrained by the presence of an alternative standard. Thus, the

[1]Rysman and Simcoe (2008) and Baron et al. (2013) show that patents are becoming increasingly important for standard-setting activities.

[2]For example, the VITA Standards Organization (2009) indicates that "the negotiation or discussion of license terms among working-group members or with third parties is prohibited at all VSO and working-group meetings," the IEEE Standards Association (2010) establishes that "participants should never discuss the price at which compliant products may or will be sold, or the specific licensing fees, terms, and conditions being offered by the owner of a potential Essential Patent Claim," and ETSI (2013) establishes that "specific licensing terms and negotiations are commercial issues between the companies and shall not be addressed within ETSI."

standard-setting process is a coalition-formation problem with inter-group externalities (Aumann and Peleg, 1960; Thrall and Lucas, 1963; Myerson, 1978; Bloch, 1996; Maskin, 2013). Taking into account inter-group externalities is important because firms may behave strategically when choosing coalitional partners, which may alter the effect of ex-ante agreements on technology choice and efficiency.

In this paper, we develop a model of coalition formation and technology choice in standard setting, and address the following questions: (i) How does the competition between groups of technology sponsors affect the standard-setting process? (ii) What is the effect of ex-ante agreements on technology choice and efficiency in standards wars?

Our model deals with the standardization of a new product, technology, or service. Firms own patents on standard-related technologies, and form coalitions to develop standards. We consider two cases. First, we study a monopoly-standard setting in which firms may join only one standard. Then, we study a standards war in which coalitions of firms compete to have their technologies adopted in the market.

Adopters of a standard must comply with its exact technical specifications. Thus, even though some technologies may not be essential for a standard *ex-ante* (before the standard is defined), they become essential *ex-post* (after the standard is defined), if they are selected to be part of the standard.

The profits of a coalition of firms depend on the complete allocation of firms into coalitions. Profit distribution within a coalition, in turn, depends on the type of contracts available to firms. We consider three cases. First, we assume that firms cannot sign ex-ante contracts determining the ex-post distribution of profits. Given that all patents in a standard are ex-post essential, all sponsors have the same marginal contribution, and consequently, profits are divided on per capita terms. Second, we assume that firms cannot sign ex-ante contracts, but can trade patents after the standard is defined. As a result, firms share profits according to the number of ex-post standard-essential patents: if a firm's share in the standard's revenues is below its share of standard-essential patents, the firm can sell its patent to an outsider, which may then claim a share of revenues. Finally, we assume that firms can sign ex-ante agreements, in which case the distribution of profits is endogenously negotiated between standard sponsors.

We allow firms to differ in two dimensions: the number of patents they hold, and the value of those patents. Thus, we can study the differential effects of per capita and patent-based sharing rules. Previous papers in the standard-setting literature do not distinguish between these two sharing rules because they either assume that firms are symmetric, or that each firm has exactly one patent.

Studying patent-based sharing rules is important because most patent pools distribute licensing revenues in this way (Layne-Farrar and Lerner, 2011), and because some practitioners have argued that they may be a good substitute for ex-ante agreements if the number of patents is related with the size of the firm's marginal contribution. Lerner and Tirole (2015) find patent-based profit distribution puzzling and identify it as an important issue for future research.

Our paper has five main results. First, we show that ex-ante agreements improve welfare in the case of monopoly standards, even when firms' patent portfolios are different. Thus, the results of previous papers studying symmetric firms extend to the case of heterogeneous patent portfolios.

Second, we show that industry interests may not coincide with the interests of individual firms. Ex-ante agreements increase total industry profits, but some firms may be worse off relative to per capita or patent-based profit-sharing rules. As a consequence, some firms may oppose ex-ante agreements, even in cases where they improve welfare and total industry profits.

Third, we show that rules that distribute profits based on the number of patents may not improve welfare, relative to per capita sharing rules, even if firms' marginal contributions are increasing in the number of patents. Thus, patent-based sharing rules may not be a good substitute of ex-ante agreements, even when the number of patents is a relatively good indicator of the value of patent portfolios.

Fourth, we find that ex-ante agreements may decrease welfare in the case of standards wars. Even though total industry profits are larger with ex-ante agreements, welfare is not necessarily larger because the interests of firms and society may not be aligned. This result contrasts with the results of previous works studying monopoly standards (Llanes and Poblete, 2014; Lerner and Tirole, 2015), in which case ex ante agreements were always found to be welfare improving.

Finally, we find that if firms can participate in multiple standards, and the first-best allocation leads to a connected network of standard sponsors, ex-ante agreements lead to better standards and higher welfare. Thus, the efficiency of ex-ante agreements is restored when the standard-setting process is open and collaborative. We also show that it is valuable to have "umbrella" firms participating in multiple standard-setting efforts, because these firms can serve as indirect links between firms with narrower interests. We note that this result does not follow from Coase's theorem (Coase, 1960), since firms cannot make or receive transfers to or from standards' adopters.

Our findings contribute to the recent debate on the optimal rules of standard-setting organizations. Antitrust enforcement agencies and standard-setting organizations are currently discussing whether licensing agreements should be allowed at the standard-setting stage. We show that ignoring the fact that standards arise from competition between endogenously-formed groups of firms may lead to wrong conclusions about the welfare effects of ex-ante agreements. We also show that the problems that ex-ante agreements pose for efficient technology choice in standards wars may be overcome by introducing rules that guarantee an open and widespread participation of firms with standard-related technologies in the standard-setting process. These rules may help prevent technological hold up and ex-post patent litigation, which are a significant concern, since they lead to large litigation costs, as the cases of Rambus and Qualcomm exemplify. More recently, Apple and Samsung have spent over a billion dollars in the ongoing smartphone war, which is partly related with patents covering the 3G standard. These litigation costs are significant, not only because they may affect the resources devoted to research and development, but also because they may influence the formation of subsequent standards, such as the 4G standard in the case of mobile telecommunications.

We also contribute to the literatures of coalition formation and equal-sharing partnerships (Farrell and Scotchmer, 1988; Levin and Tadelis, 2005; Poblete, 2015) by providing novel existence results and characterizing stable allocations in the presence of externalities, both with a fixed distribution of output and when the distribution of output is endogenous.

In the following section we study technology choice in a monopoly standard. In Section 3 we study competition between standards proposed by competing coalitions. In Section 4 we study the effects of ex-ante agreements when firms may join multiple standards. In Section 5 we present the main conclusions of the paper and discuss potential directions for further research. All proofs are in the Appendix.

2. Monopoly standards

We model standard setting as a coalition-formation process. A set of firms I holds patents covering standard-related technologies. Firms form coalitions $c \subseteq I$, and each coalition develops a standard based on the patents it owns. An allocation of firms into coalitions is stable if there does not exist a profitable coalitional deviation.

Standardization affects the relative importance of firms' marginal contributions. If a user wants to adopt a standard, she must follow its exact technical specifications. Thus, even though some technologies may not be essential for a standard *ex-ante* (before the standard is defined), all technologies included in a standard become essential *ex-post* (after the standard is defined).

When a standard is adopted by users, its sponsors capture total quasirents $H(c)$. These quasirents may come from independent or collective licensing, or from selling downstream products based on the standard. For simplicity, we assume that the sponsors of a standard form a patent pool and delegate pricing decisions on a pool administrator, who then distributes quasirents among pool members.[3]

Let $W(c)$ be the social value (welfare) of a standard based on the patents of coalition c. We say that a standard is efficient if it maximizes welfare. We assume that all firms have valuable technologies, both from a private and social point of view. Thus, $H(c') > H(c)$ and $W(c') > W(c)$ for all $c \subset c'$.

The distribution of quasirents among standard's sponsors depends on the types of contracts available to firms. We study three cases.

First, we assume that firms cannot sign ex-ante contracts determining the ex-post distribution of profits. Given that all patents in a standard are essential, all standard's sponsors have the same marginal contribution. Consequently, quasirents are divided equally among sponsors.[4] The expected per capita profit of a firm in coalition c is

$$h(c) = \frac{H(c)}{|c|},$$

where $|c|$ is the number of members of c.

Second, we assume that firms cannot sign ex-ante contracts, but can trade patents after the standard is defined. As a result, firms share quasirents according

[3] In Llanes and Poblete (2014) we study the endogenous formation of standards and patent pools, and show that ex-ante agreements may allow the formation of patent pools that are unstable otherwise. Thus, allowing for endogenous patent-pool formation would strengthen the results of this paper.

[4] Similar arguments have been used to motivate the assumption of equal sharing in the partnerships literature (Farrell and Scotchmer, 1988; Levin and Tadelis, 2005; Poblete, 2015). Recently, Bonatti and Rantakari (2014) study how equal-sharing affects project choice in organizations. See Llanes and Poblete (2014) and Lerner and Tirole (2015) for more details on the use of this assumption in standard setting.

to the number of ex-post standard-essential patents: if a firm's share in standard's revenues is below its share of standard-essential patents, the firm can sell its patent to an outsider, who can then claim a share of revenues. Patent-based profit distribution is a mechanism commonly observed in patent pools (Layne-Farrar and Lerner, 2011; Lerner and Tirole, 2015). Let n_i be the number of ex-post standard-essential patents of firm i. The expected profit of firm i in coalition c is

$$g_i(c) = \frac{n_i}{\sum_{j \in c} n_j} H(c).$$

Third, we assume that firms can sign ex-ante agreements determining the ex post distribution of profits. Thus, the distribution of quasirents is endogenously negotiated between standard sponsors.

Let $w = (w_i)_{i \in I}$ be a sharing rule, where w_i is the expected payoff of firm i. A sharing rule is feasible with respect to coalition c if $\sum_{i \in c} w_i \leq H(c)$. The equal-sharing and patent-based-sharing cases imply fixed sharing rules, and the ex-ante agreements case imply endogenous sharing rules.

Our equilibrium definitions correspond to the *core* of a cooperative game (Gillies, 1959). We consider both unilateral and multilateral deviations. In the case of fixed sharing rules, the game has non-transferable utility. In the case of ex-ante agreements, the game has transferable utility. We now define stable coalitions in games with fixed sharing rules.

Definition 1 (Stable coalition with fixed sharing rules)**.** *A coalition c is stable if there does not exist a coalition c' such that firms are strictly better off in c' than in c.*

In formal terms, with equal sharing a coalition c is stable if there does not exist a coalition c' such that $h(c') > h(c)$, and with patent-based sharing a coalition c is stable if there does not exist a coalition c' such that $g_i(c') > g_i(c)$ for all $i \in c \cap c'$.

We now compare the efficiency of equal sharing and patent-based sharing rules. Let $m_i(c) = H(c) - H(c \setminus i)$ be the (ex-ante) marginal contribution of firm i in coalition c. Marginal contributions are increasing in the number of patents if $n_i > n_j$ implies $m_i(c) > m_j(c)$ for all $i, j \in c \subseteq I$. Per-patent marginal contributions are increasing in the number of patents if $n_i > n_j$ implies $\frac{m_i(c)}{n_i} \geq \frac{m_j(c)}{n_j}$ for all $i, j \in c \subseteq I$.

Proposition 1. *A stable coalition with fixed sharing rules exists, is generally unique, and may be inefficient. Patent-based sharing may imply higher or lower* *industry profits and welfare than equal sharing, even if marginal contributions are increasing in the number of patents. If per-patent marginal contributions are increasing in the number of patents, patent-based sharing implies higher industry profits and welfare than equal sharing.*

Proposition 1 shows that stable allocations with fixed sharing rules are generally inefficient. The standard-setting process leads to an *equalizing transformation* of the marginal contributions of firms (Llanes and Poblete, 2014), which affects the incentives to form coalitions. In the equal-sharing case, all firms in the stable coalition have the same ex-post marginal contribution. Therefore, firms with large ex-ante marginal contributions may want to avoid joining a coalition with firms with small ex-ante marginal contributions. Likewise, in the patent-based sharing case, all patents in the standard have the same ex-post marginal contribution, so firms with small and valuable patent portfolios may want to avoid joining coalitions with firms with large and less-valuable patent portfolios.

Proposition 1 also shows that patent-based sharing may not lead to higher profits or welfare than equal sharing, even if the number of patents is a good indicator of ex-ante marginal contributions. To guarantee that patent-based sharing is more efficient than equal sharing, the ratio of the marginal contribution to the number of patents must be increasing in the number of patents, which is a much stronger assumption.

We now present the definition of a stable coalition with ex-ante agreements.

Definition 2 (Stable allocation with ex-ante agreements)**.** *A coalition c with associated sharing rule w is stable if there does not exist a coalition c' such that $\sum_{i \in c'} w_i < H(c')$.*

The following proposition compares the welfare properties of the different sharing rules.

Proposition 2. *A stable coalition with ex-ante agreements exists and is unique. The stable coalition with ex-ante agreements maximizes industry profits and is socially efficient.*

Stable coalitions with fixed sharing rules are generally inefficient because firms cannot commit to a distribution of profits when designing the standard. Thus, firms with a small ex-ante marginal contribution will generally capture excessive profits, and firms with a larger ex-ante marginal contribution have incentives to exclude them from the standard. Ex-ante agreements solve this problem, because firms can negotiate how to divide the profits from the standard at the same time they negotiate what technologies to include in the standard. Thus, standard sponsors will include any firm with positive marginal contribution in the standard.

We conclude this section with two remarks. First, firms choose technologies to increase expected quasirents, not to increase social welfare. However, with ex-ante agreements, the interests of firms and society are *aligned*: a higher-quality standard implies higher profits and higher welfare. Most importantly, Proposition 2 does not follow from Coase's theorem (Coase, 1960), since we do allow firms to sign contracts with adopters. Second, the interests of the industry may not coincide with the interests of individual firms. For example, even in a case in which industry profits are larger with a patent-based sharing rule than with equal sharing, firms with fewer patents may end up losing from a distribution of surplus based on patents. As a result, some firms may oppose sharing rules that increase total industry profits or welfare.

3. Standards wars

In this section, we study competition between coalitions of standards' sponsors. To focus on the simplest possible case, we assume that at most two standards may compete for adoption.[5] Studying a standards war between two standards allows us to show the basic mechanisms at play in a simple way, and is interesting in its own right since many standards wars are fought between two standards (e.g. Blu-ray versus HD-DVD, VHS versus Betamax, RCA versus Columbia in quadrophonic sound, and Sky versus BSB in satellite TV). We also assume that each firm may sponsor at most one standard. In Section 4, we relax this assumption, and study a model in which firms may sponsor multiple standards.

An allocation a is a set of non-overlapping coalitions. Let A be the set of all possible allocations. Let $H(c, a)$ be the total quasirents of coalition c in allocation $a = \{c, c'\}$, and let $W(a)$ be the social value of allocation a. Total industry profits are given by $H(c, a) + H(c', a) \leq W(a)$.

We assume that all firms have valuable technologies. Thus, $W(\{c_1', c_2\}) > W(\{c_1, c_2\})$ and $H(c_1', \{c_1', c_2\}) > H(c_1, \{c_1, c_2\})$ for all $c_1' \supset c_1$. We also assume that coalitions compete to appropriate quasirents, which means that the value

[5] In a previous version of the paper, we showed that our results extend to competition between more than two standards. Results are available upon request.

captured by one coalition weakly decreases when the standard proposed by the other coalition improves. Thus, $H(c_1, \{c_1, c_2'\}) \leq H(c_1, \{c_1, c_2\})$ for all $c_2' \supset c_2$.

Finally, we assume it is always possible to increase industry profits by including one more firm in an allocation. That is we assume that for all $a = \{c, c'\} \in A$ and all $i \notin c \cup c'$, either $H(c \cup i, \{c \cup i, c'\}) + H(c', \{c \cup i, c'\}) > H(c, \{c, c'\}) + H(c', \{c, c'\})$, or $H(c, \{c, c' \cup i\}) + H(c' \cup i, \{c, \{c' \cup i\}) > H(c, \{c, c'\}) + H(c', \{c, c'\})$, or both. Examples 1 and 2 below verify all assumptions.

As in the case of monopoly standards, the distribution of quasirents among standard sponsors depends on the types of contracts available to firms. We study three cases. First, we assume that firms cannot sign ex-ante contracts determining profit distribution. Thus, the profit of a firm in coalition c is

$$h(c, a) = \frac{H(c, a)}{|c|}.$$

Second, we assume that firms cannot sign ex-ante contracts, but can trade patents after the standard is formed. In this case, the profit of firm i in coalition c is

$$g_i(c, a) = \frac{n_i}{\sum_{j \in c} n_j} H(c, a).$$

Third, we assume firms can sign ex-ante contracts regarding profit distribution, in which case the profit of each firm is determined endogenously.

As in the previous section, we model the coalition-formation process as a cooperative game, but now adapt our equilibrium definitions to account for *inter-group externalities*.[6] The natural extensions of the core to coalition-formation games with externalities are given by the α-core and β-core of Aumann and Peleg (1960), and the partition-function games of Thrall and Lucas (1963). We follow Thrall and Lucas (1963) and assume that firms have pessimistic beliefs over deviations from a given allocation. Pessimistic beliefs mean that for a deviation to be profitable, it must be profitable for any possible reaction of non-deviators.[7]

[6] In a previous version of the paper, we showed that our results extend to a *non-cooperative* coalition-formation game based on Bloch (1996). Results are available upon request.

[7] Aumann and Peleg (1960) study games with non-transferable utility, and Thrall and Lucas (1963) study games with transferable utility. Even though our game has non-transferable utility, our definition of stability is closer to Thrall and Lucas (1963), because we assume that firms only have pessimistic expectations for deviations from the stable allocation. Aumann and Peleg (1960) also assume coalitions have pessimistic expectations *at* the stable allocation.

Intuitively, in cooperative games, equilibrium payoffs depend on the threats agents can make to each other (Myerson, 1978). Pessimistic beliefs are consistent with the worst threat that firms outside a coalition can make. Moreover, pessimistic beliefs minimize the chances for a deviating coalition to be profitable. Thus, if an allocation is stable with another belief system, it must be stable with pessimistic beliefs. Given that our results hold for any equilibrium with pessimistic beliefs, they will also hold for equilibria with other beliefs.[8]

An allocation is associated to a sharing rule $w = (w_i)_{i \in I}$, where w_i is the payoff of firm i. A sharing rule w is feasible with respect to allocation a if $\sum_{i \in c} w_i \leq H(c, a)$ for all $c \in a$. We assume that firms cannot make transfers to firms in other standards. With fixed sharing rules, we study stable allocations according to the following definition.

Definition 3 (Stable allocation with fixed sharing rules)**.** *A coalition c blocks allocation a if for any allocation a' that contains c, the members of c are strictly better off in a' than in a. An allocation is stable if a coalition blocking it does not exist.*

In formal terms, under equal sharing, coalition c' blocks allocation a if for all $a' \ni c'$ and $c \in a$ with $c \cap c' \neq \varnothing$, we have $h(c', a') > h(c, a)$. In the case of patent-based sharing, coalition c' blocks allocation a if for all $a' \ni c'$, $c \in a$, and $i \in c \cap c'$, we have $g_i(c', a') > g_i(c, a)$.

Definition 4 is analogous to the ones used in the literature on equal-sharing partnerships (Farrell and Scotchmer, 1988; Levin and Tadelis, 2005; Poblete, 2015), extending them to account for inter-group externalities. In our model, externalities play an important role, because the profit of the sponsors of a standard generally depends on the value of competing standards. We also contribute to this literature by considering sharing rules that depend on the ownership of an asset, such as patents, in addition to equal sharing. Proposition 3 characterizes stable allocations with fixed sharing rules.

Proposition 3 (Existence)**.** *A stable allocation with fixed sharing rules exists, and may be inefficient.*

[8]In a previous version of the paper, we showed that our results extend to a model in which firms have reactive expectations. That is, following a deviation, firms expect non-deviators to form the best possible coalition. In this case, the solution concept coincides with the *recursive core* (Huang and Sjöström, 2006; Kóczy, 2007). Results are available upon request.

Stable allocations with fixed sharing rules are inefficient for two reasons. First, as in the monopoly case, the standard-setting process leads to an *equalizing transformation* of the marginal contributions of firms. As a result, firms with a large ex-ante marginal contribution have an incentive to limit the entry of firms with a small ex-ante marginal contribution. Second, standard sponsors have *strategic incentives* when choosing coalitional partners: the profit of the sponsors of a standard depends on the value of competing standards. Thus, sponsors may choose their partners to reduce the value of competing standards. This effect is similar to a raising rivals' cost strategy in non-cooperative games (Salop and Scheffman, 1983), and is particular to the case of standard wars.

The definition of stable allocation with ex-ante agreements is as follows.

Definition 4 (Stable allocation with ex-ante agreements)**.** *A coalition c blocks allocation a with associated sharing rule w if for any allocation a' that contains c, $\sum_{i \in c} w_i < H(c, a')$. Allocation a, with associated sharing rule w, is stable if a coalition blocking it does not exist.*

Proposition 4 discusses the effects of ex-ante agreements in standards wars.

Proposition 4 (Ex-ante agreements in standards wars)**.** *The stable allocation with ex-ante agreements leads to maximum industry profits, but may be inefficient. Stable allocations with fixed sharing rules may provide higher or lower welfare than stable allocations with ex-ante agreements.*

Proposition 4 shows that, ex ante agreements are always good from an industry perspective. However, in the case of standards wars, industry interests may not be aligned with society's, and therefore, ex ante agreements may lead to a reduction in social welfare. Examples 1 and 2 show two cases in which profits and welfare move in opposite directions.

Example 1: Winner-takes-all industry. Following Rosenberg (1982) and Choi (1996), suppose that the value of a standard is uncertain, but that its distribution is affected by the technologies it includes. Let v be the social value of a standard, and let $F(v\,,\, c)$ be the cumulative density function of a standard proposed by coalition c. Assume that the values of different standards are independently distributed and that value realizations are not known until all standards have been proposed and implemented.

In this example, we assume that strong network effects lead to a winner-takes-all outcome (Besen and Farrell, 1994; Shapiro and Varian, 1999). Even though many standards may compete for adoption, only the standard with the highest value realization is adopted by users. Finally, assume that sponsors of the winning standard capture quasirents equal to $\pi(v) \leq v$, which are non-decreasing in v.

The timing of the game is as follows. First, firms form coalitions. Second, value realizations are known. Third, the standard with the highest value realization is adopted by users, and its sponsors capture and distribute quasirents.

Consider first an allocation with only one coalition, $a = \{c\}$. The welfare of this allocation is the expected value of the standard:

$$W(a) = \int_0^{\overline{v}} v \; dF(v, c), \tag{1}$$

and the expected profit of coalition c is

$$H(c, a) = \int_0^{\overline{v}} \pi(v) \; dF(v, c), \tag{2}$$

which is the same as total industry profits.

Consider now an allocation with two coalitions, $a = \{c, c'\}$. Welfare is the expected value of the best standard:

$$W(a) = \int_0^{\overline{v}} v \; d(F(v, c)F(v, c')),$$

which integrating by parts becomes

$$W(a) = \int_0^{\overline{v}} \Big(1 - F(v,\, c)\; F(v\,,\, c')\Big)\; dv. \tag{3}$$

The expected profit of a coalition c in an allocation $a = \{c, c'\}$ is

$$H(c, a) = \int_0^{\overline{v}} \pi(v)\, F(v, c')\, dF(v, c),$$

and total industry profits are

$$H(c, a) + H(c', a) = \int_0^{\overline{v}} \pi(v)\, F(v, c')\, dF(v, c) + \int_0^{\overline{v}} \pi(v)\, F(v, c)\, dF(v, c'),$$

which integrating by parts become

$$H(c, a) + H(c', a) = \int_0^{\overline{v}} \pi'(v)\; \Big(1 - F(v,\, c)\; F(v\,,\, c')\Big)\; dv. \tag{4}$$

Comparing equations (1) and (2) and equations (3) and (4), it is easy to see why total industry profits may be different from welfare. Firms care about $\pi(v)$ instead of v, which may lead them to form socially inefficient coalitions.

To find an example of a socially inefficient stable allocation with ex-ante agreements consider a situation with two firms, 1 and 2. There are three possible coalitions: $c_1 = \{1\}$, $c_2 = \{2\}$, and $c_{12} = \{1, 2\}$. It suffices to consider two allocations: $a = \{c_1, c_2\}$ and $a' = \{c_{12}\}$. Suppose that coalition c_k has a distribution that leads to $v = 0$ with probability 1/2 and $v = v_k$ with probability 1/2, and assume that $v_{12} > v_1 > v_2$, that is, the standard based on the patents of both firms is better than the standard based on the patents of firm 1, which is better than the standard based on the patents of firm 2. Finally, assume that $\pi(v)$ is a increasing and convex function of v, and that each firm has only one patent.

It is straightforward to calculate the welfare of the two allocations:

$$\begin{aligned} W(a) &= \frac{1}{2}v_1 + \frac{1}{4}v_2, \\ W(a') &= \frac{1}{2}v_{12}. \end{aligned}$$

With equal sharing (or patent-based sharing), firm 1 obtains $\frac{1}{2}\pi(v_1)$ in allocation a, and $\frac{1}{4}\pi(v_{12})$ in allocation a'. Suppose that

$$\frac{1}{2}v_1 + \frac{1}{4}v_2 > \frac{1}{2}v_{12},$$

which means that the socially efficient allocation is a, and also suppose that

$$\frac{1}{2}\pi(v_1) > \frac{1}{4}\pi(v_{12}),$$

which means that firms 1 and 2 would form the efficient allocation under equal sharing. If

$$\frac{1}{2}\pi(v_1) + \frac{1}{4}\pi(v_2) < \frac{1}{2}\pi(v_{12}),$$

then the stable allocation with ex ante agreements is a'. This condition is met if $\pi(v)$ is sufficiently convex. Thus, ex ante agreements may lead to inefficient standards, and may even be worse from a welfare point of view that fixed sharing rules.

Example 2: Bertrand Price Competition. Consider now a situation where two standards may survive in the industry, and welfare is given as in the previous example by the expected value of the best standard. Social welfare is still given by equation (1) when the allocation has one coalition, and (3) when the allocation has two coalitions.

Suppose there is a continuum of adopters of mass one, who have a willingness to pay for the standard equal to v, where v is the value realization from $F(v, c)$. Standards engage in Bertrand competition and the sponsors of the standard with larger value are able to extract rents equal to the difference in value between their standard and their competitor's.

If the allocation has only one coalition, profits are given by equation (2), with $\pi(v) = v$. If the allocation $a = \{c, c'\}$ has two coalitions, the expected profit of coalition c is

$$H(c, a) = \int_0^\infty \int_{\hat{v}}^\infty (v - \hat{v})\, f(v, c)\, f(\hat{v}, c')\, dv\, d\hat{v}.$$

Consider an example based on the functional forms given in the previous example. Recall that the efficient allocation is a. With equal sharing, firm 1 obtains $\frac{1}{4}v_1 + \frac{1}{4}(v_1 - v_2)$ in allocation a and $\frac{1}{4}v_{12}$ in allocation a'. Assume that

$$\frac{1}{4}v_1 + \frac{1}{4}(v_1 - v_2) > \frac{1}{4}v_{12},$$

which means that firms 1 and 2 form the efficient allocation a with equal sharing. Total profits with allocation a are

$$\frac{1}{4}v_1 + \frac{1}{4}(v_1 - v_2) + \frac{1}{4}v_2 = \frac{1}{2}v_1,$$

and with allocation a' total profits are

$$\frac{1}{2}v_{12},$$

which is always larger than $\frac{1}{2}v_1$. Thus, with ex-ante agreements, firms form allocation a', which is inefficient.

The above examples show that ex ante agreements may lead to inefficient standards, and may reduce welfare in comparison with fixed-sharing rules. Thus, ex-ante agreements are not guaranteed to be welfare improving in the case of standards wars. This result contrasts with the findings of previous works studying monopoly standards (Llanes and Poblete, 2014; Lerner and Tirole, 2015). The reason is that there exist limits to efficient bargaining: the sponsors of one standard cannot make or receive transfers to or from the sponsors of competing standards or the standards' adopters.

In the following section, we show conditions under which allowing firms to join more than one standard restores the efficiency of ex-ante agreements.

4. Multiple standard membership

In this section we study the standard-setting process when firms can participate in more than one standard. We show that if the first-best allocation implies a connected network of standard sponsors, ex-ante agreements unambiguously lead to efficient standards.

As in the previous section, an allocation is a set of coalitions. However, an allocation may now include more than two coalitions, and coalitions with non-empty intersection. Let A be the set of all possible allocations.

For each allocation, we can construct an *undirected graph*, in which firms are nodes, and two firms have a link or edge connecting them if they are members of the same coalition. Firms i and j are connected in there exists a path of links connecting them. Thus, two firms that belong to different coalitions may be connected through a sequence of direct links. An allocation is connected if any two members of any two coalitions in the allocation are connected.

As before, firms can only distribute revenues within a coalition. However, they may now make implicit transfers to firms in other coalitions by organizing a sequence of payments between connected firms.

A sharing rule is a vector $w = (w_i)_{i \in I}$ where w_i is the total expected payoff of firm i in allocation a. Let $H(c, a)$ be the total quasirents of coalition c in allocation a. A sharing rule is feasible with respect to allocation a if there exists a partition of a into connected allocations $\{a_1, a_2, \ldots, a_K\}$ such that $\sum_{i \in x_k} w_i \leq \sum_{c \in a_k} H(c, a)$ for all a_k in the partition, where $x_k = \cup_{c \in a_k} c$ is the set of all sponsors of the coalitions in a_k.

Definition 5. *A connected allocation b blocks allocation a with sharing rule w if for any allocation a' that contains b, $\sum_{i \in x_b} w_i < \sum_{c \in b} H(c, a')$, where $x_b = \cup_{c \in b} c$. Allocation a, with associated sharing rule w, is stable if it is not blocked by any connected allocation.*

In contrast with previous sections, a deviation may now involve a set of coalitions, that is, an allocation. Firms in coalitions in the deviating allocation can coordinate and redistribute profits among them. In order for the coordination between firms in different standards to be possible, we assume that the deviating allocation must be connected.

Let $W(a)$ be the social value of allocation a, and let A^* be the set of first best allocations,

$$A^* = \{a \in A \mid \nexists\, a' \neq a \text{ such that } W(a') > W(a)\}.$$

We have the following proposition.

Proposition 5. *If there exists a connected first-best allocation, all stable allocations are first-best allocations.*

Intuitively, if an allocation is not first best, it leads to lower total industry profits than the first-best allocations. Firms in the connected first-best allocation can form this allocation and distribute the larger industry profits in a way that makes all the sponsors of the inefficient allocation better off. Thus, if there exists a connected first-best allocation, there cannot be an inefficient stable allocation.

Proposition 5 shows that ex-ante agreements are desirable from a welfare perspective when the standard-setting process is open and collaborative. This proposition also shows it is valuable to have "umbrella" firms participating in multiple standard-setting efforts, because these firms can serve as indirect links between firms with narrower interests.

5. Conclusion

In this paper, we develop a model of coalition formation and technology choice in standard setting, and address the following questions: (i) How does the competition between groups of technology sponsors affect the standard-setting process? (ii) What is the effect of ex-ante agreements on technology choice and efficiency in standards wars?

We present five main results. First, we show that previous results studying the effects of ex-ante agreements in monopoly standards extend to the case in which firms' patent portfolios are heterogeneous. In particular, we show that ex-ante agreements improve welfare in the case of monopoly standards, and are thus desirable from a social point of view.

Second, we show that industry interests may not coincide with the interests of individual firms. Ex-ante agreements increase total industry profits, but some firms may be worse off relative to per capita or patent-based profit-sharing rules.

As a consequence, some firms may oppose ex-ante agreements, even in cases where they improve welfare and total industry profits.

Third, we show that rules that distribute profits based on the number of patents may not improve welfare, relative to per capita sharing rules, even if firms' marginal contributions are increasing in the number of patents. Thus, patent-based sharing rules may not be a good substitute of ex-ante agreements, even when the number of patents is a relatively good indicator of the value of patent portfolios.

Fourth, we find that allowing ex-ante agreements may decrease welfare in the case of standards wars. Even though total industry profits are larger with ex-ante agreements, welfare is not necessarily larger because the interests of firms and society may not be aligned.

Thus, it is important to interpret earlier results with caution. In particular, previous works (Llanes and Poblete, 2014; Lerner and Tirole, 2015), showed that in the case of monopoly standards, the interests of firms and society are always aligned, and thus, ex-ante agreements are welfare improving. We show that this result no longer holds in the case of standards wars, unless we impose additional restrictions on the standard-setting process.

Finally, we find that if firms can participate in multiple standards, and the first-best allocation leads to a connected network of standard sponsors, ex-ante agreements lead to better standards and higher welfare. Thus, it is valuable to have "umbrella" firms participating in multiple standard-setting efforts, because these firms can serve as indirect links between firms with narrower interests. This is the case of HP and Sun, for example, which are involved in the development of over 150 standards at a given time (Updegrove, 2003).

Our findings contribute to the recent debate on the optimal rules of standard-setting organizations. Antitrust enforcement agencies and standard-setting organizations are currently discussing whether licensing agreements should be allowed at the standard-setting stage. We show that ignoring the fact that standards arise from competition between endogenously-formed groups of firms may lead to wrong conclusions about the welfare effects of ex-ante agreements. We also show that the problems that ex-ante agreements pose for efficient technology choice in standards wars may be overcome by introducing rules that guarantee an open and widespread participation of firms with standard-related technologies in the standard-setting process. These rules may help prevent technological hold up and ex-post patent litigation, which are a significant concern, since they lead to large litigation costs, as the cases of Rambus and Qualcomm exemplify. More recently, Apple and Samsung have spent over a billion dollars in the ongoing smartphone war, which is partly related with patents covering the 3G standard. These litigation costs are significant, not only because they may affect the resources devoted to research and development, but also because they may influence the formation of subsequent standards, such as the 4G standard in the case of mobile telecommunications.

We also contribute to the literatures of coalition formation and equal-sharing partnerships (Farrell and Scotchmer, 1988; Levin and Tadelis, 2005; Poblete, 2015) by providing novel existence results and characterizing stable allocations in the presence of externalities, both with a fixed distribution of output and when the distribution of output is endogenous.

We conclude by discussing potential extensions and directions for further research. First, even though most SSOs do no allow *explicit* ex-ante licensing discussions, many of them allow (or require) FRAND (fair, reasonable and non-discriminatory) licensing commitments. FRAND commitments have been criticized for being subjective and ambiguous, since firms may differ in the level of licensing fees they consider "fair and reasonable." Recently, some researchers and judges have interpreted FRAND licenses as the license fee that should be charged based on ex-ante marginal contributions (Swanson and Baumol, 2005; Farrell et al., 2007; Layne-Farrar et al., 2007; Dehez and Poukens, 2013). However, it is important to note that FRAND licenses may be subject to greater uncertainty and higher litigation costs, which may affect technology choice if standards' sponsors try to avoid future disputes. Thus, explicit ex-ante licensing agreements will generally have different implications for the formation of standards from implicit licensing commitments such as FRAND.

Second, if a patent pool with standard-essential patents fails to form after the standard is set, fragmentation of intellectual property rights may lead to inefficiencies due to royalty stacking and transaction costs. We have abstracted from this problem by assuming that firms form a patent pool after the standard is set. In Llanes and Poblete (2014) we studied the relation between standard-setting and patent-pool formation, and showed that ex-ante agreements may improve the stability of patent pools if firms can negotiate their participation in the patent pool at the standard-setting stage. All our results on the efficiency of ex-ante agreements in standards wars hold under this assumption.

Third, the standard setting process may imply bargaining costs, which may depend on the number of sponsors of the standard and on the structure of intellectual property rights. Bargaining costs may affect our results in several ways. On one hand, firms may prefer to join standards with higher dispersion of IPRs because this guarantees that all firms have an equal footing when negotiating standards. On the other hand, firms may prefer to join standards with clear technological leaders and concentrated IPR ownership because this may reduce uncertainty and speed up the standard-setting process. The overall effect of incorporating bargaining costs is ambiguous, which presents an interesting direction for further research.

Fourth, we have focused on technology choices that are difficult to reverse after the standard is defined. However, some technologies may be easy to substitute, even after the standard is set. These technologies do not impose a serious threat to efficient standard formation, because the possibility of substitution limits the bargaining power of the firms sponsoring these technologies. Our results will hold as long as technologies become harder to substitute after they are included in a standard.

Fifth, our paper discusses optimal technology choice taking the set of existing patents as given. Recent papers have studied how standard-setting rules may affect incentives for innovation (Dequiedt and Versaevel, 2013; Cabral and Salant, 2013; Layne-Farrar et al., 2014). Incorporating incentives for innovation in a model of coalition formation and technology choice is another venue for future research.

Finally, we have assumed that standards wars are fought between coalitions in different SSOs, but competition between groups of firms sponsoring different technologies is intense even *within* SSOs. For example, the Task Group n (TGn) and the World-Wide Spectrum Efficiency Group (WWiSE) competed for control of the 802.11n Wi-Fi standard within IEEE (DeLacey et al., 2006). Our results extend directly to a model of coalition-formation within SSOs.

Appendix: Proofs of theorems in text

Proof of Proposition 1. To prove the existence of a stable allocation with per capita profit distribution, observe that $\widetilde{c} \in \arg\max_{c\in C} h(c)$ exists and is generally unique since C is a finite set. The coalition $\widetilde{c}$ is stable since since if there exists c' that blocks $\widetilde{c}$ it must be the case that $h(c') > h(\widetilde{c})$, which is impossible by the definition of $\widetilde{c}$. To show generally uniqueness notice that $\widetilde{c}$ blocks any coalition c' that does not belong to the $\arg\max_{c\in C} h(c)$, which is generally unique.

To prove the existence of a stable allocation with patent-based sharing, consider $\widehat{c}$ optimal in $\max_{c\in C} \frac{1}{\sum_{j\in c} n_j} H(c)$, then for any any firm i in $\widehat{c}$, it holds that

$$g_i(\widehat{c}) = n_i \frac{1}{\sum_{j\in \widehat{c}} n_j} H(\widehat{c}) \geq g_i(c) = n_i \frac{1}{\sum_{j\in c} n_j} H(c),$$

which implies that $\widehat{c}$ is stable. To show that the coalition is generally unique, notice that the solution to the problem $\max_{c\in C} \frac{1}{\sum_{j\in c} n_j} H(c)$ is generally unique and that $\widehat{c}$ blocks any coalition that is not a solution to this problem.

To show that the fact that marginal contributions are increasing in the number of patents does not imply that any fixed-sharing rule is better from a welfare perspective is enough to show two examples, one where per capita sharing rules dominate patent-based rules, and one where patent-based sharing rules dominate per capita rules.

Suppose first that there are three firms. Firm 1 has ex-ante essential technologies, and firms 2 and 3 do not. Suppose that $n_1 = 10$, $n_2 = 10$, $n_3 = 2$, $H(\{1\}) = 4$, $H(\{1,2\}) = 10$, $H(\{1,3\}) = 8$, and $H(\{1,2,3\}) = 10$.

Observe that n_j is increasing in m_j. With per patent distribution if the coalition (1,2) is formed, firm 1 obtain profits of $\frac{1}{2}10$. If the coalition (1,3) is formed firm 1 obtains $\frac{10}{12}8 > 5$. It straightforward to check that the only stable allocation is (1,3), any other allocation is blocked by firm 1. With per capita distribution if the coalition (1,2) is formed, firm 1 obtains $\frac{1}{2}10$. If the coalition (1,3) firm 1 obtains $\frac{1}{2}8 < 5$. It straightforward to check that the only stable allocation is (1,2). In this example per capita sharing rule leads to a more efficient standard. (Although both are socially inefficient). Now assume that the essential firm has 100 patents and generates revenues of 14 if it does not include other firms in the standard. Observe that n_j is increasing in m_j . With per patent distribution if the coalition (1,2) is formed, the essential gets $\frac{100}{110}10 > 6$. If the coalition (1,3) is formed the essential gets $\frac{100}{19}8 < \frac{100}{110}10$. It straightforward to check that the only stable allocation is (1,2). With per capita distribution if the coalition (1,2) is formed, the essential gets $\frac{1}{2}10 < 6$. If the coalition (1,3) is formed the essential gets $\frac{1}{2}8 < 6$. It straightforward to check that the only stable allocation is the essential alone.

In this example per patent sharing rule leads to a more efficient standard. To show that they may be inefficient notice in the first example above that both per capita and per patent are inefficient.

To show that if per-patent marginal contributions are increasing in the number of patents, patent-based sharing implies higher industry profits and welfare than equal sharing first notice that if n_j is increasing in $\frac{m_j}{n_j}$ then firms with larger marginal contributions have more patents, and a larger contribution per patent. That means that if in any coalition firm j is accepted, it must satisfy

$$\frac{m_j}{n_j} \geq \frac{H(c)}{\sum_{i \in c} n_i}.$$

Then $m_h > m_j$ implies $\frac{m_h}{n_h} \geq \frac{H(c)}{\sum_{i \in c} n_i}$ and firm h must be accepted on the coalition as well. So without loss of optimality the stable coalition can be constructed as in Farrell and Scotchmer (2003), recursively starting from the most productive firms. Because with both sharing rules, firms can be included in the same order to find the stable allocation, it suffices to show that the a stable coalition with per patent distribution is always weakly larger than with per capita.

First assume that firms are ranked according to their productivity. And assume firm j is included in a coalition that has per capita sharing rule. Then it must be the case that

$$m_j \geq \frac{H(c)}{|c|},$$

dividing by n_j

$$\frac{m_j}{n_j} \geq \frac{H(c)}{n_j |c|}.$$

Now notice that $n_i \geq n_j$ for every i in the coalition, so $n_j c \leq \sum_{i \in C} n_i$ and thus

$$\frac{v_j}{n_j} \geq \frac{H(c)}{n_j |c|},$$

so firm j is also included with per patent sharing rule. ∎

Proof of Proposition 2. To prove existence with ex-ante agreements consider $\widetilde{c}$ optimal in $\max_{c \in C} H(c)$ and a sharing rule that assigns all surplus to the essential firm (or equally among the subset of essential firms). Clearly coalition $\widetilde{c}$ can't be blocked as the essential firm can't receive larger payment in any other coalition.

To prove that the equilibrium with ex-ante agreement maximizes social welfare, suppose by contradiction that c' is stable with ex-ante agreements and doesn't maximize social welfare. By monotonicity this implies $H(c') < H(\widetilde{c})$. Let s be the set of firms in the intersection of $\widetilde{c}$ and c' and $|s|$, the cardinality of s. Consider coalition $\widetilde{c}$ with the following sharing rule $w_i(\widetilde{c}) = 0$ if i does not belong to s and $w_i(\widetilde{c}) = w_i(c') + (H(\widetilde{c}) - H(c'))/|s|$ for firms in s. This sharing rule improves payment for all members of c' and therefore c' is blocked. ∎

Proof of Proposition 3. Consider first per capita sharing rule. Let C be the set of all possible standards and $C\backslash c$ the set of all standards that can be formed excluding firms in c. Let $r(c)$ be the coalition that maximizes the per-capita revenues of the firms that are not in c, formally

$$r(c) = \underset{z \in C\backslash c}{\operatorname{argmax}}\ H(z, \{c, z\}).$$

We will refer to $r(c)$ as the reactive coalition. If $C\backslash c = \varnothing$, we write $r(s) = \varnothing$. Let c^* be defined as follows

$$c^* = \underset{c \in C}{\operatorname{argmax}}\ H(c, \{c, r(c)\}).$$

We refer to $a^* = \{c^*, r(c^*)\}$ as the reactive allocation.[9] We show that a^* is stable and may be inefficient.

Suppose it is not stable. Then, there exists a coalition c' that blocks this allocation. The blocking standard either contains sponsors of c^*, sponsors of $r(c^*)$, or both. Otherwise, three standards of positive value can be created, which violates the duopoly assumption.

Suppose first that c' contains a sponsor of c^*. Then, it must be the case that $H(c', \{c', z\}) > H(c^*, \{c^*, r(c^*))$ for every $z \in C\backslash c'$. By definition, $r(c') \in C\backslash c'$, thus $H(c', \{c', r(c')\}) > H(c^*, r(c^*))$, which violates the definition of c^*.

Suppose now that c' contains sponsors of $r(c^*)$ but not sponsors of c^*. Then for c' to block the allocation it must be the case that $H(c', \{c', z\}) > H(r(c^*), \{r(c^*), z\})$

[9] The reactive allocation is akin to a Stackelberg solution in a non-cooperative game. Notice, however, that the cooperative game we are studying makes no assumptions on the timing and structure of the coalition-formation process. In a previous version of the paper, we showed that the reactive allocation can be obtained as an equilibrium of a non-cooperative sequential coalition-formation game based on Bloch (1996).

for every $z \in C \backslash r(c')$. We already proved that the sponsors of c' cannot be in c^*, thus it must be the case that $H(c', \{c', c^*\})\ h > H(c^*, r(c^*))$, which violates the definition of $r(c^*)$. Therefore, a blocking standard cannot exist. The existence proof for per patent sharing rule is analogous and therefore omitted.

To show they can both be inefficient, consider a situation with three firms $i, j$and k. All of them have the same number of patents, so per capita and per patent sharing rules are equivalent. Possible coalitions are $c_1 = \{i, j, k\}$, $c_2 = \{i, j\}$, $c_3 = \{i, k\}$ $c_4 = \{j, k\}$, and firms alone. Assume that it is efficient to have only one coalition c_1, but $H(i, \{i, c_4\}) > \frac{1}{3}H(c_1)$ so the grand coalition is never stable because firm i always deviates to avoid sharing equally with j and k. ∎

Proof of Proposition 4. Remember that we assume that for all $a = \{c, c'\} \in A$ and all $i \notin c \cup c'$, either $H(c \cup i, \{c \cup i, c'\}) + H(c', \{c \cup i, c'\}) > H(c, \{c, c'\}) + H(c', \{c, c'\})$, or $H(c, \{c, c' \cup i\}) + H(c' \cup i, \{c, \{c' \cup i\}) > H(c, \{c, c'\}) + H(c', \{c, c'\})$, or both. For the purpose of this proof we refer to this assumption as assumption 1.

Let

$$\begin{aligned} b(c) &= \underset{z}{\operatorname{argmax}}\, H(z, \{c, z\}), \\ \widehat{c} &= \underset{s}{\operatorname{argmax}}\, H(s, \{s, b(s)\}) + H(b(s), \{s, b(s)\}) \end{aligned}$$

Choose any pair $\widehat{c}, b(\widehat{c})$ that satisfy this definition and notice that $\widehat{c} \cup b(\widehat{c}) \supseteq I$. This is true because $b(\widehat{c})$ by construction satisfies $b(\widehat{c}) = \operatorname{argmax}_z H(z, \{\widehat{c}, z\})$, and therefore by the assumption that revenue is increasing in the number of firms, $b(\widehat{c})$ includes all firms outside $\widehat{c}$.

First notice that $\{\widehat{c}, b(\widehat{c})\}$ maximizes overall industry profits. Suppose not, and industry profits are maximized by $\{c_1, c_2\}$. Notice first that by assumption 1, it must be the case that $c_1 \cup c_2 \supseteq I$. This means that $c_2 = b(c_1)$ but then by definition of $\widehat{c}$ overall industry profits are no less with $\{\widehat{c}, b(\widehat{c})\}$ than with $\{c_1, b(c_1)\}$.

Suppose now that an allocation $\tilde{a} = \{\widetilde{c}_1, \widetilde{c}_2\}$, with associated sharing rule w, is stable. Then, this allocation cannot be blocked by $\widehat{c}$ or $b(\widehat{c})$, which implies that:

$$\begin{aligned} \sum_{i \in \widetilde{c}_1} w_i &\geq \min_{z \in R(\widehat{c})} H(\widehat{c}, \{\widehat{c}, z\}), \\ \sum_{i \in \widetilde{c}_2} w_i &\geq \min_{z \in R(b(\widehat{c}))} H(b(\widehat{c}), \{z, b(\widehat{c})\}). \end{aligned}$$

The fact that revenues are decreasing in the quality of the competing standard implies:

$$\min_{z \in R(\widehat{c})} H(\widehat{c}, \{\widehat{c}, z\}) = H(\widehat{c}, \{\widehat{c}, b(\widehat{c})\}),$$

by construction $\widehat{c}$ includes all patents in $R(b(\widehat{c}))$ therefore,

$$\min_{z \in R(b(\widehat{c}))} H(b(\widehat{c}), \{b(\widehat{c}), z\}) = H(b(\widehat{c}), \{\{\widehat{c}, b(\widehat{c})\}\}),$$

as a result

$$H(\widetilde{c}_1, \{\widetilde{c}_1, \widetilde{c}_2\}) + H(\widetilde{c}_2, \{\widetilde{c}_1, \widetilde{c}_2\}) \geq H(\widehat{c}, \{\widehat{c}, b(\widehat{c})\}) + H(b(\widehat{c}), \{\{\widehat{c}, b(\widehat{c})\}\}).$$

Because $\{\widehat{c}, b(\widehat{c})\}$, achieve the maximum possible industry profits , so must $\{\widetilde{c}_1, \widetilde{c}_2\}$.

To see that they may be socially inefficient and a comparison with fixed sharing rules, see the examples 1 and 2 in the text. ∎

Proof of Proposition 5. Let a^* to be a first best connected allocation. Take a to be an allocation that is not first best and let w_i be the expected payment that firm i receives in such an allocation. Feasibility requires

$$\sum_{c \in a} H(c, a) = \sum_{i \in I} w_i.$$

Notice that it must be the case that a^* includes all standards of a that creates positive value and at least one more non trivial standard. If a^* does not include a standard of positive value it cannot maximize expected welfare. Therefore the expected industry profits under allocation a^* is

$$\sum_{c \in a^*} H(c, a) > \sum_{c \in a} H(c, a).$$

Define $\Delta = \sum_{c \in a^*} H(c, a) - \sum_{c \in a} H(c, a)$. Consider allocation a^* as a coalition (this can be done because a^* is connected, with expected payment $\widehat{w}$ defined as follows. $\widehat{w}_i = w_i + \frac{\Delta}{I}$. This expected payments satisfy budget constraint under any belief system because all standards with positive value are included in the coalition, moreover every firm is strictly better off, therefore allocation a is blocked. ∎

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