TECHNOLOGY CHOICE AND COALITION FORMATION IN STANDARDS WARS*

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Abstract. We study coalition formation and technology choice in standard setting, and shed light on how competition and licensing rules affect the standard-setting process. 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. We also show that ex-ante licensing 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 those of previous works studying monopoly standards. We 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 these are the case rather than the exception.[1] Chiao, Lerner, and Tirole (2007) show there is an average of fifteen standard-setting organizations (SSOs) per technology subfield, often proposing competing standards.

Recent works argue that the prospect of hold up from standard-essential patents may lead to inefficient standards (Farrell, Hayes, Shapiro, and Sullivan, 2007; Schmalensee, 2009).[2] Allowing firms to sign licensing contracts before standards are defined may solve this problem, but most SSOs have traditionally forbidden or discouraged ex-ante licensing discussions out of concern for potential antitrust exposure.[3] More recently, some SSOs have reconsidered this position and have received encouraging support from the Department of Justice and the Federal Trade Commission (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 only one standard exists (monopoly-standard 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 all 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 standard-setting process is a coalition-formation problem with inter-group externalities (Aumann and Peleg, 1960; Thrall and Lucas, 1963; Myerson, 1978;

[1] Even the well-known video-format war between VHS and Betamax was not fought solely by JVC and Sony, as it is usually conceptualized: VHS was supported by 39 firms and Betamax by 12 firms (Cusumano, Mylonadis, and Rosenbloom, 1992). Likewise, the wireless-communications standards war between WCDMA and CDMA2000 was fought between coalitions of firms (Leiponen, 2008).

[2] Patents are becoming increasingly important for standards (Rysman and Simcoe, 2008; Baron, Blind, and Pohlman, 2013). As a consequence, regulators and firms are becoming more concerned about patent hold up. The FTC has taken action against several firms, including Dell Computer (FTC file no. 931-0097), Rambus (FTC docket no. 9302), and Negotiated Data Solutions (FTC file no. 0510094) for conducts related to patent hold up. See also Broadcom Corp. v. Qualcomm Inc., 501 F.3d 297 (3d Cir. 2007).

[3] 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."

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 study coalition formation and technology choice in standard setting to shed light on how competition and licensing rules affect the standard-setting process. We 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 holding patents on standard-related technologies form coalitions to develop standards. We consider two cases. First, we study a monopoly-standard setting in which only one standard exists. 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. In the case of Rambus, for example, the FTC argued that Rambus's technologies may have not been adopted by JEDEC if Rambus had disclosed its patents while the standard was been developed, but that they became difficult to substitute after the standard was set because at this time manufacturers had made significant sunk investments in these technologies. Likewise, in the case of Dell, the FTC claimed that VESA members could have adopted an alternative technology for the VL-Bus standard had they known of Dell's patents.[4]

The profits of a coalition of firms depend on the complete allocation of firms into coalitions, but the *distribution* of profits within a coalition depends on the type of contracts available to firms. We consider three cases. First, we assume 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 firms can sign ex-ante agreements, in which case the distribution of profits is endogenously negotiated between standard sponsors.

[4]See "In the Matter of Rambus, Inc.," 2006-2 Trade Case (CCH) P 75364 4 (FTC August 2, 2006), "Rambus, Inc. v. FTC," 522 F.3d 456 (D.C. Cir. 2008), and "Dell Computer Corp.," (FTC file no. 931-0097).

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 proportional 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 proportional 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) identify proportional sharing rules as an important issue for future research.

Our paper has two main results. First, 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, proportional 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.

Second, we show 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.

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 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, and extend previous results to proportional profit sharing rules. In Sections 3 to 5 we study competition between standards proposed by competing coalitions. In Section 6 we present the main conclusions of the paper and discuss potential directions for further research.

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.

In this section, we assume some of the firms in I hold patents that are essential for any implementation of a standard. As a consequence, at most one standard may be formed in equilibrium. In the next section, we study competition between standards.

Standardization affects the relative importance of firms' marginal contributions. The reason is that, in order to conform to a standard, adopters must follow the standard's technical specifications. Thus, even though some technologies may not be essential from an *ex-ante* perspective (before the standard is defined), all technologies included in a standard become essential for its implementation *ex-post*.[5]

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 the sponsors of a standard form a patent pool and delegate pricing decisions on a pool administrator, who then distributes quasirents among pool members.[6]

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 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 $c \subset c'$.[7] Our model accounts for the fact that some firms may have redundant or substitute patents. What we assume is that each firm involved in the standard-setting process has at least one valuable patent, and thus, can potentially increase the private and social value of a standard.[8]

[5] Consider Rambus's and Dell's cases discussed in the introduction. The assumption of perfect ex-post essentiality is not essential for our results. All we need to assume is that standardization process redistributes profits from firms with high ex-ante marginal contributions to firms with low ex-ante marginal contributions.
[6] 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 stable patent pools that are unstable otherwise. Thus, allowing for endogenous patent-pool formation would only strengthen our results.
[7] These general functional forms for profits and welfare can represent a variety of situations. For example, they may represent a model in which the demand for final goods based on the standard is $v(c) - P$, where $v(c)$ is a demand parameter which depends on the coalition of standard's sponsors c and P is the sum of licensing fees to be paid to standard-essential patent holders. If patent holders form a patent pool, the optimal price is $v(c)/2$, $H(c) = v(c)^2/4$, and $W(c) = 3\,v(c)^2/8$.
[8] The model can easily be modified to allow for firms that do not add value to a standard (that is, $H(c') \geq H(c)$ or $W(c') \geq W(c)$ for some $c \subset c'$). The main results of the model would not change (e.g., there would still exist an efficient stable allocation with ex-ante agreements). The only difference is that if $H(c') \geq H(c)$ for some $c \subset c'$, the stable allocation with ex-ante agreements may not be unique.

The distribution of quasirents among standard's sponsors depends on the types of contracts available to firms. We study three types of licensing contracts and sharing rules. Studying these rules is important because variants of these rules have been proposed as ways to split revenues in SSOs and antitrust negotiations.

First, we assume 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 on *per-capita* terms, and the profit of a firm in coalition c is

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

where $|c|$ is the number of members of c.[9]

Second, we assume firms can trade patents after the standard is defined. As a result, firms share quasirents in proportion to the number of ex-post standard-essential patents they hold (if a firm's share in standard's revenues is below its share of standard-essential patents, it can sell its patent to an outsider, who can then claim a share of revenues), and the profit of firm i in coalition c is

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

where n_i be the number of ex-post standard-essential patents of firm i.

Proportional sharing rules are commonly observed in patent pools (Layne-Farrar and Lerner, 2011). For example, the WCDMA (wireless communications), MPEG-2 and MPEG-4 (audio and video compression), and DVB-T (digital terrestrial television) patent pools have proportional royalty allocations. Proportional sharing rules are easy to implement (they only require determining which patents are essential for implementing the standard) and are invariant to mergers and splitting of the IP owners (Salant, 2009). Given their practical relevance, studying the welfare effects of proportional sharing rules is one of the main contributions of this paper (Llanes and Poblete, 2014, and Lerner and Tirole, 2015, only study per-capita sharing rules).

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

Different types of ex-ante agreements have been proposed to avoid hold up problems. Swanson and Baumol (2005) argue that standard's technologies should be chosen through

[9] Similar arguments have been used to motivate the assumption of equal sharing in partnerships (Farrell and Scotchmer, 1988; Levin and Tadelis, 2005; Poblete, 2015). See Bonatti and Rantakari (2016) for a recent study on how equal-sharing affects project choice in organizations, and Llanes and Poblete (2014) and Lerner and Tirole (2015) for more details on the use of this assumption in standard setting.

ex-ante auctions in which patent holders propose price caps. The VITA Standards Organization (2009), for example, requires firms to declare the maximum royalty rate for their essential patents. Likewise, some standard-related patent pools –such as DVD3C and One-Blue (Blu-ray)– use *value-based royalty distributions*. In the case of One-Blue, for example, royalty shares depend not only on the number of essential patents, but also on the type of patents (physical format patents are given more weight than application format patents) and on firms' contributions to the development of the standard (den Uijl, Bekkers, and de Vries, 2013). Value-based royalty distributions can affect technology choice if they are negotiated before the standard is set.[10]

As in Llanes and Poblete (2014), we study ex-ante agreements as the *core* of a cooperative game with transferable utility, which puts less structure on the types of contracts that firms may sign. For example, ex-ante contracts may include price caps, value-based sharing rules, cross-licensing agreements, and side payments among standards' sponsors.

Let $w = (w_i)_{i \in I}$ be a sharing rule, where w_i is the 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 per-capita and proportional profit distributions imply *fixed sharing rules*, and ex-ante agreements imply *endogenous sharing rules*. 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 study stable coalitions according to the following definition.

Definition 1 (Stable coalitions in monopoly standards). *A coalition c with associated sharing rule w is stable if there does not exist a coalition c' with an associated feasible sharing rule w' such that $w_i' > w_i$ for all firms i in $c \cap c'$.*

In formal terms, with equal sharing a coalition c is stable if there does not exist a coalition c' such that $h(c') > h(c)$, with a proportional sharing rule a coalition c is stable if there does not exist a coalition c' such that $g_i(c') > g_i(c)$ for all $i \in c \cap c'$, and with ex-ante agreements a coalition c is stable if there does not exist a coalition c' such that $\sum_{i \in c'} w_i < H(c')$.

[10]FRAND (fair, reasonable, and non-discriminatory) commitments are another type of ex-ante agreement, but they are generally considered weak and ambiguous since firms may disagree on what is 'fair and reasonable' (see, for example, Department of Justice and Federal Trade Commission, 2007, pp. 46-47). Some researchers and practitioners defend FRAND commitments on the grounds that courts can use ex-ante marginal contributions to calculate FRAND royalty rates when firms fail to reach an agreement. For example, in the case of Apple versus Motorola, Judge Posner argued that "the proper method of computing a FRAND royalty starts with what the cost to the licensee would have been of obtaining, just before the patented invention was declared essential to compliance with the industry standard" (Apple, Inc. and Next Software Inc., v. Motorola, Inc. and Motorola Mobility, Inc., case no. 1:11-cv-08540, June 22, 2012), and the Federal Trade Commission (2011) states that "Courts should cap the royalty at the incremental value of the patented technology over alternatives available at the time the standard was chosen." Similarly, Layne-Farrar, Padilla, and Schmalensee (2007) propose to base 'fair and reasonable' licensing fees on the Shapley value calculated with ex-ante values. Our results extend to FRAND commitments if firms expect them to restrict ex-post licensing negotiations.

We now compare the efficiency of equal sharing and proportional sharing rules. Let $m_i(c) = H(c) - H(c \setminus i)$ be the (ex-ante) *marginal contribution* of firm i in coalition c. We say that *marginal contributions are increasing in the number of patents* if $n_i > n_j$ implies $m_i(c) > m_j(c)$ for all $i, j \in c \subseteq I$, and that *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 (Fixed sharing rules in monopoly standards)**.** *A stable coalition with fixed sharing rules exists. A proportional sharing rule may imply higher or lower industry profits and welfare than a per-capita sharing rule, even if marginal contributions are increasing in the number of patents. If per-patent marginal contributions are increasing in the number of patents, a proportional sharing rule implies higher industry profits and welfare than a per-capita sharing rule.*

A corollary of Proposition 1 is that stable allocations with fixed sharing rules may be socially inefficient. The reason for this result is that the standard-setting process leads to an *equalizing transformation* of the marginal contributions of firms, 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. In the proportional-sharing case, all patents in the standard have the same ex-post marginal contribution, so firms with small and/or valuable patent portfolios may want to avoid joining coalitions with firms with large and/or less-valuable patent portfolios.

Proposition 1 provides theoretical support to the observation that SSO's rules concerning licensing negotiations affect technology choice in standard setting. For example, Layne-Farrar and Lerner (2011) show that patent pools with proportional sharing rules attract fewer members and are less likely to attract firms with high-value patent portfolios. This is important because almost all modern patent pools have been formed to commercialize standard-essential patents, and pool-formation incentives affect standard-setting activities. For example, the conflict between the sponsors of Blu-ray and HD DVD was in part due to differences of opinion on how to distribute patent-pool royalties.

A good example of the effect of the equalizing transformation on standard formation is given by Betamax. Sony preferred to limit the number of members in its coalition (the Betamax coalition had 20 members at its height) in order to avoid the rent-dissipation effect of having more partners (Cusumano et al., 1992; Grindley, 1995), and this strategy had a negative effect on the quality of the standard.[11]

[11] Sony's management later recognized that they should have worked harder to get more companies to support the Betamax format (Cusumano et al., 1992).

Proposition 1 also shows that a proportional sharing rule 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 a proportional sharing rule is more efficient than a per-capita sharing rule, 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. This result is important because proportional sharing rules are widely used in practice.

Next, we compare welfare and industry profits with the different sharing rules.

Proposition 2 (Ex-ante agreements in monopoly standards)**.** *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. Ex-ante agreements are weakly more efficient than fixed sharing rules.*

Stable coalitions with fixed sharing rules may be 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 which technologies to include in the standard. Thus, sponsors will include any firm with positive marginal contribution in the standard.

Proposition 2 extends previous results to the case of proportional sharing rules.[12] To understand the importance of Proposition 2, note that this proposition does not follow from Coase's (1960) theorem, since we do not allow patent holders to sign contracts with adopters. Firms choose technologies to increase their share in quasirents, not to increase social welfare. However, in the monopoly-standards case, ex-ante agreements are efficient because the interests of firms and society are aligned: a higher-quality standard leads to higher profits and higher welfare.

In the next section, we show that the alignment of society's and firms' interests breaks down in the case of competition: ex-ante agreements still allow firms to maximize industry profits but they do not necessarily lead to welfare-maximizing standards. This result has important implications for SSOs and antitrust authorities because it shows that ex-ante agreements are not guaranteed to lead to better standards in the case of standards wars.

[12]This issue was identified as an important direction for further research by Lerner and Tirole (2015): "one would want to account for the puzzling fact that patent pools sometimes use patent counting (shares are related to the number of patents contributed to the pool)."

3. Standards wars

In this section, we study competition between coalitions of standards' sponsors. To focus on the simplest possible case, we assume at most two standards may compete for adoption.[13] 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 most standards wars are fought between two standards (e.g. Blu-ray versus HD DVD in high-definition optical discs, VHS versus Betamax in analog video, RCA versus Columbia in quadrophonic sound, and Sky versus BSB in satellite TV).[14]

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, and let $W(a)$ be the social value of allocation a. Total industry profits in an allocation $a = \{c, c'\}$ are given by $H(c,a) + H(c',a) \leq W(a)$.

We assume 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 coalitions compete to appropriate quasirents, which means that the value captured by one coalition weakly decreases when the standard proposed by the other coalition improves: $H(c_1, \{c_1, c_2'\}) \leq H(c_1, \{c_1, c_2\})$ 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 for all $a = \{c, c'\} \in A$ and all $i \notin c \cup c'$, either $H(c \cup i, \{c \cup i, c'\}) + H(c', \{c \cup i, c'\}) > H(c, \{c, c'\}) + H(c', \{c, c'\})$, $H(c, \{c, c' \cup i\}) + H(c' \cup i, \{c, \{c' \cup i\}) > H(c, \{c, c'\}) + H(c', \{c, c'\})$, or both.

As in the case of monopoly standards, the distribution of quasirents among standard sponsors depends on the types of contracts available to firms, and we study three cases.[15] First, we assume firms cannot sign ex-ante contracts determining profit distribution. Thus, firms distribute profits on *per-capita* terms, and the profit of a firm in coalition c is

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

Second, we assume firms cannot sign ex-ante contracts, but can trade patents after the standard is formed. In this case, firms follow a *proportional* sharing rule, and the profit of firm i

[13] 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.

[14] For simplicity, we assume that standards wars are fought between coalitions in different SSOs. However, 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, Herman, Kiron, and Lerner, 2006). Our results extend directly to a model of coalition-formation within SSOs.

[15] As we explain in the previous section, studying these rules is important from a policy and applied point of view because variants of these rules have been proposed as ways to split revenues in SSOs and antitrust negotiations.

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*.[16] 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 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.[17]

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 any other 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.[18]

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 firms cannot make transfers to firms in other standards, and study stable allocations according to the following definition.

Definition 2 (Stable allocation in standards wars)**.** *A coalition c blocks allocation a with associated sharing rule w if for any allocation a' that contains c, there exists a feasible sharing rule w' such that $w'_i > w_i$ for all firms i in c. 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' that contains c, and all $\hat{c} \in a$ with $\hat{c} \cap c \neq \emptyset$, we have $h(c,a') > h(\hat{c},a)$. In the case of a proportional

[16]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.

[17]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 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.

[18]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.

sharing rule, coalition c blocks allocation a if for all a' that contains c, $\hat{c} \in a$, and $i \in \hat{c} \cap c$, we have $g_i(c, a') > g_i(\hat{c}, a)$. And in the case of ex-ante agreements, coalition c blocks allocation a with associated sharing rule w if for any allocation a' that contains c, $\sum_{i \in c} w_i < H(c, a')$.

Definition 2 extends the definitions used in the literature on equal-sharing partnerships (Farrell and Scotchmer, 1988; Levin and Tadelis, 2005; Poblete, 2015) to account for inter-group externalities. In our model, externalities play an important role because the profit of the sponsors of a standard 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 (Fixed sharing rules in standards wars)**.** *A stable allocation with fixed sharing rules exists and is generally inefficient.*

Stable allocations with fixed sharing rules are generally 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.

Strategic incentives imply that firms will compete strongly to obtain coalitional partners. For example, Intel's support of HD DVD was at the time seen as a big step back for Blu-ray, and TDK's support of Blu-ray was crucial for that standard because TDK provided a hard thin polymer coating (Durabis) which was essential for preventing scratches in the physical discs. Proposition 3 shows that such competition may be inefficient from an industry and welfare point of view when ex-ante agreements are not possible. The following proposition shows that ex-ante agreements allow firms to achieve maximal industry profits, but do not necessarily lead to social efficiency in the case of standards wars.

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

Proposition 4 shows that, in a standards war, ex-ante agreements are always good from an industry perspective but may decrease social welfare. Ex-ante agreements allow standards' sponsors to internalize the pecuniary externalities among them. However, firms do not internalize the effects on adopters' utility. As a result, their decisions may negatively affect social welfare.

The result that coalitions form to maximize industry profits is surprising because firms cannot make side payments across standards.[19] Likewise, the result that ex-ante agreements may not be socially efficient this result does not hold in the case of monopoly standards. Previous works (Llanes and Poblete, 2014; Lerner and Tirole, 2015) recommended ex-ante agreements as a policy rule for SSOs based on their analysis of monopoly standards. In this paper, we show that this recommendation must be interpreted with caution when standards result from competition.

In the following sections, we discuss two reasons for the inefficiency of ex-ante agreements in standards wars. First, we show that when standards compete *for the market*, firms' aggregate risk preferences may differ from society's, and as a consequence the equilibrium allocation may provide too little or too much experimentation from a social point of view.Second, we show that when standards compete *in the market*, sponsors' profits depend on adopters' *relative* valuations, and thus firms may have incentives to choose coalitional partners to decrease the value of competing standards, rather than to increase their own.

4. Experimentation and competition for the market

Rosenberg (1982) and Choi (1996) explain the central role of experimentation in standard setting. Consistent with this view, suppose that the value of a standard is uncertain, but that its distribution is affected by the technologies it includes. Thus, society may benefit from experimenting with different standards (ex-ante) before choosing which standard to adopt (ex-post).

Let $v \in [0, \overline{v}]$ be the social value of a standard, and let $F(v\,,\,c)$ be the cumulative density function of the 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, implemented, and tested by adopters.

To abstract from competition *in the market*, in this section we assume that strong network effects lead to a winner-take-all outcome (Besen and Farrell, 1994; Shapiro and Varian, 1999). Thus, even though many standards may compete for adoption, only the standard with the highest value realization is adopted by users. The sponsors of the winning standard capture quasirents equal to $0 \leq \pi(v) \leq v$, which are non-decreasing in v. This will be the case for example if at the standard negotiation stage, standard sponsors agree to set up a patent pool that will price in order to maximize royalty revenues and firms agree on how to divide the proceeds (this arrangement is known in the industry as an agreement on royalty allocation).

[19] If firms can make side payments across standards, the result follows from Coase's theorem.

In this setting with uncertainty, the monotonicity assumption implies that for every possible state of the world, adding a firm to a coalition does not decrease its value. That is, $F(v, c') \leq F(v, c)$ and $F(\pi(v), c') \leq F(\pi(v), c)$ for all $c \subset c'$. As in previous sections, we assume standards can be ordered in the sense of first order stochastic dominance. Specifically for coalitions c and c' then either $F(v, c') \leq F(v, c)$ or $F(v, c') \geq F(v, c)$.

Our assumptions imply that the value captured by the sponsors of a standard once it wins the market does not depend on the value of competing standards. Although at first this may seem an extreme assumption, it actually fits many industries in which firms cannot credibly commit to long term prices and network externalities are strong.

Consider, for example, the recent video-format war between Blu-ray and HD DVD. Once Blu-ray was adopted in 2007, its pricing and consumption were independent on how well HD DVD would have performed, since strong network externalities prevent HD DVD from being a valid current alternative for customers and downstream developers. The lack of ex-post competition has historically been the case in video-format wars (such as the ones won by VHS, CD, DVD and Blu-ray). In other cases, "in the market" competition has been as important as competition "for the market". In the next section, we study competition "in the market," in which case the value a standard can capture after it wins the market depends on the value of competing standards.

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.

Observe that although profits and welfare have different functional forms, when we consider allocations formed by one coalition, the allocation that maximizes industry profits also maximizes welfare. To see this result clearly, observe that integrating by parts, $W(a) = \int_0^{\overline{v}} (1 - F(v, c))dv$ and so given our monotoncity assumption, the best standard from a welfare perpective satisfies $F(v, c) \leq F(v, \widehat{c})$ for every $v, \widehat{c}$ and thus also maximizes industry profits since $\int_0^{\overline{v}} \pi(v) \, dF(v, c) = \int_0^{\overline{v}} \pi'(v) \, (1 - F(v, c))dv$.

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 becomes

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

If the marginal revenue obtained from the standard, $\pi'(v)$, is constant, then firms capture a constant share of the value they create, and the socially best allocation coincides with the one that maximizes overall profits. However, if $\pi(v)$ is concave or convex, this result no longer holds.

To understand why this is the case, consider a situation in which $\pi(v)$ is convex. In this case, standard sponsors have a greater preference for risk than consumers, and conduct too little exploration from a social point of view.

To see this result in a simple numerical example, suppose there are 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 a standard with value $v = 0$ with probability $1/2$ and $v = v_k$ with probability $1/2$, and assume $v_{12} > v_1 > v_2$. This means 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 $\pi(v)$ is an increasing and convex function of v, and that each firm has the same number of patents.

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.

With equal sharing, coalition formation will be efficient if

$$\frac{1}{2}\,\pi(v_1) > \frac{1}{4}\,\pi(v_{12}), \tag{5}$$

because in this case firm 1 is not willing to share revenues with firm 2, and therefore both standards are introduced in the market. If, on the other hand, it holds that

$$\frac{1}{2}\,\pi(v_1) + \frac{1}{4}\,\pi(v_2) < \frac{1}{2}\,\pi(v_{12}), \tag{6}$$

then the stable allocation with ex ante agreements is a'. Conditions 5 and 6 can hold simultaneously 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 than fixed sharing rules.

In this example allocation a' is too risky for society, because with probability 1/2 implies that finally no value is created as opposed to allocation a in which value is created with probability 3/4. However a' is preferred by firms for the chance of obtaining a higher profit $\pi(v_{12})$ due to the convexity of the profit function.

If the profit function is concave, the opposite result results. Firms expected revenues are larger under less risky distributions, so ex-ante agreements lead to over exploration from the society's perspective.

There are reasonable situations in which profits $\pi(v)$ may be convex and thus $\pi'(v)$ is increasing. For example if there are economies of scale of production and advertising, or fixed costs of enforcing property rights.

It is also possible for $\pi(v)$ to be concave. Suppose, for example, that at some cost counterfeits can be produced. Then if the value created by the standard is too large, the firm owners will not be able to capture all the value by rising prices because that incentivize the production of counterfeit products that don't pay the royalties. If $\pi(v)$ is concave ex-ante agreements may induce excessive exploration. Excessive exploration implies that too many standards are tried in the market at the expense of forming more efficient coalitions.

The model in this section shows the fragility of the results on the efficiency of ex-ante agreements presented by Llanes and Poblete (2014) and Lerner and Tirole (2015). Because adopters are not included in the ex-ante agreement between standards' sponsors, the Coase theorem does not apply. If *for the market* competition is introduced through the possibility to explore, a difference in risk preferences between firms and adopters makes the efficiency results of ex-ante agreements vanish.

From the example it is also clear that *for the market* competition prevents ex-ante agreements from achieving efficiency only if there is uncertainty regarding the value of standards. A formal proof of this point follows directly from equations (3) and (4). In the next example, we show that if there is market competition then inefficiencies can arise in standard's formation even if firms and society have the same risk preferences.

5. Ex-post competition between standards

Consider now a situation where two standards may survive in the industry. 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 ex-post. Thus, the sponsors of the standard with the largest value realization are able to extract rents equal to the difference in value between their standard and their competitor's. For simplicity, also assume standard members form a patent pool that maximizes the standard's royalty revenues.

As in the previous section, social welfare is given by (1) when the allocation has one coalition and (3) when the allocation has two coalitions, and the monotonicity assumption implies that including one more firm in a coalition increases the performance of the standard it sponsors in the sense of weak first-order stochastic dominance.

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

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

The assumptions in this section are reasonable in a market where two standards can survive either because network externalities are not too strong, or because the cost of changing standard are not to large. A market that fits this description is the market for mobile-phone operating systems. The amount of value that Microsoft or Apple can capture with Windows Mobile or iOS depends on the performance of competing operating systems.

With *in the market* competition a new source of inefficiency arise. Because ex-ante agreements maximize industry profits, patents will not be assigned to the standard that creates more value but rather to the one that creates more value relative to competitors. Because competition destroys revenue but not value, firms will form coalitions to inefficiently prevent market competition. As shown in the numerical example below, one way to weaken competition is to include many firms to one coalition, rather than allocating them to different coalitions.

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

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

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 to 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).

6. Conclusion

We have presented a model of coalition formation and technology choice in standard setting to 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 have presented two main results. First, 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, proportional 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.

Second, we show 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.

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.

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.

Our analysis and results can be extended in several directions. First, 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 in the monopoly-standards case, 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. To the best of our knowledge, the relationship between standards and patent pools in standards wars has not been studied.

Second, 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.

Finally, 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, Llobet, and Padilla, 2014). Incorporating incentives for innovation in a model of coalition formation and technology choice is another venue for future research.

Appendix: Proofs

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 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 a proportional sharing rule, 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 rule dominates proportional sharing rule, and one where proportional sharing rule dominates per capita rule.

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 obtains profits of $\frac{1}{2}10$. If the coalition (1,3) is formed firm 1 obtains $\frac{10}{12}8 > 5$. It is 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 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, a proportional sharing rule 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 a proportional sharing rule is always weakly larger than with per capita.

First assume 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

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

so firm j is also included with a proportional 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 there exists $\widetilde{c}$ so that $H(c') < H(\widetilde{c})$. 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 $C\backslash c = \emptyset$, we write $r(c) = \emptyset$. 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.[20] 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 $H(c', \{c', z\}) > H(r(c^*), \{r(c^*), z\})$ 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 proportional 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 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. ■

[20] 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).

Proof of Proposition 4. Remember that we assume 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

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

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. ∎

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