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Larouche, Pierre; Schütt, Florian

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by
Pierre Larouche
Florian Schuett

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Repeated interaction in standard setting*

Pierre Larouche† Florian Schuett‡

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Abstract

As part of the standard-setting process, certain patents become essential. This may allow the owners of these standard-essential patents to hold up implementers of the standard, who can no longer turn to substitute technologies. However, many real-world standards evolve over time, with several generations of standards succeeding each other. Thus, standard setting is a repeated game in which participants can condition future behavior on whether or not hold-up has occurred in the past. In the presence of complementarity between the different patents included in the standard, technology contributors have an incentive to discipline each other and keep royalties low, which can be achieved by threatening to exclude contributors who have engaged in hold-up from future rounds of the process. We show that repeated standard setting can sustain FRAND royalties provided the probability that another round of standard setting will occur is sufficiently high. We also examine how the decision-making rules of standard-setting organizations affect the sustainability of FRAND royalties.

Keywords: standard setting, repeated interaction, FRAND royalties

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†TILEC and Tilburg Law School, Tilburg University. E-mail: pierre.larouche@uvt.nl.

‡TILEC, CentER, and Department of Economics, Tilburg University. E-mail: f.schuett@uvt.nl.

1 Introduction

Technology standards are a pervasive feature of the information and communication technology (ICT) industries. Adopting a standard can be welfare-enhancing because it allows industry participants to coordinate on one of several potential solutions, thereby harnessing network effects and avoiding duplication of investments (Farrell and Saloner, 1985). At the same time, there is a concern that standardization may give rise to hold-up problems. When several different technologies are able to perform the same function, competition among these technologies can hold license fees in check. Standardization, however, often selects one particular technology to be included in the standard. The patent on the technology then becomes *standard essential*, and its holder gains market power because the standard effectively eliminates substitute technologies. This may allow the patent holder to hold up implementers of the standard and charge higher royalties than those that would have been negotiated *ex ante*, i.e., before the adoption of the standard (Farrell *et al.*, 2007; Ganglmair *et al.*, 2012). Standard-setting organizations (SSOs) have responded to this concern by imposing commitments to license on "fair, reasonable and non-discrimatory" (FRAND) terms, which has been interpreted as reflecting an ex ante view (Swanson and Baumol, 2005). In practice, however, the vagueness of these commitments and the informational difficulties associated with their ex post enforcement make them unlikely to have much bite in restraining patent holders (Lerner and Tirole, 2015).

This paper builds on two additional features of the standard-setting process which we argue are important for understanding the risk of hold-up: technological complementarities and repeated interaction. As many observers have noted, products in high-tech industries frequently combine several complementary technologies (Heller and Eisenberg, 1998; Shapiro, 2001). This may lead to *royalty stacking* (better known to economists as the multiple marginalization or Cournot complements problem): because individual patent holders do not take into account the effect of their royalties on the demand for licenses addressed to other patent holders, their royalty rates will tend to exceed the level that would maximize joint profits.

An important implication of this is that a high royalty rate on one essential patent (e.g., due to hold-up) decreases the demand for the standard, and thus the profits of the remaining contributors.

In addition, there is repeated interaction between firms participating in the standard-setting process. Many real-world standards evolve over time, with several generations of the standard succeeding each other, each building on the previous generation. The set of standards for mobile communications is probably the best-known example thereof. In the 1990s, earlier mobile systems were replaced by systems using TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access), like GSM and D-AMPS.[1] In the 2000s, the sector moved to standards based on improvements of CDMA such as UMTS and CMDA2000.[2] At the time it became increasingly common to refer to these standards in generational terms as 3G, or third-generation.[3] A generation represents a new set of standards that is not backwards compatible with the previous generation. This generational view has now become so widespread that the current set of standards is known as 4G,[4] and work has begun on the next generation, already christened 5G.[5] Roughly speaking, a new generation of mobile communications standards ascends to primacy every decade, i.e., 1G up to the 1990s, 2G in the 1990s, 3G in the 2000s, 4G in the 2010s, and 5G set to be introduced from 2020 onwards. Each generation is characterized by significant tech-

[1] GSM initially stood for Groupe Spécial Mobile (a working group at ETSI), and later for Global System for Mobile communications. Developed in the EU, this standard went on to be deployed worldwide. D-AMPS stands for the Digital version of the Advanced Mobile Phone System (AMPS) standard, deployed mostly in North America.

[2] UMTS stands for Universal Mobile Telecommmunications System, which evolved from GSM and is based on a technology called W-CDMA. CDMA2000 is an alternative to UMTS, based on a technology called cdmaOne.

[3] TDMA-based standards constitute the second generation, and their predecessors, the first. The generational approach gained currency with the adoption, in 1997, of an ITU instrument, ITU-R Recommendation M.687-2 on International Mobile Telecommunications-2000 (IMT-2000), which introduced the idea of a family of standards meeting certain specifications.

[4] One of the 4G standards, Long-Term Evolution (LTE), is also known with its own acronym.

[5] Intermediate iterations of the various generations have also received fractional numbers, such as 2.5G (the General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE) specifications) and 3.5G (the High Speed Packet Access (HSPA) specifications). Both aimed to increase the speed of data communications compared to the baseline.

nological improvement, as translated in higher performance characteristics. 2G ushered in digital cellular technology, 3G strengthened data communications, 4G marked the move to an IP-based network (where voice is merged with data communication) and 5G is intended to support the data communications forecast with the Internet of Things.

As this brief description shows, in the ICT sector, standardization itself can no longer be seen as an *ad hoc* phenomenon, but should rather be considered an institution. Once an activity or a functionality is successfully standardized, established standard-setting organizations are expected to work continuously on maintaining and improving standards, and thus to produce successive generations of standards over time. Next to mobile communications standards, industry players and users are now accustomed to generations of standards regarding computing and communications equipment interfaces (USB, Bluetooth), local data communications (Wi-Fi), computer components (RAM) or television. Importantly, often the same firms contribute to the different generations of the standard.

In this paper, we show that the combination of technological complementarities and repeated interaction may alleviate the hold-up problem. Complementarities mean that technology contributors have an interest in keeping royalty rates of other contributors low. Repeated interaction means that contributors are able to discipline others that charge excessive royalties by excluding them from future generations of the standard. Indeed, most standard-setting organizations (SSOs) are consensus building bodies whose decisions are made through some sort of voting procedure (Chiao *et al.*, 2007; Rysman and Simcoe, 2008; Simcoe, 2012; Baron and Spulber, 2015). This creates scope for participants to punish a contributor who misbehaved by voting against the inclusion of its technologies in the next generation of the standard. Thus, complementarities create the *incentive* and repeated interaction the *ability* for technology contributors to mitigate hold-up.

We develop a stylized model of standard setting that captures the repeated nature of the process. After each generation of the standard, there is some probability that the standard will evolve to another generation. In each generation, there are two perfectly complementary technologies A and B, neither of which have stand-alone value. Technology A is developed by a single firm, while technology B is developed in two competing versions by firms B_1 and B_2. Firm B_1 makes the more valuable version of the technology. Under ex ante licensing, competition would drive the royalty rate of B_1 down to the incremental value of its technology over B_2's inferior version; following Swanson and Baumol (2005) and Layne-Farrar and Llobet (2014), we adopt this incremental value rule to define the FRAND rate of royalties. In our setting, the FRAND rate cannot be sustained in a one-shot setting: firm B_1 is able to exploit the market power conferred on it by the standard to hold up technology implementers and charge a royalty rate exceeding the incremental value of its technology. Implementers and the contributor of technology A are left with lower profit, and consumers receive less surplus.

Under repeated standard setting, however, contributor A can condition its behavior on the history of play, and thus on whether hold-up has occurred in the past. We show that if the probability of another round of standard setting is high enough, there exists a subgame perfect equilibrium in which firm B_1's technology is adopted as the standard in each period, B_1 charges the FRAND rate, and firm A punishes deviations from the FRAND rate by voting against the inclusion of B_1's technology for a number of rounds; during these punishment rounds, the inferior technology supplied by B_2 is adopted as the standard with some probability. This outcome does not depend on enforcement by competition authorities.

Technically, this result is an application of the famous *Folk Theorem* for infinitely repeated games (Fudenberg and Tirole, 1991). Our approach is analogous to that adopted in the economic analysis of collusion. We first identify the critical discount factor (here, the critical continuation probability) above which the FRAND outcome can be sustained in equilibrium. Then, we ask how the procedural rules of the SSO affect this critical continuation probability. In particular, we show that the effectiveness of punishment, and thus the sustainability of FRAND royalties, depends on the super-majority requirement used by the SSO. Only a sufficiently high super-majority requirement allows for effective punishment. The intuition is that, in addition to B_1, non-strategic voters (i.e., the technology implementers in our model) will vote for the superior technology provided by B_1. The super-majority requirement must be chosen in such a way as to make it impossible to adopt a proposal with only the votes of B_1 and the implementers.

The practical relevance of our model crucially depends on whether the set of firms contributing technologies to a standard is relatively stable over time, i.e., across different generations. Are the technological breakthroughs that lead to new generations of a standard usually ushered in by newcomers, or do they originate with the same firms whose innovations the previous generation was built upon? To provide at least a tentative answer to this question, we study four important ICT standards which evolved through several well-defined generations: mobile (cellular) communications, Wi-Fi, USB, and Bluetooth. We compare the set of important contributors to each generation and find substantial overlap. This suggests that a fair share of technological advances is made by contributors that were already present in previous rounds of standard setting.

Several alternative solutions to the hold-up problem have been proposed in the literature. Llanes and Poblete (2014) examine ex ante agreements about participation in, and the distribution of dividends from, a patent pool. Lerner and Tirole (2015) study ex ante price commitments, whereby SSOs would require patent holders to commit to the royalty rates they would charge were their technologies selected into the standard. Lemley and Shapiro (2013) advocate a system of binding final offer arbitration between litigants to establish FRAND rates.[6] We show that the difficulties associated with those alternative solutions, such as the problem of determining royalties before knowing the exact composition of the standard, can be avoided in settings where standards evolve through several generations, provided the rules of SSOs are properly designed.

The paper contributes to a recent literature suggesting that the problems associated with standard setting may be less severe than initially thought. Rey and Salant (2012) consider a vertical industry with upstream complements, Cournot competition downstream, and entry. They show that royalty stacking can alleviate the problem of socially excessive entry in the downstream sector that arises in this setup. Schmidt (2014) finds that the use of two-part tariffs can eliminate royalty stacking. Spulber (2015) presents a

[6]For a critical analysis of the Lemley-Shapiro proposal, see Larouche *et al.* (forthcoming).

model in which complementary monopolists set quantities, which determine the size of the pie, and then bargain over the distribution of the pie. He shows that in the unique equilibrium, the players choose the efficient size of the pie.

The remainder of the paper is organized as follows. Section 2 sets out a simple model of repeated standard setting. Section 3 considers the benchmark case in which there is a single round of standardization. Section 4 characterizes a subgame perfect equilibrium of the repeated standardization game in which FRAND royalties prevail and analyzes how SSO rules affect the sustainability of this equilibrium. Section 5 presents evidence on the prevalence of repeated interaction in several important ICT standards. Finally, Section 6 concludes. All proofs are relegated to the Appendix.

2 The model

Consider the following stylized model of standardization. Standard setting takes place in several rounds $t = 1, 2, \ldots$ After each round, there is a probability δ that there will be another round of standard setting; with probability $1 - \delta$ the game ends.[7] There are two complementary technologies to be included in the standard, one of which is developed by a single upstream innovator A while the other is developed in two competing versions by innovators B_1 and B_2. Neither technology has any stand-alone value. All three innovators are infinitely lived. Each of the innovators produces successive improvements of their technologies.

There is a perfectly competitive downstream sector with a continuum of implementers. All implementers operate with zero marginal cost of production. They face demand $Q^t(p^t) = v_i^t - p^t$ for a product incorporating the technologies developed by A and B_i. That is, v_i^t represents the demand intercept for a product based on a standard combining A's and B_i's technologies, $i = 1, 2$. The demand for a product including at most one of the three technologies is normalized to zero. Assume that including all three technologies in the standard is never desirable: after all, the whole point of standardization is to coordinate on one particular technical specification,

[7] As usual, δ can also capture time discounting.

perhaps to reap the benefits of network effects or avoid duplication.[8] To streamline the exposition, we make the following assumption.

Assumption 1. *Each successive improvement generates the same value, and B_1 always produces the more valuable version of the B technology: $v_i^t = v_i$ for all t, and $v_1 > v_2 \geq 0$.*

Assumption 1 implies that we are within the framework of an indefinitely repeated game, which simplifies the analysis considerably.

Ex ante licensing and the FRAND rate. All technology firms simultaneously propose a per-unit royalty to the downstream firms. Let r_A^t and r_i^t denote the royalty rates proposed in round t by firms A and B_i, respectively. To establish a benchmark, consider the hypothetical scenario in which licensing negotiations take place ex ante and the innovators commit to the royalty rates they would practice were their technologies adopted. Because the downstream sector is perfectly competitive, the downstream firms then choose the B technology that maximizes consumer surplus given the proposed royalty rates, r_1^t and r_2^t. If the technology developed by B_s is selected, with $s \in \{1, 2\}$, the price of the final product (suppressing the index t for brevity) is $p = r_A + r_s$, the quantity sold is $Q = v_s - r_A - r_s$, and consumer surplus is $(v_s - r_A - r_s)^2/2$. Hence, if faced with royalty offers r_1 and r_2, the downstream firms would select B_1 (i.e., $s = 1$) if and only if

$$\frac{(v_1 - r_A - r_1)^2}{2} \geq \frac{(v_2 - r_A - r_2)^2}{2},$$

or $v_1 - r_1 \geq v_2 - r_2$. Since $v_1 > v_2$ by Assumption 1, B_1 can always outbid B_2. In the Bertrand-Nash equilibrium, B_2 thus sets $r_2 = 0$. In turn, A sets r_A to solve

$$\max_{r_A} \ (v_1 - r_A - r_1)\, r_A,$$

while B_1 sets r_1 to solve

$$\max_{r_1} \ (v_1 - r_A - r_1)\, r_1 \quad \text{subject to } r_1 \leq v_1 - v_2.$$

[8] Thus, we implicitly assume that there are some unmodeled costs of failing to coordinate on one of the B technologies. Alternatively, inclusion in the standard may make both B_1 and B_2 essential, which due to multiple marginalization would lead to even higher total royalties than hold-up by B_1.

Solving for the equilibrium royalty rates ignoring the constraint yields $r_A = r_1 = v_1/3$. Hence, the constraint is binding if and only if the following assumption holds:

Assumption 2. *B_2's technology is sufficiently valuable to impose a competitive constraint on B_1 under ex ante licensing: $v_2 > \frac{2}{3}v_1$.*

Assumption 2 ensures that under ex ante licensing, Bertrand competition between B_1 and B_2 drives royalty rates down to the following levels: $r_1 = v_1 - v_2$, $r_2 = 0$. In what follows we refer to $\bar{r} = v_1 - v_2$ as the *fair, reasonable and non-discriminatory* (FRAND) royalty rate for technology 1 (Swanson and Baumol, 2005; Layne-Farrar and Llobet, 2014). Note also that under ex ante licensing, A best-responds by charging $r_A = (v_1 - \bar{r})/2 = (v_2 - 0)/2 = v_2/2$ regardless of whether B_1's or B_2's technology is adopted by the downstream firms. The downstream equilibrium price with B_1's technology is $\bar{p} \equiv v_2/2 + \bar{r} = v_1 - v_2/2$.

Standard setting. The standard setting process works as follows. In each round t the SSO issues a call for proposals. B_1 and B_2 can propose a standard $s_t \in \{1, 2\}$ at a proposal cost c. Standard $s_t = 1$ includes A's technology and B_1's, while standard $s_t = 2$ includes A's and B_2's. Assume $c < \bar{r}v_2/2$; otherwise FRAND royalties are too low to justify the cost of proposing a standard and can never be part of an equilibrium. The SSO then puts all proposals received to a sequential vote. The order in which proposals are voted on is random. All participants in the standard-setting process (A, B_1, B_2, and the downstream firms) are eligible to vote. Each innovator has one vote, while the downstream firms together hold voting rights equal to $D \geq 0$. A proposal is adopted if it receives a super-majority of at least a share $\gamma > 1/2$ of the votes. Assume $\gamma \leq (2 + D)/(3 + D)$, so that a single vote cannot block adoption. As soon as a proposal is adopted, the process stops; otherwise, the other proposal is put to a vote. If no proposal receives a super-majority, the outcome is determined as follows.[9] With probability $1 - \alpha$, the SSO does not adopt a standard in the current

[9] We will later relate the likelihood of different outcomes to the procedures and characteristics of the SSO.

round ($s_t = \varnothing$) and reopens the process in round $t+1$ (if it occurs). Assume that if no standard is adopted, all players receive a payoff of zero in round t. With probability α, the SSO selects one of the proposed technologies as the standard. If there are two proposals on the table, then it chooses B_1's with probability β and B_2's with probability $1-\beta$. Like the rest of the literature (e.g., Farrell and Simcoe, 2012; Bonatti and Rantakari, 2016), we rule out side payments between participants.

This decision-making procedure is consistent with the available evidence on the voting rules used by SSOs. According to Bonatti and Rantakari (2016), most SSOs use rules whereby votes on proposals are based on motions; this implies that they are taken sequentially. Chiao *et al.* (2007) survey 59 SSOs and report that most SSOs in their sample use majority voting (34%), some require a super-majority (27%), and only a small fraction require unanimity (13%).[10] In Baron and Spulber's (2015) sample of 31 SSOs, 36% use a simple majority rule, 48% require a super-majority, and 16% require unanimity.

Timing. The timing of the game played in each round t is as follows. First, B_1 and B_2 simultaneously decide whether to submit a proposal to the SSO and incur the cost c if they do. The SSO adopts a standard $s_t \in \{1, 2, \varnothing\}$ according to the procedure described above. Then, A and B_{s_t} simultaneously set the royalty rates r_A^t and r_{s_t} at which they offer to license their standard-essential patents. The downstream firms choose the price p^t at which they sell the product incorporating the standardized technologies to consumers. Firm A obtains $\pi_A = (v_{s_t} - p^t)r_A^t$. Firm B_1's and B_2's payoffs (excluding proposal costs) are $\pi_{s_t} = (v_{s_t} - p^t)r_{s_t}^t$ for the firm whose technology is adopted, and $\pi_{-s_t} = 0$ for the firm whose technology is not adopted.

3 A single round of standard setting

As a benchmark, consider what happens if there is a single round of standard setting; accordingly, we drop the index t for the moment. We solve the game

[10] They do not have information on the remaining 25% of SSOs.

by backward induction. At the price-setting stage, the downstream firms set $p = r_A + r_s$. At the licensing stage, given that a standard s has been set, firms A and B_s choose $r_A = r_s = v_s/3$; in particular, the B firm whose technology has been selected as the standard (B_s) is not constrained by the existence of the alternative technology developed by B_{-s}. Given these royalty rates, downstream firms sell at a price of $(2/3)v_s$ and produce a total output of $v_s/3$. Their payoff is $\pi_D = 0$, while A's and B_s's payoffs are $\pi_A = \pi_s = (v_s/3)^2$. B_{-s}'s payoff is zero, and consumer surplus is $CS = v_s^2/18$. Note that π_A and CS are increasing in v_s, i.e., both A and consumers prefer B_1's over B_2's technology for inclusion in the standard.

The presence of a standard including only one of the two B technologies eliminates the other and therefore allows the contributor of the selected technology to charge a royalty exceeding the FRAND level. This is a version of the hold-up problem that many observers fear is caused by SSOs "picking winners." If selected, B_1 is able to charge $v_1/3$ rather than $v_1 - v_2$, and B_2 is able to charge $v_2/3$ rather than zero. Importantly, this means that innovator A best-responds by charging $r_A = v_s/3$, whereas with FRAND royalties, it could charge $r_A = v_2/2$, which strictly exceeds $v_s/3$ for any $s = 1, 2$ by Assumption 2. Innovator A would benefit from innovator B_s charging a lower royalty. The intuition, of course, is that complementary patent holders who set royalty rates independently do not internalize the effect of high royalties on other patent holders (a phenomenon known as royalty stacking). The hold-up problem thus hurts the contributors of complementary technologies (A). It also hurts implementers and consumers, and it reduces aggregate surplus by leading to higher prices. To see this, note that the equilibrium price when standard s is adopted is $p = (2/3)v_s$, whereas with FRAND royalties it would be $\bar{p} = v_1 - v_2/2 < (2/3)v_1$ if $s = 1$ and $p = v_2/2 < (2/3)v_2$ if $s = 2$. The following proposition summarizes this discussion.

Proposition 1. *In any equilibrium of the one-shot game of standard setting, the royalties charged by firm B_s and the final consumer prices exceed those that would arise under ex ante licensing. The profit of firm A is lower.*

At the voting stage, there can be many equilibria. We simplify the analysis by making the following assumption on downstream firms' voting behavior.

Assumption 3. *Downstream firms vote for the proposal that leads to higher expected consumer surplus.*

The consumer-surplus objective can be justified by the fact that, if the downstream sector is even slightly less than perfectly competitive, so that downstream firms make some profit, the profit-maximizing proposal coincides with the consumer-surplus maximizing one. The assumption, however, also contains a second element: *downstream firms vote sincerely.* This is reasonable because each downstream firm individually is too small to affect the outcome of the vote, hence there is no incentive to behave strategically.

Under Assumption 3, if there is a single proposal, all downstream firms vote in favor. If there are two proposals, downstream firms' vote depends on the order of votes. At the first vote, all downstream firms vote in favor of B_1 and against B_2, because consumer surplus is increasing in v_s. At the second vote, if B_1's proposal is on the ballot, the downstream firms vote in favor. If B_2's proposal is on the ballot, they vote in favor if and only if

$$v_2^2 \geq \alpha[\beta v_1^2 + (1-\beta)v_2^2].$$

Thus, there exists a critical value $\alpha^*(\beta)$ such that the downstream firms vote in favor if $\alpha \leq \alpha^*(\beta)$ and vote against if $\alpha > \alpha^*(\beta)$, with

$$\alpha^*(\beta) = \frac{v_2^2}{\beta v_1^2 + (1-\beta)v_2^2}.$$

Suppose firms B_1 and B_2 also vote sincerely, i.e., they vote in favor of their own and against the rival's proposal. This strategy is weakly dominant, and as Proposition 2 shows, it leads to an equilibrium in which B_1 is the only one to make a proposal, and its proposal is always adopted.

Proposition 2. *Suppose $c > 0$. If B_1 and B_2 vote in favor of their own and against the rival's proposal, the subgame-perfect Nash equilibrium of the one-shot game is such that B_1 proposes its own technology as the standard, B_2 makes no proposal, and B_1's proposal is adopted with a super-majority.*

Proposition 2 shows that if B_1 and B_2 vote sincerely, then the superior technology developed by B_1 is always adopted as the standard. The intuition is as follows. When B_1 and B_2 vote for their own and against the rival's proposal, there is always one vote in favor and one vote against. Thus, either the downstream firms or innovator A (or both) must be pivotal. Because by assumption, a single vote cannot prevent a super-majority ($\gamma \leq (2+D)/(3+D)$), a proposal is always adopted if innovator A and the downstream firms vote in favor. Similarly, because a single vote in favor is not enough to win even a simple majority, a proposal can never be adopted if A and the downstream firms vote against. The incentives of A and the downstream firms are aligned: they both prefer B_1 to be selected as the standard. Although they would sometimes vote in favor of B_2's proposal if it were on the ballot at the second vote (namely, if $\alpha \leq \alpha^*(\beta)$), the procedure never reaches that stage, for if B_1's proposal is on the ballot at the first vote, it will be adopted with certainty. The downstream firms always vote in favor, and whenever pivotal A also votes in favor. If A is not pivotal, it must be that B_1's proposal has a super-majority even without A's support (the opposite scenario, in which B_1's proposal would not have a super-majority even with A's support, would require $(2+D)/(3+D) < \gamma$, which is ruled out by assumption). Either way, B_1's proposal gets adopted.

Note that the result that there is only one equilibrium does not rely on specific values of the parameters α, β, and γ; it only relies on B_1 and B_2 voting sincerely. The next proposition shows that when we allow for non-sincere voting by B_1 and B_2, for certain constellations of α, β, and γ, outcomes can be worse than those identified in Proposition 2, in the sense that the inferior technology developed by B_2 is sometimes selected.

Proposition 3. *If $\beta < 1$, $\alpha \leq \alpha^*(\beta)$, $\gamma > (1+D)/(3+D)$, and $c < (1/2)(v_2/3)^2$, there exists a subgame-perfect equilibrium in which B_1 and B_2 both make proposals, and each gets adopted as the standard with probability 1/2.*

The proof of Proposition 3 constructs an equilibrium in which no proposal receives a super-majority at the first vote and any proposal receives a super-majority at the second vote. This can happen if all strategic players (A, B_1 and B_2) vote against at the first vote and in favor at the second; under the assumptions stated in the proposition, no player has a unilateral incentive to deviate. Proposition 3 relies on α being sufficiently low for downstream firms to vote in favor of B_2's proposal at the second vote. This is the case for example with $\alpha = 0$, which corresponds to a rule whereby proposals that have been voted down are discarded.

The likelihood of an inferior technology being selected can often be mitigated by setting α above $\alpha^*(\beta)$, so that downstream firms vote against B_2 at the second vote. To see this, suppose $D \geq 1$, and consider a candidate equilibrium in which B_2 gets adopted at the second vote with the votes of A, B_1, and B_2.[11] Then, the condition $(1+D)/(3+D) < \gamma$ in Proposition 3 implies that each of them is pivotal, since $2/(3+D) \leq (1+D)/(3+D)$ for $D \geq 1$. Thus, A and B_1 have an incentive to deviate and vote against B_2's proposal, so that B_1's is instead adopted with probability $\alpha\beta$. Because this reduces B_2's expected payoff from introducing a proposal to $(1/2)\alpha(1-\beta)(v_2/3)^2 - c$, it may even eliminate the equilibrium altogether.

A still better way of reducing the risk of B_2's inferior technology being selected is to set $\beta = 1$ and $\alpha = 1$. This corresponds to a rule whereby proposals that have been voted down are kept on the table and the winner is selected according to a technology-oriented tie-breaker. Having a neutral third party select the best technology in such a situation can be thought of as implementing $\beta = 1$. One can interpret the rule used by some real-world SSOs to have the chairman of the working group choose the best technological solution if none of the proposals has gathered a super-majority as achieving something similar. As we will show below, these results from the one-shot game do not carry over to repeated standard setting. There, an SSO procedure with $\alpha = \beta = 1$ can be counterproductive.

4 Repeated standard setting

Having seen that FRAND royalties cannot be sustained as an equilibrium in the one-shot game, we now study under which conditions repeated standard setting can overturn this result. We first introduce some notation. In each round t, firms B_1 and B_2 decide whether to propose a standard, a decision

[11] This requires $3/(3+D) \geq \gamma$. If this inequality does not hold, B_2's proposal never gets adopted when $\alpha > \alpha^*(\beta)$, and so the result is even more immediate.

we denote by $x_i^t \in \{0,1\}$. Let $x^t = \sum_i x_i^t$ denote the sum of proposals submitted, so that $x^t \in \{0,1,2\}$. Denote by $\tilde{s}_1^t$ the proposal that is on the ballot first and by $\tilde{s}_2^t$ the proposal that is on the ballot second, with $\tilde{s}_\vartheta^t \in \{1,2,\varnothing\}$ for $\vartheta = 1,2$. Denote by $\phi_{\vartheta j}^t \in \{0,1\}$ player j's decision to vote in favor at the ϑth vote, with $j \in \{A,1,2\}$.[12] We maintain Assumption 3, so that the downstream firms vote as described in Section 3. Thus an action profile in t is given by

$$a_t \equiv (x_1^t, x_2^t, \phi_{1A}^t, \phi_{11}^t, \phi_{12}^t, \phi_{2A}^t, \phi_{21}^t, \phi_{22}^t, r_A^t, r_1^t, r_2^t).$$

Let h_t denote the complete history of play up to period $t-1$, i.e., $h_t \equiv (a_1, a_2, \ldots, a_{t-1})$.

Let us now look at each player's strategy in the repeated game. For firm A, a strategy is

$$\sigma_A^t = (\phi_{1A}^t(\tilde{s}_1^t, x^t, h^t), \phi_{2A}^t(\tilde{s}_2^t, h^t), r_A^t(s^t, h^t)).$$

That is, firm A's strategy prescribes whether to vote in favor at the first and second vote as a function of the proposal on the ballot, the number of proposals submitted, and the history of play, as well as which royalty to charge as a function of the standard adopted and the history of play.[13] For firm B_i, a strategy is

$$\sigma_i^t = (x_i^t(h^t), \phi_{1i}^t(\tilde{s}_1^t, x^t, h^t), \phi_{2i}^t(\tilde{s}_2^t, h^t), r_i^t(s^t, h^t)).$$

That is, firm B_i's strategy prescribes whether to submit a proposal given the history of play, whether to vote in favor at the first and second vote as a function of the proposal on the ballot, the number of proposals submitted, and the history of play, as well as which royalty to charge as a function of the standard adopted and the history of play.

We will look for an equilibrium in which B_1's technology is adopted as the standard, B_1 sets its royalty at the FRAND level ($r_1 = \bar{r}$), and A enforces this outcome by punishing deviations from the FRAND rate.

[12] As previously, $\phi_{\vartheta 1}^t$ denotes B_1's decision and $\phi_{\vartheta 2}^t$ denotes B_2's decision.

[13] The royalty could in principle condition also on which proposals were submitted and how the standard was adopted (first vote, second vote, or runoff). We do not need such a dependence for the equilibrium that we construct below, however, and therefore adopt this simpler description of strategies.

The punishment takes the form of A voting against the inclusion of B_1's technology in the standard (and in favor of B_2's) for a number of rounds following the deviation. For such a punishment to be effective, it must lead to B_1's technology sometimes not being adopted as the standard; this can happen either if B_2's technology is adopted as the standard, or if no standard is adopted. Let q_1 denote the probability that B_1's technology is adopted as the standard *during the punishment phase* and q_2 the probability that B_2's is. The following proposition first shows under which conditions on q_1 and q_2 such an equilibrium can be constructed. Later we determine how q_1 and q_2 depend on the rules of the standard-setting process.

Proposition 4. *Suppose $c \leq q_2(v_2/3)^2$ and $q_1 < \bar{q}$, where*

$$\bar{q} \equiv \frac{v_2(v_1 - v_2)/2}{(v_1/3)^2}.$$

If δ is sufficiently close to 1, there exists a subgame-perfect equilibrium of the repeated game in which B_1's technology is adopted as the standard in every round and B_1 charges FRAND royalties (i.e., $r_1^t = \bar{r}$ for all t).

In the proof of Proposition 4 we construct strategies that can sustain FRAND royalties as an equilibrium. In this equilibrium, there is a temptation for B_1 to deviate from the FRAND rate and hold up the downstream firms by charging $r_1^t = v_1/3$ (as in the equilibrium of the one-shot game). The trick is to dissuade B_1 from deviating from the FRAND rate by means of a *credible* threat of punishment. Punishment here takes the form of A voting against B_1's technology and in favor of B_2's for $L \geq 1$ periods following the deviation. The proposition identifies a threshold $\bar{q}$ such that punishment is effective if $q_1 < \bar{q}$, i.e., if it prevents adoption of B_1's technology sufficiently often. B_2 is happy to carry out the punishment as long as it leads to adoption of its own technology as the standard sufficiently often to justify the proposal cost, i.e., if $c \leq q_2(v_2/3)^2$. However, punishing B_1 is costly to A, because it leads to an inferior technology sometimes being implemented, and thus to lower demand and lower royalties.

To make punishment credible, we must reward A *after the end of the punishment*. In doing so, we must be careful not to also reward the deviator B_1. As the proof shows, the reward for A can be achieved by having

B_1 charge a royalty $\tilde{r}$ below the FRAND level after the punishment. This is possible as long as $\tilde{r}$ is sufficiently large for B_1 to prefer to stick to the equilibrium strategy rather than deviate and get punished. The proof shows that, if δ is sufficiently close to 1, we can always make the number of punishment rounds L large enough to find a value of $\tilde{r}$ that rewards A without prompting B_1 to deviate.

Note that the strategies constructed in Proposition 4 are self-enforcing: they can sustain FRAND royalties without the need for external enforcement by courts or competition authorities. In fact, external enforcement can even crowd out private enforcement here. This is because during the punishment phase, when firm B_2's technology is selected as the standard, B_2 does not charge the FRAND rate, but instead charges $v_2/3$. If competition authorities or courts were to enforce the FRAND rate against B_2, this would diminish B_2's incentive to submit a proposal to the SSO during the punishment phase. This, in turn, would make it harder to punish B_1 for deviating from the FRAND rate.

The next proposition restricts the number of punishment periods to 1. In that case, we can characterize the critical discount factor δ^* above which there exists an equilibrium in which B_1 charges FRAND royalties.

Proposition 5. *Suppose $c = 0$. There exists $v_2^* \in ((2/3)v_1, v_1)$ such that, for all $v_2 < v_2^*$, B_1 charging FRAND royalties can be sustained as a subgame-perfect equilibrium with a single round of punishment if $q_1 \leq \tilde{q}(v_2)$, given by*

$$\tilde{q}(v_2) \equiv \frac{(v_1 - v_2)v_2 - ((v_1 - v_2/2)/2)^2}{(v_1/3)^2},$$

and $\delta \geq \delta^* \in (0,1)$. The critical discount factor δ^* solves

$$\delta^* \left[\left(\frac{v_1 - \underline{r}(\delta^*, q_1)}{2} \right)^2 - \left(\frac{v_1 - \bar{r}}{2} \right)^2 \right] = (1 - \delta^*) \left[(1 - q_1) \left(\frac{v_1}{3} \right)^2 - q_2 \left(\frac{v_2}{3} \right)^2 \right], \quad (1)$$

where

$$\underline{r}(\delta, q_1) = \frac{1}{2} \left(v_1 - \sqrt{v_1^2 - \frac{8}{1+\delta} \left[\left(\frac{v_1 - v_2/2}{2} \right)^2 + \delta q_1 \left(\frac{v_1}{3} \right)^2 \right]} \right).$$

A single punishment period may not suffice to implement FRAND royalties. If the condition $v_2 < v_2^*$ does not hold, a single round of punishment is never enough to sustain FRAND royalties in equilibrium, regardless of the discount factor δ and the probability of adopting B_1's technology during the punishment phase, q_1. The intuition is that, when v_2 is too close to v_1, the FRAND rate $\bar{r} = v_1 - v_2$ is so low that it becomes too tempting for firm B_1 to deviate. Proposition 5 shows that if $v_2 < v_2^*$ and $q_1 \leq \tilde{q}(v_2)$, i.e., if B_2's technology is substantially worse than B_1's and the probability of adopting B_1's technology during the punishment phase is sufficiently low, then FRAND royalties can be sustained if the continuation probability (or discount factor) δ is sufficiently close to 1.

Proposition 6. *An increase in q_2 reduces the critical discount factor δ^*. An increase in q_1 has ambiguous effects on δ^*.*

The intuition for the result in Proposition 6 is as follows. Changes in q_1 and q_2 affect the critical discount factor δ^* through two channels: firm A's willingness to punish, and firm B_1's fear of being punished. An increase in q_2 – i.e., an increase in the probability that B_2's technology is adopted as the standard during the punishment phase – makes punishment less costly *ceteris paribus* for firm A and does not affect firm B_1's payoff. An increase in q_1 – i.e., an increase in the probability that B_1's technology is adopted during punishment – also makes punishment less costly for A. At the same time, however, it makes firm B_1 less afraid of being punished. The net effect of these two opposing forces is ambiguous.

The next proposition relates the probabilities of adopting B_1 and B_2 during the punishment phase to the rules of the standard-setting organization.

Proposition 7. *A necessary condition for $q_1 < 1$ is $\gamma > (1 + D)/(3 + D)$. Suppose this condition is satisfied and $c = 0$. Then, q_1 and q_2 depend on α, β, and γ as follows:*

$$(q_1, q_2) = \begin{cases} (0, 1) & \text{for } \gamma \leq 2/(3 + D) \\ (\alpha\beta/2, (1 + \alpha(1 - \beta))/2) & \text{for } \gamma > 2/(3 + D) \text{ and } \alpha \leq \alpha^*(\beta) \\ (\alpha\beta, \alpha(1 - \beta)) & \text{for } \gamma > 2/(3 + D) \text{ and } \alpha > \alpha^*(\beta). \end{cases}$$

Proposition 7 has several implications for the design of SSO rules. First, it shows that if the super-majority requirement is too low, punishment for deviations from FRAND royalties is not possible: if $\gamma \leq (1+D)/(3+D)$, the technologically superior proposal by B_1 is always adopted as the standard, even against the vote of A and B_2. As a result, FRAND royalties cannot be sustained in equilibrium, as $q_1 < 1$ is required for the equilibrium constructed in Proposition 4. Note that the relevance of this condition depends on the voting rights of the non-strategically voting downstream firms: if $D < 1$, then $\gamma > (1+D)/(3+D)$ is satisfied for any $\gamma > 1/2$, so the condition is never binding. In that case, setting a *low* super-majority requirement ($\gamma \leq 2/(3+D)$) actually facilitates punishment, as it implies that B_2's proposal can be adopted with certainty during the punishment phase ($q_2 = 1$ and $q_1 = 0$).

If instead $D \geq 1$, then $2/(3+D) \leq 1/2$, so setting γ below that threshold is not possible. In that case, the effectiveness of punishment depends on α and β. If $\alpha > \alpha^*(\beta)$, q_1 is higher and q_2 lower than if $\alpha \leq \alpha^*(\beta)$. In the limit as α and β both tend to one, q_1 approaches 1 so that punishment becomes completely ineffective.[14] Recall that with a single round of standard setting, setting $\alpha = \beta = 1$ tends to improve outcomes, as it eliminates the possibility that B_2's inferior technology is selected. By contrast, with repeated standard setting, setting this same policy ($\alpha = \beta = 1$) has adverse welfare effects: by eliminating outcomes that are inefficient in a one-shot game, it also makes it harder to punish deviations – and thus to sustain more efficient outcomes – in the repeated game.

More generally, decreasing α makes it more likely that the conditions $q_1 \leq \bar{q}$ from Proposition 4 and $q_1 \leq \tilde{q}(v_2)$ from Proposition 5 are satisfied, so that an equilibrium with FRAND royalties can be sustained for some δ. At the same time, the effect of small changes in α on the critical discount factor δ^* in Proposition 5 is generally ambiguous. Starting from $\alpha < \alpha^*(\beta)$, an increase in α first raises q_2, making FRAND royalties easier to sustain. At $\alpha = \alpha^*(\beta)$, however, there is a discrete jump down from $q_2 = (1+\alpha(1-\beta))/2$ to $q_2 = \alpha(1-\beta)$, which has the opposite effect. Furthermore, an increase in

[14] This illustrates that $\gamma > (1+D)/(3+D)$ is necessary but not sufficient to implement punishment.

α also raises q_1, the effect of which may go either way (see Proposition 6).

Bonatti and Rantakari (2016) show that raising the super-majority requirement (γ) and implementing a rule removing projects that have not been adopted from further consideration (which corresponds to $\alpha = 0$ in our setup) can induce project proposers to compromise, thus moving the proposed projects closer to the socially optimal ones. This provides a rationale for the evidence in Baron and Spulber (2015), according to which most SSOs require a super-majority, rather than a simple majority or unanimity, and for the prevalence of rules discarding proposals that have been voted down. Our model provides an alternative rationale for such rules, based on dynamic considerations. It suggests that super-majority requirements and rules to discard unsuccessful proposals make it easier to discipline participants in their royalty setting behavior and prevent hold-up.

5 Evidence on repeated interaction in ICT standardization

Much like popular hardware and software products are issued in new versions at regular intervals, ICT users have grown accustomed to successful product standards moving over time from one generation to the next, in tune with technological evolution. In this section, we investigate a number of important ICT standards comprising multiple generations. The objective is to assess the extent to which the set of firms contributing to a given generation overlaps with the set of contributors to other generations. We look at mobile communications and Wi-Fi standards, which are set within well-established SSOs and often cited as prime examples of hold-up and royalty stacking (see,e.g. Lemley and Shapiro, 2007), as well as USB and Bluetooth standards, which are set within narrower, industry-driven SSOs.

Mobile communications standards. As discussed in the introduction, the standards for cellular communications networks are the prime example of a standard evolving over several well-defined generations. While second-generation standards where developed independently by several regional SSOs – in particular, GSM in Europe by the European Telecommunications

Table 1: Top 10 SEP holders for mobile communications standard generations

2G (GSM)[a]	2.5G (GPRS)[b]	3G (UMTS)[c]	4G (LTE)[d]
Nokia: 1456	Qualcomm: 517	Qualcomm: 2799	InterDigital: 808
Motorola: 1116	Ericsson: 514	InterDigital: 2337	Qualcomm: 524
Ericsson: 843	Motorola: 451	Motorola: 1961	Samsung: 322
InterDigital: 675	Siemens: 100	Nokia: 1631	Ericsson: 315
Qualcomm: 422		Philips: 529	Motorola: 293
Philips: 175		Siemens: 421	Huawei: 281
Nokia Siemens Networks: 164		Huawei: 380	ZTE: 235
Alcatel: 88		Ericsson: 349	NTT: 212
Siemens: 69		NEC: 208	LG: 208
Toshiba: 62		Nokia Siemens Networks: 180	Nokia: 197

Source: Disclosed Standard Essential Patents (dSEP) Database (Bekkers *et al.*, 2012).
[a]: ETSI project GSM.
[b]: ETSI project GPRS.
[c]: Includes ETSI projects UMTS, UMTS/CDMA, UMTS FDD, UMTS Release 99, UMTS Release 4, UMTS Release 5, UMTS Release 6, UMTS Release 7, UMTS Release 8, UMTS Release 9, WCDMA, and TD-SCDMA.
[d]: Includes ETSI projects LTE, LTE Release 8, LTE Release 9, LTE Release 10, HSPA+, HSUPA, and E-UTRA.

Standards Institute (ETSI) – starting with the third generation, development occurred within the Third Generation Partnership Project (3GPP), a collaboration of seven SSOs from Asia, Europe, and North America. 3GPP developed both the UMTS (3G) and LTE (4G) standards. Its intellectual property rights (IPR) policy requires its members to disclose any IPR they believe to be (potentially) essential to the work done within 3GPP. ETSI, which runs the day-to-day business of 3GPP, keeps a public record of these disclosures. Using data from the Disclosed Standard-Essential Patents Database (dSEP) compiled by Bekkers *et al.* (2012),[15], Table 1 shows the 10

[15] The database is available at http://www.catalini.com/dsep/ (last accessed on 5 February 2016).

leading SEP holders for the different generations of mobile communications standards (2G, 2.5G, 3G, and 4G) maintained or developed by 3GPP.[16,17] Next to the commonly-used name of the firm, we have listed the number of SEP disclosures recorded in the database.[18]

Table 1 shows a recurring core of SEP holders. In particular, Ericsson, Motorola, and Qualcomm are among the top 10 in each of the four generations; Interdigital, Nokia and Siemens (also via Nokia Siemens Networks) are present in three out of four generations; and Philips and Huawei are present in two out of four generations.

Wi-Fi standards. We perform a similar exercise for Wi-Fi (the IEEE 802.11 family of standards), also using data from the dSEP database. Wi-Fi standards are developed at the IEEE (Institute of Electrical and Electronics Engineers), an international organization dedicated to the advancement of technology, including through standardization. Given the smaller number of SEPs and of SEP holders in Wi-Fi, only the top 5 are listed.

Table 2 also shows a recurring small core of SEP holders. Though no firm is among the top 5 in all four generations of Wi-Fi, France Télécom (now Orange) and Télédiffusion de France are present in three out of four. Overall, the pattern is less clear here than in mobile communications, however.

USB. The USB generations of standards (USB 1.0, 2.0 and now 3.0) were developed at the USB Implementers Forum (USBIF). Using data collected from the USBIF website, it is possible to compile a list of contributing parties and specification owners, mentioned as such in the USB specifications. These firms are designated as 'promoters' within the USBIF. Table 3 indicates

[16] In the case of GPRS, the number of SEP holders is small and the numbers of SEPs declared drops dramatically after the 4th-ranked firm, hence the shorter list.

[17] The names of all patent owners mentioned in this document are harmonized, and thus indicate the name of the company or organization that made the disclosure. The information in the database accounts for different spellings of a firm name within or across SSOs, but does not account for mergers and acquisitions after the date of disclosure. In the case of a third party disclosure, the patent owner is not the one that also submitted the declaration.

[18] To be precise, these disclosures include both specific IPR and so-called "blanket disclosures," whereby a form simply declares that it owns relevant IPR, without specifying the patents (or patent applications) concerned.

Table 2: Top 5 SEP holders for Wi-Fi standard generations

802.11a,b	802.11g	802.11n	802.11ac
France Télécom: 62	France Télécom: 62	AT&T: 24	Broadcom: 1
Télédiffusion de France: 62	Télédiffusion de France: 62	Nortel: 10	Celeno Comms: 1
Panasonic: 16	Agere Systems: 13	France Télécom: 7	ETRI: 1
Golden Bridge: 5	Intersil Corp: 5	Télédiffusion de France: 7	Lantiq: 1
Wi-Lan: 4	Philips: 2	Panasonic: 5	Qualcomm: 1

Source: Disclosed Standard Essential Patents (dSEP) Database (Bekkers *et al.*, 2012).

which companies had ‘promoter’ status in the successive USB generations from 1998 until 2015.

Here as well, the table reveals a core of firms involved throughout the main events surrounding the evolution of the USB standard, including (in alphabetical order) HP, IBM, Intel, and Microsoft.

Bluetooth. Much like USB, the Bluetooth standard is governed by a private SSO, the Bluetooth Special Interest Group (SIG). There have been four generations of the standard so far. Data was collected from the website of the Bluetooth SIG and checked against relevant literature (Keil, 2002). As with USB, leading firms are designated as ‘promoters.’ Table 4 indicates, on a yearly basis, which companies had the role of ‘promoters’.[19]

Even if the yearly table does not quite give a sense of how the core contributors might have varied from one generation to the next, it does point to a stable core of members, around Ericsson, Intel, Lenovo, Microsoft, Motorola, Nokia, and Toshiba.

[19]Data for 2011 was unavailable.

Table 3: Promoters in the USB specification generations

	USB 1.0	USB 2.0	USB icon	USB 3.0	USB-C	Current
Compaq	x	x	x			
DEC	x					
IBM	x		x		x	
Intel	x	x	x	x		x
Microsoft	x		x	x		x
NEC	x	x	x	x		
Nortel	x					
HP		x	x	x		x
Lucent		x	x			
Philips		x				
Dell			x			
Gateway			x			
ST NXP-Wireless				x		
Texas Instruments				x		
Renesas Electronics						x
STMicroelectronics						x

Source: data collected from the USB Implementers Forum (USBIF) website (www.usb.org).

Table 4: Promoters in the Bluetooth SIG, year by year

	2006	2007	2008	2009	2010	2012	2013	2014	2015
Ericsson	x	x	x	x	x	x	x	x	x
Lenovo		x	x	x	x	x	x	x	x
Intel	x	x	x	x	x	x	x	x	x
Microsoft	x	x	x	x	x	x	x	x	x
Motorola	x	x	x	x	x	x	x	x	x
Nokia	x	x	x		x	x	x	x	x
Toshiba	x	x	x	x	x	x	x	x	x
Agere Systems	x								
IBM	x								

Source: data collected from the Bluetooth Special Interest Group (SIG) website (www.bluetooth.org).

6 Conclusion

As part of the standard-setting process, certain patents become essential. This may allow the owners of these standard-essential patents to hold up implementers of the standard, who can no longer turn to substitute technologies. However, many real-world standards evolve over time, with several generations of standards succeeding each other. Thus, standard setting is a repeated game in which participants can condition future behavior on whether or not hold-up has occurred in the past. In the presence of complementarity between the different patents included in the standard, technology contributors have an incentive to discipline each other and keep royalties low, which can be achieved by threatening to exclude contributors who have engaged in hold-up from future rounds of the process. We show that repeated standard setting can sustain FRAND royalties provided the probability that another round of standard setting will occur is sufficiently high. This result does not rely on intervention by competition authorities or courts. We also examine how the decision-making rules of standard-setting organizations affect the sustainability of FRAND royalties.

Appendix: Proofs

Proof of Proposition 2. Consider first the case in which a single proposal has been submitted, say by i ($s = i$). By assumption, B_{-i} votes against the proposal, while B_i and the downstream firms vote in favor. A's vote only matters if it is pivotal, i.e., if

$$\frac{1+D}{3+D} < \gamma \leq \frac{2+D}{3+D}. \tag{2}$$

The second inequality in (2) is satisfied by assumption. If the first inequality is not satisfied (i.e., $(1+D)/(3+D) \geq \gamma$), the proposal is adopted regardless of A's vote. If the first inequality is satisfied, the proposal is adopted if and only if A votes in favor. Voting in favor yields A a payoff of $(v_s/3)^2$, while voting against yields $\alpha(v_s/3)^2$; hence for any $\alpha < 1$, A votes in favor when pivotal, and for $\alpha = 1$, the proposal gets adopted even if A votes against. In sum, when there is a single proposal, it is adopted.

Now consider the case where B_1 and B_2 have both submitted proposals. By assumption, B_1 and B_2 vote in favor of their own proposal and against the rival's. To determine the behavior of the downstream firms and innovator A, we start at the second vote and work backward to the first.

Second vote:

If B_1 is on the ballot, the downstream firms always vote in favor. If $(1 + D)/(3 + D) \geq \gamma$, the proposal is adopted regardless of A's vote, while if $(1 + D)/(3 + D) < \gamma$, the proposal is adopted if and only if A votes in favor. Voting in favor yields A a payoff of $(v_1/3)^2$, while voting against yields $\alpha[\beta(v_1/3)^2 + (1 - \beta)(v_2/3)^2]$. Hence, for any $\alpha < 1$ or $\beta < 1$, A votes in favor when pivotal, and for $\alpha = \beta = 1$, the proposal gets adopted even if A votes against.

If B_2 is on the ballot, the voting behavior of A and the downstream firms depends on whether $\alpha \leq \alpha^*(\beta)$:

- If $\alpha \leq \alpha^*(\beta)$, the downstream firms vote in favor. Again, if $(1 + D)/(3 + D) \geq \gamma$, the proposal is adopted regardless of A's vote, while if $(1+D)/(3+D) < \gamma$, the proposal is adopted if and only if A votes in favor. Voting in favor yields A a payoff of $(v_2/3)^2$, while voting against yields $\alpha[\beta(v_1/3)^2 + (1 - \beta)(v_2/3)^2]$. Because $\alpha \leq \alpha^*(\beta)$, A votes in favor.

- If $\alpha > \alpha^*(\beta)$, the downstream firms vote against. A is pivotal if

$$\frac{1}{3 + D} < \gamma \leq \frac{2}{3 + D}. \tag{3}$$

  The first inequality is always satisfied since $1/(3 + D) < 1/2 < \gamma$. If the second inequality is not satisfied (i.e., $\gamma > 2/(3+D)$), the proposal is rejected regardless of A's vote. If the second inequality is satisfied (i.e., $\gamma \leq 2/(3 + D)$), the proposal is adopted if and only if A votes in favor. Voting in favor yields A a payoff of $(v_2/3)^2$, while voting against yields $\alpha[\beta(v_1/3)^2 + (1 - \beta)(v_2/3)^2]$. Because $\alpha > \alpha^*(\beta)$, A votes against.

To summarize, B_1's proposal is always accepted at the second vote, while B_2's proposal is accepted if and only if $\alpha \leq \alpha^*(\beta)$ and rejected otherwise.

First vote:
Regardless of whether $\alpha \leq \alpha^*(\beta)$, consumer surplus from adopting B_1's proposal at the first vote is always greater than the expected consumer surplus from holding a second vote on B_2's proposal:

$$v_1^2 \geq \max\{v_2^2, \alpha[\beta v_1^2 + (1-\beta)v_2^2]\}.$$

Conversely, rejecting B_2's proposal and holding a second vote on B_1's proposal yields higher consumer surplus than adopting B_2 at the first vote. Hence, the downstream firms vote in favor of B_1 and against B_2. Because A's payoff is also increasing in v_s, A similarly votes for B_1 and against B_2 whenever pivotal at the first vote. Finally, note that B_2's proposal cannot be adopted without A's support as $1/(3+D) < 1/2 < \gamma$, and B_1's proposal cannot be rejected without A voting against as $\gamma \leq (2+D)/(3+D)$. Thus, B_1's proposal is adopted and B_2's rejected at the first vote regardless of whether or not A is pivotal.

The equilibrium thus always involves B_1's proposal receiving a super-majority. B_2's proposal never receives a super-majority unless it is the only proposal. Moving back to the proposal stage, it follows that for any proposal cost $0 < c < (v_1/3)^2$, the unique subgame perfect equilibrium is such that only B_1 makes a proposal. By assumption, $c > 0$. Moreover, $c < \bar{r}v_2/2$, so Assumption 2 implies $\bar{r}v_2/2 = (v_1 - v_2)v_2/2 < (v_1/3)^2$ and hence $c < (v_1/3)^2$. □

Proof of Proposition 3. Consider the following equilibrium candidate. Both B_1 and B_2 make proposals for standards. At the first vote, everybody votes against B_2 and everybody except the downstream firms votes against B_1. At the second vote, everybody votes in favor of B_1 and B_2. We now show that this strategy profile forms an equilibrium under the assumptions stated in the proposition.

The assumption $\alpha \leq \alpha^*(\beta)$ implies that the downstream firms vote in favor of B_1 and B_2 at the second vote. Because a single vote cannot prevent a super-majority, none of the other three players can change the outcome of the vote by unilaterally deviating and voting against. Thus, everybody voting in favor of either proposal is an equilibrium in the subgame following rejection at the first vote. Moving back to the first vote, the downstream firms vote in favor of B_1 and against B_2. If B_2 is on the ballot, none of the other players can change the outcome by unilaterally deviating and voting in favor. If B_1 is on the ballot, a unilateral deviation by one of the other three players results in a share of favorable votes of $(1+D)/(3+D)$, which by assumption is less than γ so it does not change the outcome. Thus, everybody except the downstream firms voting against any proposal at the first vote is an equilibrium.

Hence, in equilibrium the proposal that is on the ballot at the second vote is adopted. Since B_1 and B_2 are equally likely to be first and second, each proposal gets adopted with probability 1/2. Firm B_i's expected payoff from introducing a proposal is $(1/2)(v_i/3)^2 - c$, $i = 1, 2$. Thus if $(1/2)(v_2/3)^2 \geq c$ both introduce proposals. □

Proof of Proposition 4. We construct three phases of play called C, P and R. The phases are associated with the following stage-game strategies:

C**:** Only B_1 proposes a standard ($x_1^t = 1$, $x_2^t = 0$). Everybody votes in favor of B_1's and against B_2's proposal: for all ϑ and j, $\phi_{\vartheta j}^t(\tilde{s}_\vartheta^t) = 1$ if and only if $\tilde{s}_\vartheta^t = 1$. The royalties charged are $r_1^t(s^t) = \bar{r}$ for all s^t, $r_2^t(s^t) = v_2/3$ for all s^t, $r_A^t(1) = (v_1 - \bar{r})/2$, $r_A^t(2) = v_2/3$.

P**:** B_2 proposes a standard ($x_2^t = 1$). B_1 proposes a standard ($x_1^t = 1$) if $q_1(v_1/3)^2 - c \geq 0$ and does not propose a standard ($x_1^t = 0$) otherwise. A and B_2 vote in favor of B_2 and against B_1, while B_1 votes in favor of B_1 and against B_2: for all ϑ and for $j = A, B_2$, $\phi_{\vartheta j}^t(\tilde{s}_\vartheta^t) = 1$ if and only if $\tilde{s}_\vartheta^t = 2$, while for all ϑ, $\phi_{\vartheta 1}^t(\tilde{s}_\vartheta^t) = 1$ if and only if $\tilde{s}_\vartheta^t = 1$. The royalties charged are $r_1^t(s^t) = v_1/3$ for all s^t, $r_2^t(s^t) = v_2/3$ for all s^t, $r_A^t(1) = v_1/3$, $r_A^t(2) = v_2/3$.

R**:** Only B_1 proposes a standard ($x_1^t = 1$, $x_2^t = 0$). Everybody votes in favor of B_1's and against B_2's proposal: for all ϑ and j, $\phi_{\vartheta j}^t(\tilde{s}_\vartheta^t) = 1$ if and only if $\tilde{s}_\vartheta^t = 1$. The royalties charged are $r_1^t(s^t) = \tilde{r}$ for all s^t, $r_2^t(s^t) = v_2/3$ for all s^t, $r_A^t(1) = (v_1 - \tilde{r})/2$, $r_A^t(2) = v_2/3$.

Transitions between phases are as follows. At $t = 1$, start in phase C. Remain in phase C as long as B_1 does not deviate. If B_1 deviates, move to phase P for L rounds. If someone other than B_1 deviates return to C; if B_1 deviates restart phase P. If no one deviates during the L rounds, move to phase R. Remain in phase R unless someone deviates. If B_1 deviates, move to P for L rounds and then return to R. If A deviates, return to C. Deviations by B_2 are inconsequential. This determines how strategies depend on the history of play.

During the punishment phase, B_i's proposal is adopted with probability q_i, $i = 1, 2$, with $q_1 + q_2 \leq 1$; (q_1, q_2) depends on the parameters α, β, and γ as specified in Proposition 7. For this proof we work with the reduced-form probabilities q_1 and q_2.

Note that A and B_2 have no unilateral incentive to deviate from C since they play static best responses. Thus we do not need separate punishment phases for these players. What we need to show is that, for δ close to 1,

(a) A and B_2 are willing to carry out the punishment. Specifically, B_2 must be willing to introduce a proposal ($x_2^t = 1$), while A must be willing to vote in favor of B_2 and against B_1. B_2 is willing to make a proposal if and only if $c \leq q_2(v_2/3)^2$. This condition is satisfied by assumption (provided A sticks to the punishment strategy). To check that A is willing to vote for B_2 and against B_1, suppose that B_1 has submitted a proposal. Suppose also that A is pivotal, in the following sense: if A votes for B_2 and against B_1, B_i's proposal is adopted with probability q_i, but if A deviates by voting for B_1 and against B_2, B_1's proposal is adopted with probability 1. During phase P firm A's per-period payoff is $q_1(v_1/3)^2 + q_2(v_2/3)^2$. During phase C its payoff is $((v_1 - \bar{r})/2)^2$. During phase R it is $((v_1 - \tilde{r})/2)^2$. Since $(v_s/3)^2 < ((v_1 - \bar{r})/2)^2 = (v_2/2)^2$ for $s = 1, 2$, a necessary condition for A to be willing to carry out the punishment is $\tilde{r} < \bar{r}$. A sufficient condition is

$$\sum_{\tau=1}^{L} \delta^{\tau-1} \left[q_1 \left(\frac{v_1}{3}\right)^2 + q_2 \left(\frac{v_2}{3}\right)^2 \right] + \frac{\delta^L}{1-\delta} \left(\frac{v_1 - \tilde{r}}{2}\right)^2 \geq \left(\frac{v_1}{3}\right)^2 + \frac{\delta}{1-\delta} \left(\frac{v_1 - \bar{r}}{2}\right)^2. \quad (4)$$

The left-hand side represents the payoff from L rounds of phase P followed by phase R forever. The right-hand side represents the payoff from deviating, which results in one round of B_1's proposal being adopted, B_1 charging $r_1^t = v_1/3$, and A best-responding by charging $r_A^t = v_1/3$, yielding a payoff of $(v_1/3)^2$, followed by phase C forever. Multiplying both sides by $(1-\delta)$, we have

$$(1-\delta)\sum_{\tau=1}^{L}\delta^{\tau-1}[q_1(v_1/3)^2 + q_2(v_2/3)^2] + \delta^L\left(\frac{v_1-\tilde{r}}{2}\right)^2 \geq$$
$$(1-\delta)\left(\frac{v_1}{3}\right)^2 + \delta\left(\frac{v_1-\bar{r}}{2}\right)^2.$$

As $\delta \to 1$, this inequality tends to

$$\left(\frac{v_1-\tilde{r}}{2}\right)^2 \geq \left(\frac{v_1-\bar{r}}{2}\right)^2,$$

which is satisfied for $\bar{r} > \tilde{r}$.

(b) B_1 does not want to deviate during phase C. B_1's payoff during phase C is $\bar{r}(v_1-\bar{r})/2 - c$ while during P it is $\max\{0, q_1(v_1/3)^2 - c\}$ and during R it is $\tilde{r}(v_1-\tilde{r})/2 - c$. If it deviates from $\bar{r}$, its best deviation is $r_1^t = (v_1 - v_2/2)/2$, which is the best response to A charging $r_A^t = (v_1-\bar{r})/2 = v_2/2$ and yields $((v_1-v_2/2)/2)^2 - c$. Thus the relevant condition is

$$\frac{1}{1-\delta}\left(\frac{\bar{r}(v_1-\bar{r})}{2} - c\right) \geq \left(\frac{v_1-v_2/2}{2}\right)^2 - c$$
$$+\sum_{\tau=1}^{L}\delta^{\tau}\max\left\{0, q_1\left(\frac{v_1}{3}\right)^2 - c\right\} + \frac{\delta^{L+1}}{1-\delta}\left(\frac{\tilde{r}(v_1-\tilde{r})}{2} - c\right). \quad (5)$$

(c) B_1 does not want to deviate during phase R. The condition is

$$\frac{1}{1-\delta}\left(\frac{\tilde{r}(v_1-\tilde{r})}{2} - c\right) \geq \left(\frac{v_1-v_2/2}{2}\right)^2 - c$$
$$+\sum_{\tau=1}^{L}\delta^{\tau}\max\left\{0, q_1\left(\frac{v_1}{3}\right)^2 - c\right\} + \frac{\delta^{L+1}}{1-\delta}\left(\frac{\tilde{r}(v_1-\tilde{r})}{2} - c\right). \quad (6)$$

Because $\bar{r} > \tilde{r}$, (5) is implied by (6), so we can focus on the latter. Noting that payoffs on the left and right-hand side are equal after the last punishment period, for $\delta = 1$ (6) becomes

$$(L+1)\left(\frac{\tilde{r}(v_1-\tilde{r})}{2} - c\right) \geq \left(\frac{v_1-v_2/2}{2}\right)^2 - c + L\max\left\{0, q_1\left(\frac{v_1}{3}\right)^2 - c\right\}. \quad (7)$$

Since we can choose $\tilde{r} = \bar{r} - \varepsilon$, where $\varepsilon > 0$ can be arbitrarily small, and $c < \bar{r}(v_1 - \bar{r})/2$ by assumption, the left-hand side is strictly positive and increasing in L for ε sufficiently small. There are two cases. If $q_1(v_1/3)^2 - c \leq 0$, the right-hand side is constant in L. Hence, it suffices that $L + 1 > (v_1 - v_2/2)^2/[2v_2/(v_1 - v_2)]$. If $q_1(v_1/3)^2 - c > 0$, we can rewrite (7) as

$$L\left(\frac{\tilde{r}(v_1 - \tilde{r})}{2} - q_1\left(\frac{v_1}{3}\right)^2\right) \geq \left(\frac{v_1 - v_2/2}{2}\right)^2 - \frac{\tilde{r}(v_1 - \tilde{r})}{2}.$$

For $\tilde{r} = \bar{r} - \varepsilon$ and $q_1 < \bar{q}$, the left-hand side is again strictly positive and increasing in L for ε small, while the right-hand side is constant in L. Hence, we can find a finite L such that the inequality is satisfied. By continuity, for δ sufficiently close to 1, B_1 has no incentive to deviate.

We conclude that for $q_1 < \bar{q}$ and $c \leq q_2(v_2/3)^2$, we can always find a finite L such that the above strategies form a subgame-perfect equilibrium if δ is close to 1. □

Proof of Proposition 5. The two conditions that need to be satisfied are (4) and (6). Rewriting (4) for the case where $L = 1$ and multiplying by $(1 - \delta)$ yields

$$\delta\left[\left(\frac{v_1 - \tilde{r}}{2}\right)^2 - \left(\frac{v_1 - \bar{r}}{2}\right)^2\right] \geq (1 - \delta)\left[(1 - q_1)\left(\frac{v_1}{3}\right)^2 - q_2\left(\frac{v_2}{3}\right)^2\right]. \quad (8)$$

Rewriting (6) for the case $c = 0$ and $L = 1$, we obtain, after simplifying,

$$(1 + \delta)\left(\frac{\tilde{r}(v_1 - \tilde{r})}{2}\right) \geq \left(\frac{v_1 - v_2/2}{2}\right)^2 + \delta q_1\left(\frac{v_1}{3}\right)^2. \quad (9)$$

Since $\tilde{r} < \bar{r}$ is needed to satisfy (8) and $\bar{r} = v_1 - v_2 \leq v_1/3$ by Assumption 2, the left-hand side of (9) is increasing in $\tilde{r}$. Noticing that

$$\left(\frac{v_1 - v_2/2}{2}\right)^2 = \max_{r_1} r_1\left(v_1 - \left(\frac{v_1 - \bar{r}}{2}\right) - r_1\right) \geq \bar{r}\left(v_1 - \left(\frac{v_1 - \bar{r}}{2}\right) - \bar{r}\right)$$
$$= \frac{\bar{r}(v_1 - \bar{r})}{2} > \frac{\tilde{r}(v_1 - \tilde{r})}{2},$$

(9) cannot be satisfied at $\delta = 0$, and cannot be satisfied unless $\tilde{r}(v_1 - \tilde{r})/2 > q_1(v_1/3)^2$. Thus, a necessary condition for (9) is that it holds for $\delta = 1$ and

$\tilde{r} = \bar{r}$, which requires

$$\bar{r}(v_1 - \bar{r}) \geq \left(\frac{v_1 - v_2/2}{2}\right)^2 + q_1 \left(\frac{v_1}{3}\right)^2,$$

or $q_1 \leq \tilde{q}(v_2)$. Since $\tilde{q}((2/3)v_2) = 1 > 0 > \tilde{q}(v_1) = -(3/4)^2$ and $\tilde{q}(v_2)$ is an inverse-U shaped quadratic expression in v_2, there exists a unique cutoff $v_2^* \in ((2/3)v_1, v_1)$ such that $\tilde{q}(v_2) > 0$ if and only if $v_2 < v_2^*$.

We can then solve for the lowest $\tilde{r}$ satisfying (9) as a function of q_1 and δ, yielding $\underline{r}(\delta, q_1)$. Hence, the critical discount factor δ^* is such that (8) evaluated at $\tilde{r} = \underline{r}(\delta, q_1)$ holds with equality. What remains to be shown is that $\delta^* < 1$. By construction, for $v_2 < v_2^*$ and $q_1 \leq \tilde{q}(v_2)$, we have $\underline{r}(1, q_1) < \bar{r}$. Continuity implies that for δ sufficiently close to 1, the left-hand side of (8) is positive and increasing in δ. Because $q_1 + q_2 \leq 1$ and $v_1 > v_2$, the right-hand side is decreasing in δ and tends to zero as δ approaches 1. We conclude that there exists a δ^* as claimed. □

Proof of Proposition 6. Let $f(\delta, q_1, q_2) \equiv g(\delta, q_1)\delta - h(q_1, q_2)(1 - \delta)$, where

$$g(\delta, q_1) \equiv \left(\frac{v_1 - \underline{r}(\delta, q_1)}{2}\right)^2 - \left(\frac{v_1 - \bar{r}}{2}\right)^2$$
$$h(q_1, q_2) \equiv (1 - q_1)\left(\frac{v_1}{3}\right)^2 - q_2\left(\frac{v_2}{3}\right)^2.$$

By Proposition 5, δ^* is implicitly defined by $f(\delta, q_1, q_2) = 0$. Thus, applying the implicit function theorem,

$$\frac{\partial \delta^*}{\partial q_1} = -\frac{\partial f/\partial q_1}{\partial f/\partial \delta} = \frac{(1-\delta)(\partial h/\partial q_1) - \delta(\partial g/\partial q_1)}{g + (\partial g/\partial \delta)\delta + h}$$
$$\frac{\partial \delta^*}{\partial q_2} = -\frac{\partial f/\partial q_2}{\partial f/\partial \delta} = \frac{(1-\delta)(\partial h/\partial q_2)}{g + (\partial g/\partial \delta)\delta + h}.$$

We have

$$\frac{\partial g}{\partial q_1} = -\underbrace{\frac{\partial \underline{r}}{\partial q_1}}_{>0}\underbrace{\left(\frac{v_1 - \underline{r}(\delta, q_1)}{2}\right)}_{>0} < 0$$
$$\frac{\partial h}{\partial q_1} = -\left(\frac{v_1}{3}\right)^2 < 0$$
$$\frac{\partial h}{\partial q_2} = -\left(\frac{v_2}{3}\right)^2 < 0.$$

Finally, the argument in the proof of Proposition 5 implies that $g+(\partial g/\partial\delta)\delta+h>0$ in the vicinity of δ^*, which establishes the sign of the effects of q_1 and q_2 on δ^*. □

Proof of Proposition 7. Suppose $\gamma \leq (1+D)/(3+D)$. Because B_1 and the downstream firms always vote in favor of B_1, B_1's proposal is adopted whenever it is on the ballot. Moreover, A's and B_2's votes are not enough to adopt B_2 at the first vote as $(1+D)/(3+D) \geq \gamma > /2$ implies $2/(3+D) < 1/2 < \gamma$. Hence, $q_1 = 1$, establishing the first claim.

Now suppose $(1+D)/(3+D) < \gamma \leq 2/(3+D)$. Then, the above results are reversed: A and B_2 can adopt B_2's proposal by voting in favor whenever it is on the ballot, and the votes of B_1 and the downstream firms are not enough to adopt B_1 when it is on the ballot first. Hence, $q_1 = 0$ and $q_2 = 1$.

If instead $\gamma > \max\{(1+D)/(3+D), 2/(3+D)\}$, neither A and B_2 nor B_1 and the downstream firms have a super-majority. Thus, none of the two proposals can be adopted at the first vote. There are two cases to consider:

(i) For $\alpha \leq \alpha^*(\beta)$, the downstream firms vote in favor of B_2 at the second vote. Hence, B_2 gets adopted if B_1 is on the ballot first and B_2 second (probability 1/2). If instead B_2 is on the ballot first and B_1 second (probability 1/2), neither of them receives a super-majority, so B_1 is adopted with probability $\alpha\beta$ and B_2 with probability $\alpha(1-\beta)$.

(ii) For $\alpha > \alpha^*(\beta)$, the downstream firms vote against B_2 at the second vote. Hence, no proposal ever receives a super-majority, so B_1 is adopted with probability $\alpha\beta$ and B_2 with probability $\alpha(1-\beta)$.

□

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