NBER WORKING PAPER SERIES

PATENT DISCLOSURE IN STANDARD SETTING

Bernhard Ganglmair
Emanuele Tarantino

Working Paper 17999
http://www.nber.org/papers/w17999

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
April 2012

Financial support from the Center for the Analysis of Property Rights and Innovation (CAPRI) at the University of Texas at Dallas and the NET Institute (www.NETinst.org) is gratefully acknowledged. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 17999
April 2012
JEL No. D71,D83,L15,O34

ABSTRACT

In a model of industry standard setting with private information about firms' intellectual property, we analyze (a) firms' incentives to contribute to the development and improvement of a standard, and (b) firms' decision to disclose the existence of relevant intellectual property to other participants of the standard-setting process. If participants can disclose after the end of the process and fully exploit their bargaining leverage, then patent holders aspire to disclose always after the end of the process. However, if a patent holder cannot rely on the other participants to always contribute to the process, then it may be inclined to disclose before the end of the process. We also analyze under which conditions firms enter cross-licensing agreements that eliminate the strategic aspect of patent disclosure, and show that, in an institutional setting that implies a waiver of intellectual property rights if patents are not disclosed timely, firms aspire to disclose before the end of the process. Finally, we study the effect of product-market competition on patent disclosure.

Bernhard Ganglmair
University of Texas at Dallas
Naveen Jindal School of Management
800 W. Campbell Rd (SM31)
Richardson, TX 75080
ganglmair@utdallas.edu

Emanuele Tarantino
Department of Economics - University of Bologna
Piazza Scaravilli, 1
40126 Bologna Italy
emanuele.tarantino@unibo.it

1 Introduction

Industry standards are developed and implemented to facilitate the interoperability of products and increase their value to customers (Scotchmer, 2004:289ff; Shapiro and Varian, 1998). Other benefits are the reduction of production cost (Thompson, 1954), improvement in the rate of diffusion of new technologies (Rysman and Simcoe, 2008), and the elimination of mis-coordination among producers (Farrell and Klemperer, 2007:2026f). In this paper, we study how the effectiveness of the process of developing and improving a standard is affected when new technologies are patent-protected. We ask to what extent strategic disclosure of these patents undermines the work of a standard setting organization (SSO).

Chiao, Lerner, and Tirole (2007) study the relationship between intellectual property disclosure rules and the level of license prices[1] and find that firms' propensity to disclose depends on the value of the royalty fees they expect to raise. This result suggests that disclosure of patents may be used strategically as it can provide the patent holder with a bargaining leverage over prospective users. This is often referred to as patent holdup,[2] an issue at the core of many high profile antitrust cases.[3] In addition, the empirical analysis in Layne-Farrar (2011b) documents that, in absence of a clear rule, firms postpone the disclosure of relevant patents until the end of the standard-setting process, i.e., after the publication of a standard version (*ex-post* disclosure). The introduction of a disclosure rule, clarifying firms' obligation to declare (i.e., disclose) relevant patents before the publication of a standard, then triggers earlier patent declarations (*ex-ante* disclosure).[4]

We develop a formal game theoretic model to shed light on firms' incentives to contribute to a standard-setting process and to disclose patents they hold. We answer the following questions: Is *ex-ante* disclosure ever feasible in absence of an obligation, and what is the impact of the disclosure rules on the timing of patent disclosure? What are the incentives to enter a cross-licensing agreement and thus, to contractually solve

[1]Throughout the paper we refer to patents as the source of intellectual property rights.

[2]See Farrell, Hayes, Shapiro, and Sullivan (2007), Lemley and Shapiro (2007), Farrell and Shapiro (2008), Ganglmair, Froeb, and Werden (forthcoming), Shapiro (2010), or Tarantino (2011), among others. The patent holdup problem is a greatly debated issue in the law and economics literature—with dissonant positions. Lemley and Shapiro (2007), for instance, stress the adverse impact of holdup on licensing decisions in industries with complex products, whereas Geradin (2009) suggests the real impact of patent holdup on the correct functioning of standard setting organizations be over-rated.

[3]In the FTC matters against Dell Computer Corp. (*Dell Computer Corp., FTC Docket NO. C-3658, 121 F.T.C. 616 (1996)*) and Rambus Inc. (*FTC v. Rambus Inc., 522 F.3d 456, D.C. Cir. 2008*), the European Commission against Rambus (*"Antitrust: Commission confirms sending a Statement of Objections to Rambus", MEMO/07/330*), or *Broadcom Corp. v. Qualcomm Inc., 501 F.3d 297, 3d Cir. 2007*, accusers contended that patentees failed to comply with the SSO's disclosure rules.

[4]Layne-Farrar (2011b) studies the timing of more than 14,000 patent declarations (i.e., disclosure) in the European Telecommunication Standards Institute (ETSI) as of December 2010. The dataset contains declarations to important mobile telecom related ETSI projects, such as GPRS, GSM, UMTS, and WCDMA. In November 2005, ETSI modified its disclosure rule to clarify what was meant by "timely" disclosure in relation to the development of standards and technical specifications.

the patent holdup problem prior to standard setting? Finally, what role does market competition play and how does it affect firms' incentives? We address these questions by means of a dynamic model with asymmetric information that draws on Stein (2008), in which two firms are engaged in the process of standard setting. They contribute to the standard by taking turns in suggesting new ideas for standard improvements.

The model is based on three main assumptions: First, ideas for improvements are complementary insofar as a firm can find a new idea only if the other firm has suggested an idea in the previous round (Hellmann and Perotti, 2011; Stein, 2008).[5] Second, firms may hold a patent on an idea they communicate, and we assume asymmetric information about the existence of such a patent. This means, a firm j does not know about a firm i's patent but has prior beliefs. Likewise, firm i does not know about firm j's patent, but has prior beliefs.[6] The implication of this assumption is that, unless disclosed by its holder, members of an SSO may at best have a prior belief as to whether a given (essential) technology in the standard is patent-protected. Third, the patent holder can demand the payment of license fees from other firms producing within the standard. These license fees depend on and are strictly increasing in the patent holder's bargaining leverage which in return, is a result of the technology users' lock-in. Such lock-in arises when firms rely on the standard (yet to be published and adopted), make a standard-specific investment, and manufacture final products based on the present state of the standard proposal.[7] We assume that the extent of lock-in increases as the patent holder delays disclosure of its patent.

For our baseline model, participants can disclose after the end of the process (*ex post*) and fully exploit their bargaining leverage without incurring any cost. Under this modeling assumption, we show that if a patent holder expects the other participant to always contribute to the process with an idea for standard improvement, then it is in its best interest to contribute itself and disclose as late as possible (Proposition 2). This implies—consistent with the empirical evidence in Layne-Farrar (2011b)—that if the participants prefer the standard-setting process to continue, we expect *aspired* patent disclosure to be *ex post*. However, if a patent holder cannot rely on the other participant to always contribute to the process, then in equilibrium the disclosure decision is constrained and the patent holder may be inclined to disclose *ex ante*. We

[5] If a firm j in $t+1$ does not exchange a new idea, then firm i gains no new insights and information. If, then, firm i were to find a new idea in $t+2$, it would have already found and communicated the idea in t.

[6] Chiao, Lerner, and Tirole (2007:911) report that "due to the ... complexity of patent portfolios, rivals frequently could not determine 'the needle in the haystack': that is, which patents were relevant to a given standard-setting effort." More generally, as reported in a public hearing conducted by the Department of Justice and the Federal Trade Commission in 2007, the identification of a patent that is relevant to the development of a specific standard imposes significant search costs on SSO participants (U.S. Dep't of Justice & Fed. Trade Comm'n, 2007:43).

[7] Firms, e.g., in highly innovative and dynamic industries, invest in standard-specific technologies during the process because they expect the market for the final standard-based product to be short-lived. Only by such early investment can they capitalize on respective market opportunities. See Farrell and Klemperer (2007) for a comprehensive review of the literature on lock-in.

thus show that *ex-ante* equilibrium disclosure is observable even in the absence of a disclosure rule (Propositions 3 and 4). Such a constrained disclosure decision arises when the other firm expects to pay a large license fee were the process to continue without disclosure, inducing it to stop (absent disclosure) and limit the patent holder's bargaining leverage. The motivation for the patent holder to reveal private information is to salvage the standard-setting process.

In two extensions, we analyze the impact of licensing and standard-setting specific institutions on disclosure. We first introduce the possibility of cross-licensing eliminating the strategic aspect of patent disclosure. Firms can enter cross-licensing agreements by which they commit to license each other any intellectual property they may hold. We show that such agreements are feasible when at least one firm is *pessimistic* about the size and scope of its patent portfolio and thus, its chances to gain higher expected profits in a non-cooperative environment than with the cross-licensing agreement (Proposition 5).[8]

We then assume an institutional setting that implies a *waiver* of intellectual property rights if patents are not disclosed in a timely manner to other participants.[9] As before, firms are inclined to delay disclosure in order to increase their bargaining leverage (i.e., license fees), but by such a delay, they run the risk of not getting to disclose in time and see their intellectual property rights waived. We find that the introduction of a disclosure rule with an implied waiver induces firms to disclose *ex ante*, that is before the end of the process (Proposition 6). This result is consistent with the finding in Layne-Farrar (2011b) that the introduction of such a rule prompts earlier disclosure.

In a final step, we assume that standard-setting participants compete on the product market. We thus introduce the very tradeoff analyzed in Stein (2008): A longer standard-setting process increases the quality of the standard, so firms share a common interest in continuing to contribute to the process as long as possible. On the other hand, if a firm stops contributing and does not reveal a new idea for improvement, it gains a competitive advantage over its product-market rival.[10] This latter effect introduces an additional incentive not to contribute but to halt communication during the

[8]Other studies in this literature discuss the use of cross-licensing to reduce the level of royalty rates (Shapiro, 2001), look at the relationship between cross-licensing and the pace of the innovation race (Fershtman and Kamien, 1992), or show that firms with higher asset specificity have greater incentive to cross-license (Galasso, forthcoming).

[9]The United States Court of Appeals for the Federal Circuit ruled in *Qualcomm Inc. v. Broadcom Corp., Docket Number 07-1545, Nos. 2007-1545, 2008-1162*, at http://caselaw.findlaw.com/us-federal-circuit/1150919.html: *"[W]e agree with the district court that, '[t]he working policy of disclosure of related patents is treated by the group ... as imposing an obligation to disclose information.' ... [W]e conclude that it was within the district court's authority ... to determine that Qualcomm's misconduct falls within the doctrine of waiver ... and remand with instructions to enter an un-enforceability remedy limited in scope to any [standard]-compliant products."* See also the European Commission's decision on the Rambus case at http://europa.eu/rapid/pressReleasesAction.do?reference=IP/09/1897.

[10]Layne-Farrar (2011a) argues that, due to the incremental nature of the standard-setting process in ETSI, firms often develop valuable ideas right after standard publication and use them opportunistically to gain an advantage on the product market. This evidence is consistent with the type

standard-setting process. Accordingly, we find that competition reduces firms' incentives to contribute to the process implying an even stronger prevalence of constrained disclosure (Proposition 8). Second, we show that product market collusion spurs firms' communication and hence limits the scope for disclosure to be constrained in equilibrium. Third, we analyze a standard setting environment characterized by the presence of a "lead firm" that has access to a larger market than its competitor. We show that this reduces incentives to contribute to the standard-setting process, constrains firms' disclosure decision, and results in earlier disclosure.

The literature on standard setting has typically focused on the importance of SSOs in limiting producers mis-coordination (Farrell and Klemperer, 2007) and has analyzed the strategic conflicts that may influence their technology adoption decisions (Farrell and Simcoe, forthcoming; Lerner and Tirole, 2006; Simcoe, 2012).[11,12] This view is consistent with the instances of standard definitions in the presence of a limited number of competing technologies, such as Matsushita's *VHS* vs. Sony's *Betamax* or Sony's *Blu-ray Disc* vs. Toshiba's *HD-DVD*. Our modeling approach, on the other hand, captures standard setting in environments characterized by a genuine need to develop a standardized technology. This is the case in SSOs such as ETSI or JEDEC, where firms repeatedly meet to develop a standard by exchanging ideas in a cooperative environment. Our findings suggest that the functioning of these processes is by asymmetric information or product market competition.[13]

Chiao, Lerner, and Tirole (2007) analyze the interaction between firms' disclosure and licensing decisions. In their theoretical setup, a patent holder decides to disclose by trading off the need to reassure users that they will not be held up against the fear to reveal its own technological strategies. They show, theoretically and empirically, that if a patent holder expects to raise a higher royalty rate, then its incentives to disclose its patent increase.[14] We develop on their analysis by characterizing the timing of the disclosure decision and by relating this decision to standard setting and market

of competitive advantage that a firm acquires by concealing an idea for improvement to the other standard setting participant in our model.

[11]Farrell and Simcoe (forthcoming) study the impact of vested interests on SSOs technology adoption. In their setup, the standard-setting process is modeled as a war of attrition between two technology owners. Simcoe (2012) develops a model of standard setting in the presence of conflicting interests among technology proponents and shows that Internet commercialization caused a slowdown in standard setting at the Internet Engineering Task Force (IETF). Lerner and Tirole (2006) analyze the role of SSOs as technology certifiers. In their model, the technology owner chooses an SSO to solve the trade-off between trying a tough certifier (reducing the probability of technology endorsement) or a soft certifier (making users less likely to adopt the standard).

[12]The empirical literature shows that these strategic effects are likely to be amplified if the standard incorporates intellectual property. See Weiss and Sirbu (1990) or Farrell and Klemperer (2007). Also, Feldman, Graham, and Simcoe (2009) document that patents disclosed to SSOs are highly litigated.

[13]See Layne-Farrar (2011a) who characterizes the implementation details of the UMTS standard as innovation incremental in nature. Another example of this innovative class of standard-setting processes is IETF. Simcoe (2012:312f) describes the early IETF as an SSO that "creates and maintains" standards, with early members being academic and government researchers.

[14]More specifically, their empirical investigation shows that a stricter intellectual property rule

institutions. We thus provide a setup that helps identify whether a patent holder has incentives to hold up prospective users, a critical issue in the antitrust cases mentioned above.

Our results further contribute to the literature on knowledge diffusion and collective decision making. Hellmann and Perotti (2011) analyze the "symbiotic interaction" of firms and markets in the process of developing and promoting new ideas. Stein (2008) presents a model in which product market competitors exchange ideas to increase the value of the market but at the same time have an incentive not to contribute to this process to reap profits from this increased market value. Our model, built on the basic framework in Stein (2008), extends his analysis by considering the effect on this process of patents and their disclosure. Haeussler, Jiang, Thursby, and Thursby (2009) build a model of knowledge diffusion among academic scientists. As in our analysis, complementary information is needed to solve a problem. Yet, while they assume that each agent can quit the information sharing game with their own solution to the problem, in our model a successful standard-setting process requires collaboration of all parties involved.[15]

We also contribute on the literature that studies the impact of competition on the incentives to share knowledge. In particular, our result that competition inhibits the communication of ideas for improvement (see Propositions 7 and 8) is consistent with the findings in von Hippel (1987) and Pérez-Castrillo and Sandonís (1996) where cooperative communication between competitors can take place provided tough competition is not at work.[16] We deliver the analogous result that harsher competition threatens firms' discussions and prevents cooperative standard-setting.

The paper is structured as follows: In Section 2 we introduce the setup, in Section 3 we present the equilibrium results for the baseline model. We discuss the extensions of cross-licensing and disclosure rules in Section 4 and the extension of product-market competition in Section 5. Section 6 concludes. The formal proofs of the results are relegated to the Appendix.

2 Basic Model

We consider two firms, A and B, that take turns in creating or improving an existing technology as industry standard. They do this by exchanging ideas for improvement

(such as a mandating royalty-free provision) is negatively associated with the presence of a disclosure requirement.

[15] Anton and Yao (2002) consider disclosure of knowledge (from pure ideas to inventions) when intellectual property rights offer only limited protection. Disclosure in this context is related to the sale of ideas and not a contribution to a creative process.

[16] von Hippel (1987) discusses an example from the aerospace industry, where firms competing for an important government contract report not to trade information with rivals. Pérez-Castrillo and Sandonís (1996) argue that in research joint ventures partners have little incentive to share information when they are simultaneously competitors in other markets.

that arrive with exogenous probability.[17] Once the process comes to an end, the standard comprises the stock of ideas exchanged. The larger the number of improvements, the more valuable the standard is to the firms. Firms may hold patents on these ideas that allow them to collect license fees. Below we describe in more detail the standard-setting process and the firms' payoffs.

2.1 Standard-Setting Process

The firms take turns with A moving at stages $t = 1, 3, 5, \ldots$ and B moving at stages $t = 2, 4, 6, \ldots$. We denote the first stage at which a firm i gets to move by t_i^0 so that $t_A^0 = 1$, $t_B^0 = 2$, and $T_i := \{t_i^0, t_i^0 + 2, t_i^0 + 4, \ldots\}$. At stage $t = 1$, firm A has access to a patent-protected technology χ_1, and firm B has a prior belief $\pi^B > 0$ this technology is protected by a patent. If, at $t = 1$, firm A shares this technology with firm B, then B observes with probability $p \in (0, 1)$ a technology or idea χ_2 that improves firm A's technology and thus increases the value of the standard. Firm A has a prior belief $\pi^A > 0$ that this χ_2 is patent-protected. All future ideas χ_t, $t \geq 3$, are not patent-protected. Beliefs $Pr(i = i_1) = \pi^j$ and $Pr(i = i_0) = 1 - Pr(i = i_1) = 1 - \pi^j$, where $i = i_1$ denotes a patent holder i and $i = i_0$ a non-patent holder i, are common knowledge.

Once a new idea has arrived, firm A at any odd $t \in T_A$ and firm B at any even $t \in T_B$ have three possible actions: (1) *stop*, S (not share χ_t), (2) *continue*, C (share χ_t but not the fact that $\chi_{t_i^0}$ is patent-protected), or (3) *disclose*, D (share χ_t and, if not done so at an earlier stage, the fact that $\chi_{t_i^0}$ is patent-protected). Let $\tau_i \geq t_i^0$ denote the period in which firm i discloses the patent, then the firms' action sets at each t are:

$$\mathcal{S}_{1|t \leq \tau_i} = \{S, C, D\}, \qquad \mathcal{S}_{1|t > \tau_i} = \mathcal{S}_{0|t} = \{S, C\}. \tag{1}$$

Note that if firm i chooses to continue but not to disclose the patent at $t = t_i^0$, it can reconsider and disclose at any later t. The structure of the game is depicted in Figure 1.[18]

A firm cannot credibly communicate that it does *not* have a patent on its technology. Moreover, patents are fully verifiable,[19] implying that a non-patent holder cannot credibly claim that she does have a patent. We restrict firms' pre-commitment as follows:

ASSUMPTION 1. *Firms cannot at any time t precommit to disclose at $t+k$, $k \geq 2$.*

[17]Firms may have a lot of ideas, yet ideas that actually improve the standard arrive with constant probability.

[18]Figure 1 depicts only the part of the decision tree in which firm A is a patent holder. Due to the one-sidedness of the decision tree, firm B's information sets are not depicted. As long as i has not disclosed, firm j forms posterior beliefs π_t^j as to whether firm i's initial technology is patent-protected. Firm j's posterior beliefs are given in brackets. Decision nodes without this bracket notation have posterior beliefs of $\pi_t^j = 1$ because i has disclosed the patent.

[19]Patents are identifiable through a unique patent number. In the U.S. and other jurisdictions, the directory of patents can be accessed by the public.

The decision to disclose can take place either before the standard-setting process has come to an end or after the process is over. We refer to disclosure before the process has come to an end as *ex-ante* disclosure, and to disclosure after the process is over as *ex-post* disclosure.

A central assumption about the process of standard setting is the strict complementarity of ideas (Hellmann and Perotti, 2011; Stein, 2008).

ASSUMPTION 2. *Ideas are strictly complementary. If a new idea does not arrive or one of the firms decides to stop, the standard-setting process ends.*

If at t a new idea has arrived and the firm decides to either *disclose* or *continue* by sharing the idea with its competitor, in $t+1$ a new idea χ_{t+1} will arrive with probability p. If a firm has not disclosed and the process comes to an end in t, then it can disclose in t.

2.2 Product Market Profits

After the standard-setting process has come to an end, firms market respective brands and profits realize. For the baseline scenario we assume that firms i and j are both monopolists in a market of unit mass. In a latter section we allow for competition in a segment of this market.

The product-market effects of the standard are of either one of the following two types: *(a)* Due to interoperability or network effects, the standard increases the consumers' reservation value of a good that manufacturers are able to produce at constant, say zero, cost (Scotchmer, 2004; Farrell and Klemperer, 2007); and *(b)* the standard lowers the costs of production of a good for which consumers have a constant reservation value of one (Thompson, 1954).

The value of the standard, i.e., the positive effect on the reservation value or the cost savings, increases with the number of ideas of improvement exchanged and thus, with the number of rounds of the standard-setting process. We denote this number by $n_S \geq 0$. A function $h(n_S)$ captures the reservation-value or cost-saving effect.

ASSUMPTION 3. *$h(n_S)$ is increasing and continuous in n_S with $h(0) = 0$ and $\lim_{n_S \to \infty} h(n_S) = 1$.*

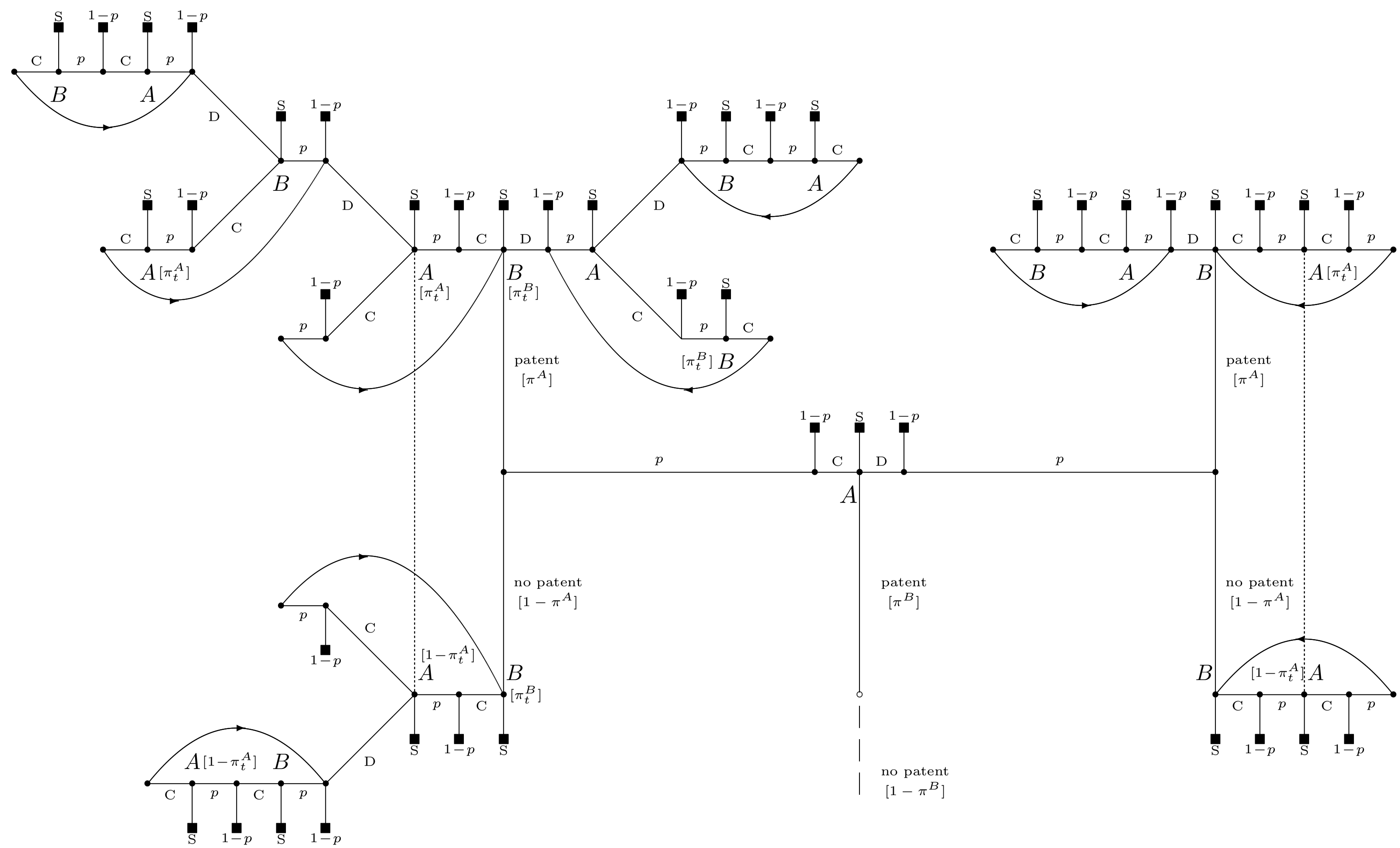
The product market profits are equal to:

$$R_i = h(n_i). \tag{2}$$

To see this, suppose the standard is of type *(a)* and increases the consumers' reservation value of the good. Let $h(n_i)$ denote this reservation value for a product i that is developed on a stock n_i of ideas. A consumer's utility from buying product i at price p_i is equal to:

$$u_i(p_i) = h(n_i) - p_i. \tag{3}$$

Figure 1: Conversation Game with Patent Disclosure When Firm A Has a Patent ($S = stop$, $C = continue$, $D = disclose$)



Consumers will purchase for any price $p_i \leq h(n_i)$, and firm i will set $p_i = h(n_i)$. If the standard-setting process stops because a new idea does not arrive, then $h(n_i) = h(n_S) = h(n_j)$. Alternatively, if firm i stops the process by not communicating an idea to firm j, then $h(n_i) = h(n_S + 1) > h(n_S) = h(n_j)$. With zero production costs, the profits are equal to the firm's revenues, $h(n_i)$.

Alternatively, suppose the standard is of type *(b)* and lowers the firms' costs of production (Stein, 2008). More specifically, a firm having access to a stock of ideas n_i produces the good at cost $1 - h(n_i)$. If firm i decides not to communicate a new idea, then firm i's production costs are $1 - h(n_S + 1) < 1 - h(n_S)$. Firm i sets a price equal to the consumers' reservation value of 1. Its profits are then equal to $h(n_i)$.

2.3 License Fees

If firm i owns a patent on one of the technologies incorporated into the standard, it can extract parts of firm j's market profits as license fees. These fees depend on the degree of lock-in of firm j and the resulting bargaining leverage for firm i (i.e., *holdup*). The function $\sigma_i : T_i \to [0, 1)$ is defined as the fraction of firm j's product market profits firm i can extract as license fees.

ASSUMPTION 4 (License Fees)**.**

1. *$\sigma_i(\tau_i)$ is continuous and strictly increasing in $\tau_i \in T_i$;*

2. *$\sigma_i(\tau_i) > 0$ if and only if $\tau_i > t_i^0$, $\sigma_i(t_i^0) = 0$ otherwise, and* $\lim_{t\to\infty} \sigma_i(t) < 1$.

The positive effect of τ_i on $\sigma_i(\tau_i)$ reflects the impact of lock-in into a standard. As more ideas for improvement, χ_t, are added to the standard, the longer the standard-setting process continues, and the more likely firms will have invested in relationship-specific assets (in reliance on the standard to be approved). Note that subscript i for the license fee function σ_i allows for firm heterogeneity. Such differences in bargaining leverage may arise, e.g., through differences in average strength of a firm's patents in its patent portfolio.

The forces that induce firms to invest before the end of the process, even at the prospect of lock-in, deserves more discussion. The standard-setting process we consider takes place in innovative and dynamic markets. For instance, firms in ETSI operate in the mobile telephony market, firms in JEDEC operate in the electronics industry. The market opportunities faced by these firms are subject to a high degree of uncertainty: Companies in related sectors, even if not direct competitors, may enter to supply new products. This means that if SSO members design their products after the standard is adopted, they lose weeks or months in which they could otherwise already market their products (had they started designing these products during the standard-setting discussions). Thus, if standard-specific investment is a time-consuming process, there is an incentive for firms to invest before the standard is decided. Moreover, if this process is sufficiently long, and the market (after standard setting) is likely to be persistent, then firms are likely to invest (and thus *lock in*) during standard setting even if they fear holdup.

Product market profits R_i in (2) are the firms' total payoffs when license fees are equal to zero. We denote the firms' total payoffs when accounting for license fees by U_i: $U_i(i,j)$ are firm i's total payoffs when both i and j have disclosed their intellectual property:

$$U_i(i,j) = (1 - \sigma_j(\tau_j))\, R_i + \sigma_i(\tau_i) R_j; \tag{4}$$

$U_i(i,0)$ are firm i's total payoffs when i has disclosed and j does not own intellectual property or has not disclosed:

$$U_i(i,0) = R_i + \sigma_i(\tau_i) R_j; \tag{5}$$

$U_i(0,j)$ are firm i's total payoffs when i has not disclosed and j has disclosed:

$$U_i(0,j) = (1 - \sigma_j(\tau_j))\, R_i + R_j; \tag{6}$$

finally, $U_i(0,0) = R_i$.

Whether or not the firms disclose their intellectual property has no impact on this value as disclosure has no social value. This is because:

$$\begin{aligned} U_i(i,j) + U_j(j,i) = U_i(i,0) + U_j(0,i) &= \\ U_i(0,j) + U_j(j,0) = U_i(0,0) + U_j(0,0) &= R_i + R_j. \end{aligned} \tag{7}$$

Hence, in a first-best world, both firms communicate respective ideas for standard improvement until a new idea fails to arrive. This maximizes the expected number of ideas, n_S, and thus, the value of the standard.

3 Equilibrium Analysis of Patent Disclosure

In this section, we present the results of the non-cooperative communication and disclosure game. By the assumption of full verifiability of patents, if a firm does not hold a patent, then it cannot disclose a patent. In the complementary case in which firms own intellectual property, we first consider the subgame in which both firms have already disclosed their patents. We then proceed to the discussion of firms' unconstrained or *aspired* disclosure date. Given that after disclosure both firms will continue the process until a new idea fails to arrive, we show that firm i's date of disclosure when firm j's communication incentives are always satisfied is *ex post*, i.e., not until the standard-setting process has come to an end. In a third step, we derive the *equilibrium* disclosure date by explicitly accounting for the possibility that firm j's communication incentives are not always satisfied so that firm i does not reach its aspired disclosure date but will, in equilibrium, disclose before then (*ex-ante* disclosure).

3.1 Post-Disclosure Communication

Suppose all firms own intellectual property and all patents have been disclosed, so that in all t, firms choose their actions from $\mathcal{S}_{1|t>\max\{\tau_i,\tau_j\}}$. In the following proposition we show that in this case, firms will in all $t > \max\{\tau_i, \tau_j\}$ continue the standard-setting process until a new idea fails to arrive.

PROPOSITION 1. *Given both firms have disclosed intellectual property, the standard-setting process will continue in all* $t > \max\{\tau_i, \tau_j\}$ *until a new idea fails to arrive.*

Following disclosure, both firms have a clear incentive to contribute to the process in order to increase the value of respective product market profits. The rationale is straightforward. Once the existence of relevant intellectual property has been revealed and $\sigma_i(\tau_i)$ and $\sigma_j(\tau_j)$ determined, it is in firm i's best interest to maximize the continuation payoffs by contributing to the process as long as possible. This is because firm i receives a fraction $1 - \sigma_j(\tau_j) + \sigma_i(\tau_i) > 0$ of the benefits of continuing standard setting. Moreover, there are no gains from stopping the process.

3.2 Unconstrained or Aspired Patent Disclosure

Before disclosure of their patent, both firms anticipate that once disclosed, the standard-setting process continues until a new idea fails to arrive. We now look at a patent holder i's *aspired* disclosure date, i.e., the date $\tau_i^a \in T_i$ for which it is individually optimal for firm i to disclose when it is not constrained by firm j's communication incentives. For this, we assume that firm j does not stop the process and its behavior is not otherwise affected by firm i's decision. Likewise, we assume for now that firm i does not find it optimal to stop the process. We reconsider this decision when we analyze equilibrium disclosure below.

A patent holder firm i in t decides whether to disclose in t or continue and (possibly) disclose in $t+2$. By Assumption 1, firm i cannot commit to disclose in either $t+2$ or $t+4$. It will instead, in $t+2$, again face the decision of whether to disclose in $t+2$ or continue in $t+2$ and possibly disclose in $t+4$. As long as the payoffs from disclosing in a period t, $\mathrm{E}_t U_i(D@t)$, are lower than the payoffs from waiting one round and reconsidering the decision in $t+2$, $\mathrm{E}_t U_i(D@t+2)$, the firm will not disclose. It will therefore disclose if, and only if,

$$\mathrm{E}_t U_i(D@t) > \mathrm{E}_t U_i(D@t+2) \tag{8}$$

with

$$\mathrm{E}_t U_i(D@t) = (1 + \sigma_i(t))\, H(t) - \pi_t^i \Lambda_t^j(\tau_j) \tag{9}$$

and

$$\mathrm{E}_t U_i(D@t+2) = H(t) + (1-p)\,\sigma_i(t+1) h(t) + p\sigma_i(t+2) H(t+1) - \pi_t^i \Lambda_t^j(\tau_j). \tag{10}$$

The expression

$$H(t) = \sum_{k=0}^{\infty} p^k (1-p)\, h(t+k) \tag{11}$$

reflects the firm's expected product market profits when the process continues until a new idea fails to arrive. The term $\Lambda_t^j(\tau_j)$ reflects firm i's expected license payments to a patent holder j. These will depend on firm i's expected product market profits and firm j's realized or anticipated disclosure date, τ_j. By our working assumptions for the case of unconstrained disclosure, τ_j is not affected by firm i's disclosure decision and is thus the same in (9) and (10). Hence, $\Lambda_t^j(\tau_j)$ is the same in (9) and (10). Moreover, beliefs π_t^i and firm i's product market profits are unaffected by firm i's decision. Note that if $\tau_j < t$, i.e., firm j has already disclosed its patent, then $\pi_t^i = 1$. Given (8), (9), and (10) we show the following:

PROPOSITION 2. *Patent holders' aspired disclosure date, $\tau_i^a \in T_i$, $i = A, B$, is after the standard-setting process has come to an end when a new idea has failed to arrive.*

The intuition for this result is straightforward. Suppose firm i has disclosed in $\tau_i < \tau_i^a$, then the fraction of firm j's profits that it can extract is $\sigma_i(\tau_i)$. Continuing communication after disclosure increases the value of the standard and thus the firms' market profits, whereas fraction $\sigma_i(\tau_i)$ is fixed for all $t \geq \tau_i$. Since $\sigma_i(\tau_i)$ is increasing in τ_i and late disclosure does not come at a cost, disclosing in $\tau_i < \tau_i^a$ is dominated by later disclosure. The latest disclosure date possible is when the process has come to an end because a new idea has failed to arrive.[20] This result is consistent with the findings of substantial *ex-post* disclosure in ETSI as documented by Layne-Farrar (2011b).

3.3 Constrained or Equilibrium Patent Disclosure

For firm i's equilibrium disclosure we have to account for firm j's incentives in $t+1$, which in return will depend on the behavior of both types of firm i. In the previous section, we assumed that firm j does not want to stop the process. But what if this is not true, what if firm j would rather stop than continue the standard-setting process? We now show that this threat of *stop* induces firm i to disclose *ex ante* and thus, alter firm j's expected payoffs such that j will indeed want to continue.

We proceed in two steps. We first assume firm j has disclosed its patent and show *ex-ante* disclosure is a possible equilibrium outcome, i.e., we show in Proposition 3 that a perfect Bayesian equilibrium in which firm i discloses its patent prior to its aspired patent disclosure date, $\tau_i^* < \tau_i^a$, exists. We then continue deriving in Proposition 4 conditions under which, in a perfect Bayesian equilibrium, firm j discloses its patent before its aspired patent disclosure date, $\tau_j^* < \tau_i^* < \tau_i^a = \tau_j^a$, when the other firm has yet to disclose.

[20] The expected disclosure date coincides with the expected duration of the standard-setting process, $E_1\tau_i^a = 1 + \sum_{k=0}^{\infty} p^k(1-p)k = \frac{1}{1-p}$.

3.3.1 Firms' Payoffs After Firm j's Disclosure

We denote by $i = i_1$ a patent holder firm i and by $i = i_0$ a non-patent holder firm i; likewise for firm j. Assume firm j has disclosed its patent (so that $j = j_1$). The payoffs for firm j in $t + 1$ and for firm i in t are as follows:

Firm j with $\mathcal{S}_{1|t>\tau_j}$: Suppose firm j has disclosed in $\tau_j < t$. In period $t + 1$ and all following, firm j either stops or continues the standard-setting process, $\mathcal{S}_{1|t>\tau_j} = \{S, C\}$. Assuming for a moment that firm i continues or discloses (that is, it does not stop, $\neg S$) in $t + 2$ if firm j continues in $t + 1$, firm j's expected payoffs are:

$$E_{t+1}U_{j_1}(S@t+1|\tau_j) = \left(1 - \pi^j_{t+1}\sigma_i(t+1)\right) h(t+1) + \sigma_j(\tau_j)h(t); \tag{12a}$$

$$\mathrm{E}_{t+1}U_{j_1}(C@t+1|\tau_j, \neg S) = H(t+1) - \pi^j_{t+1}\Lambda^i_{t+1}(\tau_i) + \sigma_j(\tau_j)H(t+1), \tag{12b}$$

where, by Lemma A1 in the appendix,

$$\Lambda^i_{t+1}(\tau_i) = \sum_{k=0}^{\tau_i-(t+2)} p^k(1-p)\sigma_i(t+2+k)h(t+1+k) + p^{\tau_i-(t+1)}\sigma_i(\tau_i)H(\tau_i) \tag{13}$$

denotes firm j's expected license payments to firm i when firm i is a patent holder and anticipated to disclose in $\tau_i \geq t + 2$ (given firm j continues in $t + 1$). It is increasing in τ_i (Lemma A1). Note that if firm j anticipates firm i to disclose when aspired, $\tau_i = \tau_i^a$, then:

$$\Lambda^i_{t+1}(\tau_i^a) := \lim_{\tau_i\to\infty} \Lambda^i_{t+1}(\tau_i) = \sum_{k=0}^{\infty} p^k(1-p)\sigma_i(t+2+k)h(t+1+k).$$

Firm $i = i_0$ with $\mathcal{S}_{0|t}$: A non-patent holder firm i's expected payoffs in t with choice set $\mathcal{S}_{0|t} = \{S, C\}$, given firm j's anticipated move in $t + 1$, are:

$$U_{i_0}(S@t|\tau_j) = (1 - \sigma_j(\tau_j))\, h(t); \tag{14a}$$

$$\mathrm{E}_tU_{i_0}(C@t|\tau_j, S) = (1 - \sigma_j(\tau_j))\, h(t); \tag{14b}$$

$$\mathrm{E}_tU_{i_0}(C@t|\tau_j, C) = (1 - \sigma_j(\tau_j))\, H(t). \tag{14c}$$

Firm $i = i_1$ with $\mathcal{S}_{1|t\leq\tau_i}$: A patent holder firm i's expected payoffs in t with choice set $\mathcal{S}_{1|t\leq\tau_i} = \{S, C, D\}$, given firm j's anticipated move in $t + 1$, are:

$$U_{i_1}(S@t|\tau_j) = (1 - \sigma_j(\tau_j))\, h(t) + \sigma_i(t)h(t-1); \tag{15a}$$

$$\mathrm{E}_tU_{i_1}(C@t|\tau_j, S) = (1 - \sigma_j(\tau_j))\, h(t) + \sigma_i(t+1)\left[ph(t+1) + (1-p)h(t)\right]; \tag{15b}$$

$$\mathrm{E}_tU_{i_1}(C@t|\tau_j, C) = (1 - \sigma_j(\tau_j))\, H(t) + \Lambda^i_t(\tau_i); \tag{15c}$$

$$\mathrm{E}_tU_{i_1}(D@t|\tau_j, S) = (1 - \sigma_j(\tau_j))\, h(t) + \sigma_i(t)\left[ph(t+1) + (1-p)h(t)\right]; \tag{15d}$$

$$\mathrm{E}_tU_{i_1}(D@t|\tau_j, C) = (1 - \sigma_j(\tau_j) + \sigma_i(t))\, H(t). \tag{15e}$$

Analogous to (13), $\Lambda_t^i(\tau_i)$ denotes the expected license payments from firm j to firm i, where expectations are formed in t. Observe that unlike in expression (12b), a patent holder i_1 knows its type and anticipates these expected license payments with certainty.

3.3.2 Firm i's Disclosure After Firm j's Disclosure

We now derive sufficient conditions for firm i to disclose in t so as to induce firm j—which would stop otherwise—to continue in $t+1$. The equilibrium results are summarized in Proposition 3. The firms' decisions in t and $t+1$ are determined by their types and what they anticipate the other firm will do in the subsequent period. First, note that if firm i discloses, then by Proposition 1 firm j will continue.

Firm j in $t+1$: In $t+1$, firm j continues the process if (12b) $\geq$ (12a), i.e., if π_{t+1}^j is sufficiently low, $\pi_{t+1}^j \leq \bar{\pi}_{t+1}^j(\tau_i)$, where:

$$\bar{\pi}_{t+1}^j(\tau_i) = \frac{(1+\sigma_j(\tau_j))\left[H(t+1)-h(t+1)\right] + \sigma_j(\tau_j)\left[h(t+1)-h(t)\right]}{\Lambda_{t+1}^i(\tau_i) - \sigma_i(t+1)h(t+1)}. \tag{16}$$

Observe that $\Lambda_{t+1}^i(\tau_i) > \sigma_i(t+1)h(t+1)$ for all $\tau_i \geq t+2$ so that $\bar{\pi}_{t+1}^j(\tau_i) > 0$ (Lemma A1). Since $\Lambda_{t+1}^i(\tau_i)$ is increasing in τ_i, this threshold $\bar{\pi}_{t+1}^j(\tau_i)$ is decreasing in τ_i. Intuitively, firm j is more inclined to continue the standard-setting process *(i)* the lower its belief π_{t+1}^j that firm i owns a patent (associated with a lower probability of paying license fees) and *(ii)* the earlier it anticipates firm i to disclose (associated with lower license fees). Since $\bar{\pi}_{t+1}^j(\tau_i) > 0$, there will always be values of π_{t+1}^j such that firm j continues.

Firm j in t: In t, if a non-patent holder $i = i_0$ anticipates firm j to continue in $t+1$, firm i always continues since (14c) $\geq$ (14a) by:

$$(1-\sigma_j(\tau_j))\left[H(t)-h(t)\right] \geq 0. \tag{17}$$

However, if firm i anticipates firm j to stop in $t+1$, then a non-patent holder $i = i_0$ is, by the respective payoffs in (14a) and (14b), indifferent between *stop* and *continue*.

In t, if a patent holder $i = i_1$ anticipates firm j to continue in $t+1$, then firm i will not disclose since the payoffs from *disclose* in (15e) are strictly smaller than the payoffs from *continue* in (15c).[21] Moreover, the patent holder will not stop but continue, since (15a) $\leq$ (15c) or:

$$(1-\sigma_j(\tau_j))\left[H(t)-h(t)\right] + \left[\Lambda_t^i(\tau_i) - \sigma_i(t)h(t-1)\right] \geq 0 \tag{18}$$

holds, by $\Lambda_t^i(\tau_i) > \sigma_i(t)h(t-1)$ (Lemma A1), for all t and $\tau_i \geq t+1$.

[21] By Proposition 2, if firm i anticipates the other firm to continue the process in subsequent periods, it is never optimal to disclose the patent.

If, instead, patent holder $i = i_1$ anticipates firm j to stop in $t+1$, then, as is readily shown, the payoffs from *stop* in (15a) are strictly smaller than the payoffs from *continue* in (15b), and the patent holder will not stop. If the patent holder discloses in t, then firm j, by Proposition 1, will continue in $t+1$. Firm i anticipates this and prefers *disclose* (with payoffs in (15e)) to *continue* (with payoffs in (15b)) if

$$\frac{(1-\sigma_j(\tau_j))\,[H(t)-h(t)]+\sigma_i(t)H(t)}{\sigma_i(t+1)[(1-p)h(t)+ph(t+1)]} \;\; \geq \;\; 1. \tag{19}$$

Two conditions are central for the result on firm i's *ex-ante* equilibrium disclosure: First, firm j's belief in $t+1$ must be sufficiently high, $\pi^j_{t+1} > \bar{\pi}^j_{t+1}(\tau_i)$, so that it will stop in $t+1$ if it observes firm i to continue in t. Second, anticipating that firm j will continue in $t+1$ if firm i discloses in $t+1$, firm i in t must prefer *disclose* (and see the standard-setting process continued until a new idea fails to arrive) over *continue* (and see it stopped by firm j in $t+1$); i.e., condition (19) must be satisfied. Firm i thus salvages the standard-setting process by disclosing earlier than aspired, $\tau_i^* < \tau_i^a$. In the following proposition we show that this is the outcome of a separating equilibrium. Other equilibria exist, and we provide a more extensive discussion of these equilibria in the proof of the proposition.

PROPOSITION 3. *Suppose firm j has disclosed its patent in $\tau_j < t$. Then, firm i discloses in $\tau_i^* < \tau_i^a$ if (19) holds and firm j's prior belief is $\pi^j > \bar{\pi}^j_{t+1}(\tau_i^a)$. This implies ex-ante disclosure if the standard-setting process reaches $t = \tau_i^*$.*

Firm i's incentives to disclose early, i.e., before the aspired disclosure date, in this equilibrium stem from firm j's threat to stop the process in $t+1$. By stopping, firm j caps firm i's bargaining leverage and limits the license fees to be paid to firm i. This induces firm i to disclose its patent in t. By doing so, it itself caps its bargaining leverage, but it also ensures the continuation of the standard-setting process (as seen in Proposition 1). With the license fees being constant shares of the other firm's product market profits, it is then in the best interest of both firms to continue the standard-setting process as long as possible.

Proposition 3 gives rise to immediate implications when the firms are "asymmetric" in the following sense: Consider an environment in which one firm approaches other firms with an initial idea, say χ_1, that is highly developed and almost complete in its specifications.[22] Furthermore, assume that because of the advanced state of this initial technology, it is common knowledge that the proposer, say j, has a patent. Firm i's prior beliefs are thus equal to one. This is equivalent to saying that firm j discloses its patent at the beginning of the process, $\tau_j = t_j^0$. This implies, by Assumption 4, that $\sigma_j(\tau_j) = 0$, rendering both conditions in the proposition less binding. In such an environment with "asymmetric" firms, *ex-ante* disclosure (by the non-initiating firm) is more likely to arise in equilibrium.

[22] An initiative of this sort has led to the development of the DSL standard, see DeLacey, Herman, Kiron, and Lerner (2006:23ff).

3.3.3 Firms' Payoffs Before Firm j's Disclosure

We now consider firm j's decision to disclose the patent if no firm has disclosed yet. We show that the reference to the results in Proposition 1, namely that if both firms have disclosed then both firms will continue the process until a new idea fails to arrive, is not necessary for a firm to disclose *ex ante*. This means, there are cases in which firm j discloses before the other firm i has disclosed (so that Proposition 1 does not apply). We first present the payoffs for firm j in $t-1$ and then for firm i in t. Firm j's payoffs in $t+1$ and firm i's payoffs in $t-2$ and $t+2$ are analogous. We then derive sufficient conditions for firm j to disclose in $t-1$ below. Proposition 4 summarizes the equilibrium results.

Firm $j = j_0$ with $\mathcal{S}_{0|t-1}$: A non-patent holder firm j's expected payoffs in $t-1$ with choice set $\mathcal{S}_{0|t-1} = \{S, C\}$, given firm i's anticipated move in t, are:

$$\mathrm{E}_{t-1}U_{j_0}(S@t-1) = \left(1 - \pi^j_{t-1}\sigma_i(t-1)\right) h(t-1); \tag{20a}$$

$$\mathrm{E}_{t-1}U_{j_0}(C@t-1|S) = \left(1 - \pi^j_{t-1}\sigma_i(t)\right) h(t-1); \tag{20b}$$

$$\mathrm{E}_{t-1}U_{j_0}(C@t-1|\neg S) = H(t-1) - \pi^j_{t-1}\Lambda^i_{t-1}(\tau_i) \tag{20c}$$

where $\Lambda^i_{t-1}(\tau_i)$ for $\tau_i \geq t$ is analogous to the expression in (13).

Firm $j = j_1$ with $\mathcal{S}_{1|t-1\leq\tau_j}$: A patent holder firm j's expected payoffs in $t-1$ with choice set $\mathcal{S}_{1|t-1\leq\tau_j} = \{S, C, D\}$, given firm i's anticipated move in t, are:

$$\mathrm{E}_{t-1}U_{j_1}(S@t-1) = \left(1 - \pi^j_{t-1}\sigma_i(t-1)\right) h(t-1) + \sigma_j(t-1)h(t-2); \tag{21a}$$

$$\begin{aligned}\mathrm{E}_{t-1}U_{j_1}(C@t-1|S) = {}& \left(1 - \pi^j_{t-1}\sigma_i(t)\right) h(t-1) \\ & + \sigma_j(t)\left[ph(t) - (1-p)h(t-1)\right];\end{aligned} \tag{21b}$$

$$\mathrm{E}_{t-1}U_{j_1}(C@t-1|\neg S) = H(t-1) - \pi^j_{t-1}\Lambda^i_{t-1}(\tau_i) + \Lambda^j_{t-1}(\tau_j); \tag{21c}$$

$$\begin{aligned}\mathrm{E}_{t-1}U_{j_1}(D@t-1|S) = {}& \left(1 - \pi^j_{t-1}\sigma_i(t)\right) h(t-1) \\ & + \sigma_j(t-1)\left[ph(t) + (1-p)h(t-1)\right];\end{aligned} \tag{21d}$$

$$\mathrm{E}_{t-1}U_{j_1}(D@t-1|\neg S) = H(t-1) - \pi^j_{t-1}\Lambda^i_{t-1}(\tau_i) + \sigma_j(t-1)H(t-1). \tag{21e}$$

Firm $i = i_0$ with $\mathcal{S}_{0|t}$: A non-patent holder firm i's expected payoffs in t with choice set $\mathcal{S}_{0|t} = \{S, C\}$, given firm j's anticipated move in $t+1$, are:

$$\mathrm{E}_tU_{i_0}(S@t) = \left(1 - \pi^i_t\sigma_j(t)\right) h(t); \tag{22a}$$

$$\mathrm{E}_tU_{i_0}(C@t|S) = \left(1 - \pi^i_t\sigma_j(t+1)\right) h(t); \tag{22b}$$

$$\mathrm{E}_tU_{i_0}(C@t|\neg S) = H(t) - \pi^i_t\Lambda^j_t(\tau_j) \tag{22c}$$

with $\Lambda^j_t(\tau_j)$ for $\tau_j \geq t+1$ analogous to (13).

Firm $i = i_1$ with $\mathcal{S}_{1|t\leq\tau_i}$: A patent holder firm i's expected payoffs in t with choice set $\mathcal{S}_{1|t\leq\tau_i} = \{S, C, D\}$, given firm j's anticipated move in $t+1$, are:

$$\mathrm{E}_t U_{i_1}(S@t) = \left(1 - \pi_t^i \sigma_j(t)\right) h(t) + \sigma_i(t) h(t-1); \tag{23a}$$

$$\mathrm{E}_t U_{i_1}(C@t|S) = \left(1 - \pi_t^i \sigma_j(t+1)\right) h(t) + \sigma_i(t+1)\left[ph(t+1) + (1-p)h(t)\right]; \tag{23b}$$

$$\mathrm{E}_t U_{i_1}(C@t|\neg S) = H(t) - \pi_t^i \Lambda_t^j(\tau_j) + \Lambda_t^i(\tau_i); \tag{23c}$$

$$\mathrm{E}_t U_{i_1}(D@t|S) = \left(1 - \pi_t^i \sigma_j(t+1)\right) h(t) + \sigma_i(t)\left[ph(t+1) + (1-p)h(t)\right]; \tag{23d}$$

$$\mathrm{E}_t U_{i_1}(D@t|\neg S) = H(t) - \pi_t^i \Lambda_t^j(\tau_j) + \sigma_i(t) H(t). \tag{23e}$$

3.3.4 Firm j's Disclosure

The incentives for firm j to disclose in $t-1$ are similar to the incentives for firm i to disclose in t: Firm j can salvage the standard-setting process by disclosing its patent and thus inducing firm i to continue when it would otherwise stop. This is the case when in $t-1$ firm j anticipates that firm i stops in t if firm j continues in $t-1$, but, by (17) and (18), i continues in t if j discloses in $t-1$.

Firm j in $t+1$: In $t+1$, firm j types continue (assuming firm i does not stop in $t+2$) if the payoffs from *continue* in (20c) (for the non-patent holder) and (21c) (for the patent holder) are at least as high as the payoffs from *stop* in (20a) (for the non-patent holder) and (21a) (for the patent holder).[23] The two conditions can be rewritten as:

$$\pi_{t+1}^j \leq \hat{\pi}_{t+1}^j(\tau_i) := \frac{H(t+1) - h(t+1)}{\Lambda_{t+1}^i(\tau_i) - \sigma_i(t+1)h(t+1)} > 0 \tag{24}$$

for the non-patent holder and:

$$\pi_{t+1}^j \leq \frac{H(t+1) - h(t+1) + \Lambda_{t+1}^j(\tau_j) - \sigma_j(t+1)h(t)}{\Lambda_{t+1}^i(\tau_i) - \sigma_i(t+1)h(t+1)} \tag{25}$$

for the patent holder. Observe that condition (24) for the non-patent holder is more restrictive than condition (25) for the patent holder. This should not come as a surprise. The patent holder has stronger incentives to continue the standard-setting process as it increases the license payment it can extract from firm i.

Firm i in t: In t, when anticipating that firm j continues in $t+1$, firm i types stop if the payoffs from *stop* in (22a) (for the non-patent holder) and (23a) (for the patent holder) are strictly greater than the payoffs from *continue* in (22c) (for the non-patent

[23] It is readily established that the payoffs from *continue* in (21c) are strictly greater than the payoffs from *disclose* in (21e), and *disclose* is dominated. See Proposition 1 for a discussion.

holder) and (23c) (for the patent holder). These two conditions can be rewritten as:

$$\pi_t^i > \frac{H(t) - h(t)}{\Lambda_t^j(\tau_j) - \sigma_j(t)h(t)} \tag{26}$$

for the non-patent holder and:

$$\pi_t^i > \bar{\pi}_t^i(\tau_j) := \frac{H(t) - h(t) + \Lambda_t^i(\tau_i) - \sigma_i(t)h(t-1)}{\Lambda_t^j(\tau_j) - \sigma_j(t)h(t)}. \tag{27}$$

for the patent holder. Observe that (26) for the non-patent holder is less restrictive than condition (27) for the patent holder. This is because the patent holder's incentives to stop are weaker as it forgoes higher license payments from firm j. Moreover, if firm j has disclosed in $t-1$, then, by (17) and (18), firm i continues in t.

Firm j in $t-1$: Anticipating that firm i in t stops if (27) holds true and firm j continues in $t-1$, a patent holder j_1 discloses in $t-1$ if the payoffs from *disclose* in (21e) are strictly greater than the payoffs from *continue* in (21b). Moreover, the payoffs from *disclose* must be strictly greater than the payoffs from *stop* in (21a). The former condition can be rewritten as:

$$\pi_{t-1}^j \leq \tilde{\pi}_{t-1}^j(\tau_i) := \frac{(1+\sigma_j(t-1))\,H(t-1) - p\sigma_j(t)h(t) - (1-p)\,h(t-1)}{\Lambda_{t-1}^i(\tau_i) - \sigma_i(t)h(t-1)} > 0. \tag{28}$$

It is binding if the payoffs from *continue* are greater than the payoffs from *stop.* This holds true as long as:

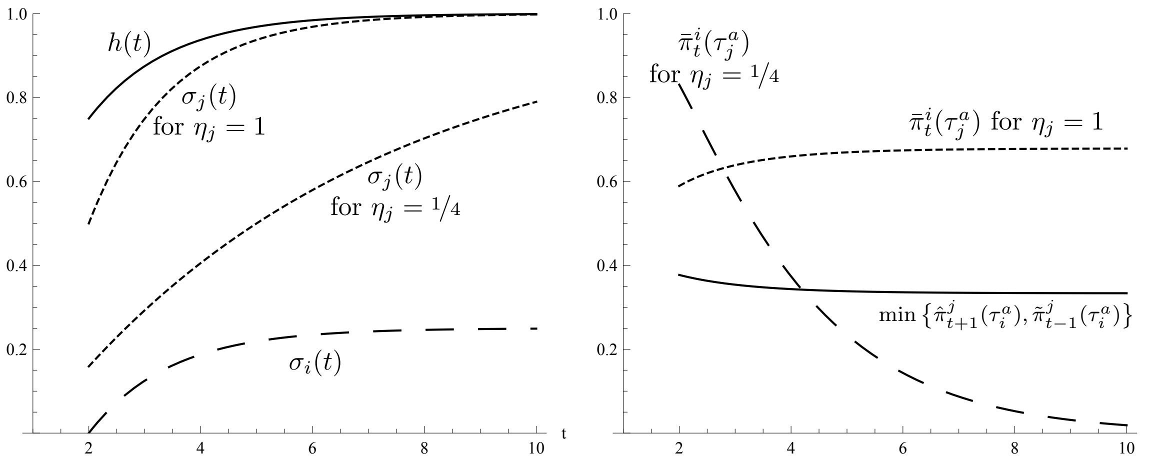
$$\pi_{t-1}^j \leq \frac{\sigma_j(t)h(t-1) - \sigma_j(t-1)h(t-2) + p\sigma_j(t)\left[h(t) - h(t-1)\right]}{\sigma_i(t)h(t-1) - \sigma_i(t-1)h(t-1)}; \tag{29}$$

$\sigma_j(t) \geq \sigma_i(t)$ for all t is sufficient for this latter condition to hold true for all π_{t-1}^j. In fact, the condition holds for all π_{t-1}^j as long as $\sigma_j(t) - \sigma_i(t)$ is not too negative. For the results below we assume that this is the case so that stopping is dominated and (28) is the relevant constraint.

Conditions (24), (27), and (28) describe the conditions that are sufficient for a patent holder firm j to disclose its patent in $t-1$: Condition (24) guarantees that firm j continues in $t+1$. Anticipating this, firm i in t stops if condition (27) is satisfied. In $t-1$, firm j anticipates that firm i will stop, and thus discloses so that, by (17) and (18), firm i continues instead. Proposition 4 establishes this pattern as the outcome of a perfect Bayesian equilibrium.

PROPOSITION 4. *If $\pi^j \leq \min\left\{\hat{\pi}_{t+1}^j(\tau_i^a), \tilde{\pi}_{t-1}^j(\tau_i^a)\right\}$ and $\pi^i > \bar{\pi}_t^i(\tau_j^a)$, then firm j discloses in $\tau_j^* = t-1 < \tau_j^a$.*

Figure 2: Parameterization of Proposition 4



(a) $h(t)$, $\sigma_i(t)$, and $\sigma_j(t)$ (b) $\min\{\hat{\pi}^j_{t+1}(\tau^a_i), \tilde{\pi}^j_{t-1}(\tau^a_i)\}$ and $\bar{\pi}^i_t(\tau^a_j)$

Unlike in Proposition 3, in Proposition 4 we consider firm j's disclosure decision when the other firm has yet to disclose. We show that the conditions that need to be fulfilled for equilibrium disclosure to be *ex ante* require firm j's prior beliefs on the existence of i's intellectual property (π^j) to be small enough and firm i's prior beliefs (π^i) to be large enough. If π^j is small, then firm j's decision to continue the standard-setting process (with or without disclosure) is not put at risk by the possibility that firm i owns a patent. Conversely, if π^i is large, it is firm i's fear to have part of its rents extracted by firm j at aspired disclosure date τ^a_j that inhibits it to continue the standard-setting process.

In Figure 2 we provide a parametric example for the conditions in Proposition 4, so to show that the set of parameter values in which those conditions are satisfied is not empty. For $h(\cdot)$ we use the same functional form employed by Stein (2008):

$$h(t) = 1 - \alpha^t. \tag{30}$$

Instead, the functional form for $\sigma(\cdot)$ is:

$$\sigma_i(t) = \gamma_i \left(1 - \beta^{\eta_i (t - t^0_i)}\right). \tag{31}$$

Note that $\alpha = 1/2$ and $\beta = 1/2$. We assume a weaker bargaining leverage for firm i, $\gamma_i = 1/4$ and $\gamma_j = 1$; $\eta_i = 1$ for all plots. Firm j is the firm that initiates the standard-setting process, so that $t^0_j = 1$ and $t^0_i = 2$. In Figure 3(a) we plot $h(t)$ (solid), $\sigma_i(t)$ (dashed), and $\sigma_j(t)$ for $\eta_j = 1$ and $\eta_j = 1/4$ (dotted). In Figure 3(b) we plot the conditions from Proposition 4. The solid line depicts the upper bound for firm j's prior beliefs, π^j. This upper bound is strictly positive, and there exist values for π^j such that the conditions in Propositon 4 hold. The dotted (for $\eta_j = 1$) and dashed ($\eta_j = 1/4$) lines depict the lower bound for firm i's prior beliefs, π^i. The lower bounds are strictly less than unity, so there exist values for π^i such that the conditions in the proposition hold true. This implies that under relatively mild assumptions on the relative bargaining position of each patent holder (that is, if i's bargaining leverage is weaker than j's) the conditions in Proposition 4 are supported by a non-empty space of parameter values.

4 Institutions

In this section we consider two institutional extensions of our model: We first allow firms to enter a cross-licensing agreement before the standard-setting process is initiated, at a stage at which firms are still uncertain as to whether they hold relevant intellectual property. We show that the wedge between a firm's degree of uncertainty on its own intellectual property and the beliefs it holds on the existence of intellectual property owned by the other participant shapes the decision to enter a cross-licensing agreement. Second, we introduce a common disclosure rule in standard setting organizations requiring firms to disclose intellectual property. For such a rule, we show that unlike in the baseline model, a firm's aspired disclosure is *ex ante*.

4.1 Cross-Licensing Agreements

In order to avoid patent holdup, firms often resort to cross-licensing agreements. In the context of our model such an agreement implies that before the standard-setting process is initiated, at time $t = 0$ firms commit to license each other any intellectual property they may hold in some extensive technology class (Galasso, forthcoming).

For our discussion of cross-licensing agreements we assume that, once such an agreement has been entered, communication incentives are satisfied, meaning that neither firm has an incentive to stop the standard-setting process. We also assume that in the non-cooperative equilibrium, firms exchange ideas until a new idea fails to arrive. Moreover, for the sake of the argument we assume *ex-post* disclosure, $\tau_i^* = \tau_i^a$, for both firms.

Under a cross-licensing agreement, firms' joint expected surplus, at $t = 0$, is equal to:

$$2H(0), \tag{32}$$

which is equal to the sum of firms' expected profits in a cooperative environment. A cross-licensing agreement is *feasible* at stage $t = 0$ if firms expect to be jointly better off under such an agreement relative to the non-cooperative equilibrium outcome analyzed in the previous section.

For their respective expected payoffs from the non-cooperative game, $\mathrm{E}_0 U_i$ for $i = A, B$, we need to introduce two additional elements. First, at the pre-game stage $t = 0$ firms do not know yet whether or not they own intellectual property. Earlier we referred to π^i as firm i's beliefs that firm j holds a patent. Furthermore, let $\bar{\pi}^i$ be firm i's own expectations that it will hold a patent. This probability reflects firm i's *ex-ante* uncertainty over the existence of proprietary technology. Let

$$\delta_i := \bar{\pi}^i - \pi^j. \tag{33}$$

We will refer to a firm i as *optimistic* if $\delta_i > 0$ and its own beliefs are higher than firm j's beliefs. Likewise, firm i is said to be *pessimistic* if $\delta_i < 0$.

Second, we assume that at stage $t = 0$, firm i anticipates to be the initiator of the process with probability $1/2$; and responder with probability $1/2$. It then anticipates a license-fee function

$$\bar{\sigma}_i(t) = \frac{\sigma_i(t_i^0 + t - 1) + \sigma_i(t_i^0 + t - 2)}{2} \tag{34}$$

for $t \geq 2$ and $\bar{\sigma}_i(1) = 0$. The distinction between *initiator* ($t_i^0 = 1$) and *responder* ($t_i^0 = 2$) is subtle but important. It controls for the fact that at a given t, the bargaining leverage for an initiator i is different from the bargaining leverage for a responder i. This is obvious in $t = 2$. For an initiator, Assumption 4 yields $\sigma_i(2) = \sigma_i(t_i^0 + 1) > 0$, yet for a responder it is $\sigma_i(2) = \sigma_i(t_i^0) = 0$.

Given *ex-post* disclosure, $\tau_i = \tau_i^a$, the firms' expected payoffs from the non-cooperative equilibrium are:

$$\mathrm{E}_0 U_i = H(0) + \bar{\pi}^i \Lambda_0^i(\tau_i^a) - \pi^i \Lambda_0^j(\tau_j^a) \tag{35a}$$

$$\mathrm{E}_0 U_j = H(0) + \bar{\pi}^j \Lambda_0^j(\tau_j^a) - \pi^j \Lambda_0^i(\tau_i^a) \tag{35b}$$

with

$$\Lambda_0^i(\tau_i^a) = \sum_{k=0}^{\infty} p^k \,(1-p)\, \bar{\sigma}_i(k+1) h(k) \tag{36}$$

the expected (at $t = 0$) license payment to firm i. A cross-licensing agreement is thus feasible if, and only if,

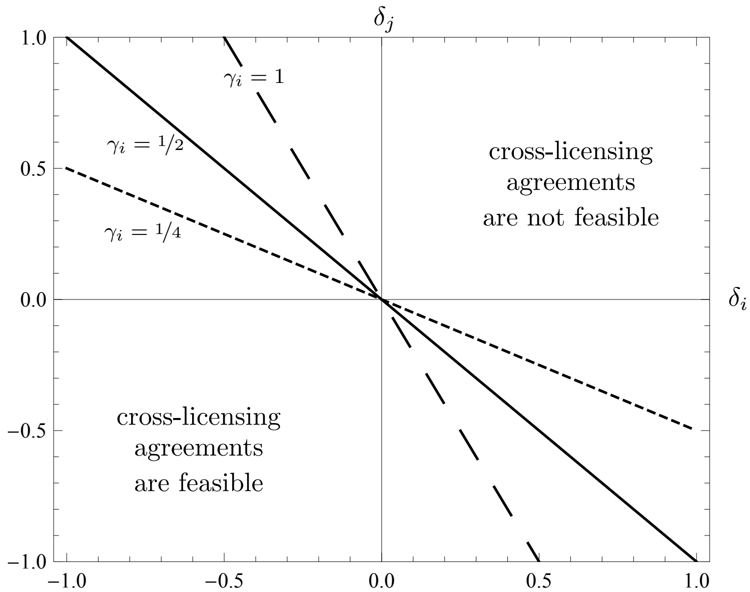
$$2H(0) \geq \mathrm{E}_0 U_i + \mathrm{E}_0 U_j.$$

By equations (32), (33), (35a), and (35b) this feasibility condition is rewritten as:

$$\delta_i \Lambda_0^i(\tau_i^a) \leq -\delta_j \Lambda_0^j(\tau_j^a). \tag{37}$$

Two immediate conclusions can be drawn from condition (37). First, if both firms are (weakly) optimistic, $\delta_i > 0$ and $\delta_j \geq 0$, then a cross-licensing agreement is not feasible. In this scenario, both firms expect to receive larger license payments from their competitors than their competitors expect to pay them. In expectations, the total net transfers are strictly positive, whereas under a cross-licensing agreement they are equal to zero. Due to misaligned expectations about intellectual property, firms believe to (jointly) gain under licensing in the non-cooperative game. Second, if both firms are weakly pessimistic, $\delta_i < 0$ and $\delta_j \leq 0$, then a cross-licensing agreement is

Figure 3: Feasibility of Cross-Licensing Agreements in (δ_i, δ_j)-space



feasible. Both firms expect to receive smaller license payments from their competitors than their competitors expect to pay them, and the expected total net transfers are negative.

The scenario of interest is the one where one firm is optimistic and the other pessimistic, $\delta_i > 0$ and $\delta_j < 0$. Then, the feasibility of a cross-licensing agreement depends on the degree of optimism and pessimism as well as the shape of firms' license-fee functions $\bar{\sigma}_i(\cdot)$. We illustrate this last point in Figure 3 in which we plot the (δ_i, δ_j) pairs such that the feasibility condition (37) is satisfied with strict equality. We use the functional forms in (30) and (31) and parameter values $\alpha = 1/2$, $\beta = 1/2$, $\eta_i = \eta_j = 1$, and $\gamma_j = 1/2$. To vary firm i's bargaining leverage (and license fees) we assume $\gamma_i = 1/2$ (solid line), $\gamma_i = 1$ (dashed line) and $\gamma_i = 1/4$ (dotted line). By condition (37), cross-licensing agreements are not feasible for all (δ_i, δ_j) to the upper right of the lines, but are feasible to the lower left of the lines.

For $\gamma_i = 1/2$, the firms are completely symmetric, and the solid line is the $-45°$ line. Suppose a cross-licensing agreement is just feasible (on the solid line). If, in the upper left quadrant, firm i becomes more pessimistic (δ_i becomes smaller), then firm j must be more optimistic by the same "amount" ($\Delta|\delta_i| = \Delta|\delta_j|$) to render the cross-licensing agreement feasible. Let $-\delta_i = \delta_j = 1/2$. If the pessimistic firm i's bargaining leverage is weaker than the optimistic firm j's, $\gamma_j > \gamma_i$ (dotted line with $\gamma_i = 1/4$), then the cross-licensing agreement is not feasible. Conversely, if i's bargaining leverage is stronger than j's, $\gamma_j < \gamma_i$ (dashed line with $\gamma_i = 1$), then a cross-licensing agreement is feasible.

We summarize the feasibility results for cross-licensing agreements in Proposition 5 with a formal proof in the appendix.

PROPOSITION 5 (Cross-Licensing Agreements)**.** *A cross-licensing agreement is feasible only if at least one firm is pessimistic. If exactly one firm is pessimistic, then a cross-licensing agreement is more likely to be feasible the stronger (weaker) the bargaining leverage, $\bar{\sigma}_i(\cdot)$, of the pessimistic (optimistic) firm.*

The interesting cases are where (at least) one firm is pessimistic. Proposition 5 shows that, for given degrees of optimism and pessimism, firms enter a cross-licensing agreement if the pessimistic (optimistic) firm's expected licensing revenue in the non-cooperative environment is relatively large (small). The intuition for this result is simple. The condition that determines the feasibility of cross-licensing compares the joint payoffs under cross-licensing and non-cooperative licensing. The latter are smaller if the expected profits that an optimistic firm can raise in the non-cooperative environment are sufficiently low and if the expected profits that a pessimistic firm can raise in the non-cooperative environment are sufficiently high. Therefore, we can conclude that the agreement is more feasible if for an optimistic firm the opportunity cost of renouncing to the non-cooperative licensing payoff is small and for a pessimistic firm the opportunity cost of giving up the non-cooperative licensing revenue is large.

4.2 Disclosure Rule and Implied Waiver

We assume the rules of the standard-setting organization to be such that firms must disclose intellectual property prior to the conclusion of the standard-setting process. Enforcement of this rule implies that, if patents on $\chi_{t_i^0}$ have not been disclosed by the time the standard-setting process comes to an end, patents are considered to be waived.

ASSUMPTION 5 (Implied Waiver)**.** *If the patent has not been disclosed by the time the standard-setting process comes to an end, then $\sigma_i(\tau_i) = 0$.*

Ex-post disclosure comes with a loss of intellectual property. In t, a patent holder i faces the following problem: With a probability of $1 - p^2$ it will not reach stage $t + 2$ and will thus not get to disclose. It will then lose its bargaining leverage and fraction $\sigma_i(t)$ of j's product market profits. Conversely, by not delaying but disclosing in t, firm i forgoes some license fees because $\sigma_i(t) < \sigma_i(t+2)$. In what follows, we show how firm i solves this tradeoff.

Since at any stage t firms cannot commit to disclose at any $t + k$, $k \geq 2$, a patent holder firm i can either stop, disclose, or continue and reconsider the disclosure decision in $t+2$. It will delay disclosure if, and only if, its expected payoffs from *disclose* in $t+2$ (*continue* in t and *disclose* in $t + 2$), are at least as high as the expected payoffs from *disclose* in t. Due to the lack of commitment, this does not imply that firm i indeed discloses in $t + 2$, but it will then reconsider its decision in $t + 2$.

Firm i's expected payoffs from *disclose* in t, $\mathrm{E}_t\hat{U}_i(D@t)$, and *continue* in t and *disclose* in $t+2$, $\mathrm{E}_t\hat{U}_i(D@t+2)$ are:

$$\mathrm{E}_t\hat{U}_i(D@t) = H(t) + \sigma_i(t)H(t) - \Gamma_t^j \tag{38a}$$

$$\mathrm{E}_t\hat{U}_i(D@t+2) = H(t) + p^2\sigma_i(t+2)H(t+2) - \Gamma_t^j \tag{38b}$$

with

$$\Gamma_t^j = \begin{cases} \pi_t^i\hat{\Lambda}_t^j(\tau_j) = \pi_t^i p^{\tau_j - t}\sigma_j(\tau_j)H(\tau_j) & \text{if } t < \tau_j \text{ and } j \text{ has not yet disclosed;} \\ \sigma_j(\tau_j)H(t) & \text{if } t > \tau_j \text{ and } j \text{ has disclosed in } \tau_j \end{cases} \tag{39}$$

firm i's expected license payment to a patent holder j for the case where j has not yet disclosed, $t < \tau_j$, and the case where j disclosed in $\tau_j < t$. Firm i continues in t and delays disclosure for all t as long as $\mathrm{E}_t\hat{U}_i(D@t) \leq \mathrm{E}_t\hat{U}_i(D@t+2)$ and discloses in t if, and only if,

$$\mathrm{E}_t\hat{U}_i(D@t) > \mathrm{E}_t\hat{U}_i(D@t+2). \tag{40}$$

For firms i and j aspired disclosure, we assume that both firms' communication constraints are satisfied and *stop* is dominated by either *disclose* in t or *continue* in t and *disclose* in $t+2$. Moreover, note that both firms continue after both patent holders disclose (see Proposition 1). In Lemma 1 we show that a patent holder i delays disclosure if $\sigma_i(t_i^0+2) > 0$. This is because i's payoffs from disclosure in $t = t_i^0$ are strictly smaller than the payoffs from continuing and disclosing in $t = t_i^0 + 2$.

LEMMA 1. *Firm i delays disclosure of its patent so that $\tau_i \in T_i \setminus \{t_i^0\}$ if, and only if, $\sigma_i(t_i^0+2) > 0$.*

In the next lemma we further characterize the result in Lemma 1 and show that, if the process allows, meaning if enough new ideas arrive, a firm i will always find it optimal to disclose *before* the process stops. Let $\hat{\tau}_i^a$ be the aspired disclosure date when firm i discloses before firm j and $\hat{\tau}_i^a(\tau_j)$ be the aspired disclosure date after firm j has disclosed.

LEMMA 2. *The aspired disclosure date, $\hat{\tau}_i^a > t_i^0$ ($\hat{\tau}_i^a(\tau_j) > t_i^0$), is finite.*

The result in Lemma 2 implies *ex-ante* disclosure by firm i. We can now determine firm i's aspired disclosure date when communication incentives are not binding so that the only reason for the standard-setting process to come to an end is when a new idea fails to arrive.

PROPOSITION 6. *Let both firms' pre-disclosure communication incentives be satisfied and $\sigma_i(t_i^0+2) > 0$. Patent holders' aspired disclosure date is $0 < \hat{\tau}_i^a < \infty$ ($0 < \hat{\tau}_i^a(\tau_j) < \infty$). This aspired disclosure date $\hat{\tau}_i^a$ ($\hat{\tau}_i^a(\tau_j)$) is equal to the smallest $\hat{t}_i \in T_i \setminus \{t_i^0\}$ such that (40) holds for all $t_i^0 \leq t < \hat{t}_i$, and $>$ for some $\hat{t}_i \leq t < \hat{t}_i + 2$. Firm j's disclosure does not affect firm i's aspired disclosure, $\hat{\tau}_i^a = \hat{\tau}_i^a(\tau_j)$ for all $t_j^0 < \tau_j < \hat{\tau}_i^a(\tau_j)$.*

The results in Proposition 6 apply to the situation where both firms' communication constraints are satisfied, i.e., both firms will not stop the standard-setting process. This means, before disclosure, not only are the expected payoffs from delaying at least as high as the expected payoffs from immediate disclosure in t, but expected payoffs from delaying disclosure must be at least as high as the payoffs from stopping.[24] Before either firm has disclosed, this is the case if

$$H(t) - h(t) \geq \pi_t^i p^{\tau_j - t} \sigma_j(\tau_j) H(\tau_j) - p^2 \sigma_i(t+2) H(t+2). \tag{41}$$

After firm j has disclosed, the condition that induces firm i's continuation is

$$H(t) - h(t) \geq \sigma_j(\tau_j)(H(t) - h(t)) - p^2 \sigma_i(t+2) H(t+2). \tag{42}$$

Observe that in both cases, firm i's own intellectual property relaxes its communication constraint, whereas firm j's intellectual property renders the constraint more binding.

A more binding constraint implies that, in equilibrium, firm i is more inclined to disclose before its aspired disclosure date, so that $\hat{\tau}_i^* < \hat{\tau}_i^a$. Also note that if (41) and (42) are never binding, equilibrium disclosure is equal to aspired disclosure, $\hat{\tau}_i^* = \hat{\tau}_i^a$. This implies that, unlike in Propositions 3 and 4 where equilibrium disclosure is *ex ante* only if firm i can salvage the process by disclosing so that firm j continues when it otherwise would have stopped the standard-setting process, a disclosure rule with an implied waiver (Assumption 5) always induces *ex-ante* equilibrium disclosure. We therefore expect to see more frequent *ex-ante* disclosure of intellectual property in standard-setting organizations that have introduced such disclosure rules. This theoretical result is in line with the evidence documented in Layne-Farrar (2011b) that ETSI clarification of the meaning of "timely" disclosure of patents prompted a significant reduction of patent declarations' average delay.

5 Standard Setting and Market Competition

In the baseline model, firms A and B are monopolists in a market of unit mass. In the following, we extend our analysis (in line with Stein (2008)) by allowing the two firms to compete on the product market. We thus introduce the same trade-off as in Stein (2008). On the one hand, a longer standard-setting process increases the quality of the standard, so firms share a common interest in continuing contributing to the process as long as possible; on the other hand, if a firm stops and does not reveal a new idea for improvement, it obtains a competitive advantage over its product-market rival. This latter effect introduces an additional incentive not to contribute but to halt communication during the standard-setting process and is consistent with the evidence in Layne-Farrar (2011a) that, due to the incremental nature of the standard setting

[24] If firm i stops before firm j has disclosed, its payoffs are $\hat{U}_i(S@t|t < \tau_j) = h(t)$. Instead, if firm i stops after firm j has disclosed, then its payoffs are $\hat{U}_i(S@t|t > \tau_j) = (1 - \sigma_j(\tau_j))\, h(t)$.

process in ETSI, firms often develop valuable ideas right after standard publication and use them opportunistically to gain an advantage on the product market.

Assume there is a fractional overlap of size $\theta \in (0,1)$ in A's and B's customer bases. In other words, firms A and B have a monopoly on a fraction $(1-\theta)$ of their customers, but compete à la Bertrand for the remaining fraction θ. The product market profits are equal to:

$$\tilde{R}_i = (1-\theta)\, h(n_i) + \theta \max\{0, h(n_i) - h(n_j)\}\,. \tag{43}$$

For $\theta = 0$, we obtain expression (2). With $\theta > 0$, firm i raises profits equal to $h(n_i)$ in its monopoly segment (of size $1-\theta$). In the competitive segment (of size θ), firm i's profits are positive only if it has a larger stock of ideas than firm j, that is, if $n_i > n_j$. To see this, suppose that the standard increases the consumers' reservation value of the good, then a consumer's utility from buying brand i at price p_i is given in (3). In this case, if firm i stops the process, it markets a product that is developed on a stock $n_i = n_S + 1 > n_j = n_S$ of ideas. The consumers' reservation value for product i is then higher than for brand j, $h(n_i) = h(n_S + 1) > h(n_j)$. In the monopoly segment of its market, firm i sets a price equal to $p_i = h(n_i)$. In the competitive segment, firm i sets a price $p_i = \max\{0, h(n_i) - h(n_j)\}$, with j and $i \neq j$.[25] This yields (43) for firm i's total product market profits.

Alternatively, suppose the standard lowers the firms' costs of production. If firm i decides not to communicate a new idea, then its production costs are $1 - h(n_S + 1) < 1 - h(n_S)$. In the monopoly segment of its market, firm i raises a profit equal to $h(n_i)$. In the competitive segment of its market, firm i makes positive profits because its costs are strictly below those of firm j so that it can make a price offer just below firm j's. This price is just below $1 - h(n_j)$ (firm j's production costs), so that competition profits for firm i are $1 - h(n_j) - (1 - h(n_i)) = h(n_i) - h(n_j)$. This yields (43) for firm i's total product market profits.

In Section 2, we showed that in the first-best world without competition, the firms exchange the information on the existence of relevant intellectual property and communicate respective ideas for standard improvement until a new idea fails to arrive. Therefore, the first-best outcome is equaivalent to a fully cooperative equilibrium outcome. In what follows, we determine the conditions under which this outcome can be implemented with product market competition.

DEFINITION 1. *In a cooperative equilibrium, firms i and j stop or continue so as to maximize their joint payoffs, $\tilde{R}_i + \tilde{R}_j$.*

[25] To see why this is the case, assume $n_i > n_j$. For prices $p_i = p_j = 0$ consumers will buy brand i because

$$u_i(0) = h(n_i) - 0 > u_j(0) = h(n_j) - 0$$

and both firms—assuming zero production costs—make zero profits. For firm i, however, $p_i = 0$ is not the Bertrand equilibrium price. Let p_j, then consumers will buy brand i if

$$u_i(p_i) = h(n_i) - p_i \geq h(n_j) = u_j(0).$$

The highest price for which this holds true is $p_i = h(n_i) - h(n_j)$.

Note that in a cooperative world, intellectual property and license fees do not matter as they merely give rise to transfers from one firm to another and thus, do not affect the firms' joint payoffs. We show in the following proposition that disclosure and communication of ideas are not part of a cooperative equilibrium if θ is sufficiently high, with the critical value strictly greater than $1/2$ and strictly less than unity. In other words, in a highly competitive industry, standard setting cannot be sustained as cooperative equilibrium.

PROPOSITION 7 (Cooperative Equilibrium with Competition)**.** *For sufficiently high values of θ so that competition is too high, there is no communication in the cooperative equilibrium. This critical value for θ lies strictly between $1/2$ and 1.*

For the analysis of non-cooperative equilibria below, we restrict attention to sufficiently low degrees of competition. If communication cannot be implemented in a cooperative equilibrium, it will not be implementable in a non-cooperative equilibrium.

5.1 Basic Results With Competition

In Proposition 8 we discuss the impact of competition on post- and pre-disclosure communication incentives and firms' aspired disclosure.

PROPOSITION 8 (Non-Cooperative Equilibrium with Competition)**.** *Competition reduces firms' incentives to contribute to the standard-setting process. In particular, the conditions on post-disclosure communication incentives and the conditions on pre-disclosure communication incentives become more binding. Aspired disclosure is not affected by product market competition.*

Competition reduces firms' incentives to contribute to the standard, both pre- and post-disclosure, whereas the aspired disclosure date is not altered by competition. As for the analysis of firms' pre-disclosure decisions, in Proposition 8 we focus on the impact of competition on the conditions that support the separating equilibria that lead to equilibrium disclosure before the end of the process (see Propositions 3 and 4). Although the ideal disclosure date is not influenced by the degree of competition, the fact that competition constrains communication implies that a patent holder is less likely to disclose at the aspired date, so the results on constrained equilibrium disclosure become even more relevant in the presence of product market competition.

5.2 Product Market Collusion

The competition game above assumes that firms compete in a market segment of size θ, and the profitability of a deviation from the equilibrium with communication stems from the profit that the deviator can earn in this market segment. In the following, we let firms collude on θ and study how collusion affects their incentives to contribute and their disclosure decision.

This means, when firm i in t decides to continue or stop, product market collusion affects its decision as follows. If the process comes to an end because firm i stops in t, then its profits from the competitive segment are $\theta\left[h(t)-h(t-1)\right]$ under competition, whereas the firms' joint profits under collusion are $\theta h(t)$. The joint gains from a collusive agreement are $\theta h(t-1)$. If, instead, firm i decides to continue in t (and assume both firms continue until a new idea fails to arrive), the expected profits from the competitive segment under competition are 0, and the expected profits from the competitive segment under a collusive agreement are $\theta H(t)$. The joint gains from a collusive agreement are $\theta H(t)$.

The main implication from product market collusion is that communication (exchanging ideas) is easier to sustain in equilibrium because collusion adds more to the payoffs from *continue* than to the payoffs from *stop*. Suppose the collusive agreement is such that firm i receives a share of the joint gains from the agreement. Communication is easier to sustain in equilibrium because:

$$\theta H(t) > \theta h(t-1).$$

The consequence is that firm i's patent disclosure will be less constrained by firm j's communication incentives. Note, however, that the aspired disclosure date does not change because aspired disclosure is not affected by product market competition (see Proposition 8) and therefore not affected by collusion in the product market.

5.3 Market Asymmetry

Assume that firm i is the monopolist in a segment $1-\theta$ of its market while firm j is the monopolist in a segment of size $\bar{\theta}-\theta$, with $\bar{\theta}\in(\theta,1)$. As before, firms compete on the remaining fraction θ of their market.

The product market profits $\tilde{R}_i$ of firm i are not affected and as defined in equation (43). Firm j's product market profits, however, are now equal to:

$$\tilde{R}_j = \left(\bar{\theta}-\theta\right) h(n_j) + \theta \max\left\{0, h(n_j)-h(n_i)\right\}.$$

With $\bar{\theta}<1$, these product market profits are smaller than the profits in equation (2) (with $\bar{\theta}=1$). As a result, firm i's communication incentives are weaker, and an equilibrium with communication is less likely to be sustainable. The intuition is that, *ceteris paribus*, a patent holder firm i can extract smaller license fees from firm j because firm j's monopolistic segment is smaller. A non-patent holder's incentives are not affected by the size of firm j's market size.

Given that for the communication process to be sustained, both firms' communication incentives must be satisfied, if $\bar{\theta}$ is small enough, the adverse impact on i's communication constraints can threaten the sustainability of the equilibrium with communication and lead to earlier constrained disclosure. Again, since aspired disclosure does not depend on product market competition, it is not affected by market asymmetry.

The analysis under market asymmetry, together with the insights developed below Proposition 3 for the case of asymmetric firms, gives rise to immediate implications when the firms have an asymmetric business model. Suppose firm j is a pure innovator (with its technologies typically patent-protected) and not vertically integrated, i.e., it does not manufacture final goods. This has two implications: First, firm i's prior beliefs π^i that $\chi_{t_j^0}$ is patent-protected is equal to one; second, since firm j raises no profits on the product market (being a patent holder), firm i cannot extract rents (through license fees) from firm j. Firm i's communication incentives are therefore weaker than in the benchmark model. Overall, this leads to earlier equilibrium disclosure by firm i.

6 Concluding Remarks

In this paper, we study how the effectiveness of the process of developing and improving a standard is affected by the existence of patent-protected technologies. We ask to what extent strategic disclosure of these patents undermines the work of a standard setting organization. We present a model of industry standard setting and assume firms have private information about their intellectual property. Expanding on the literature on standard setting and disclosure of private information, we provide answers to two sets of questions: (a) firms' incentives to contribute to the development and improvement of a standard, and (b) firms' decisions to disclose the existence of relevant intellectual property to other participants of the standard-setting process.

We show that if participants are allowed to disclose after the end of the process and fully exploit their bargaining leverage (accruing from intellectual property), then patent holders indeed aspire to disclose after the end of the process (*ex-post* disclosure). However, if a patent holder cannot rely on the other participants to always contribute to the process (and continue the standard-setting process), then it may be inclined to disclose before the end of the process. This is the case if, absent disclosure, the other firms stops, and the patent holder can by disclosing *ex ante* salvage the standard-setting process. A similar result applies in an institutional setting that implies a waiver of intellectual property rights if patents are not disclosed in a timely manner, and the early disclosure results are stronger when the firms compete in the product market. We further show that firms enter cross-licensing agreements, eliminating the strategic aspect of patent disclosure, if at least one firm is pessimistic about the existence of its own intellectual property.

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A Appendix

Proof of Proposition 1

Proof. First, note that the post-disclosure game is one of complete information. To show that for both firms i and j *continue* in all $t > \max\{\tau_i, \tau_j\}$ is a subgame perfect Nash equilibrium strategy, and a continued standard-setting process (until a new idea fails to arrive) the outcome in subgame perfect Nash equilibrium, we start with the working assumption that both firms always continue, and show that neither has an incentive to deviate from this strategy.

Firm i's expected payoffs when both firms always continue are given by $\mathrm{E}_t U_i(C@t|\tau_i, \tau_j) = [1 - \sigma_j(\tau_j) + \sigma_i(\tau_i)]\, H(t)$ with

$$H(t) = \sum_{k=0}^{\infty} p^k\,(1-p)\,h(t+k).$$

This $H(t)$ reflects the firms' respective expected product market profits. With probability $(1-p)$, there will be no further ideas after time t, so the standard comprises $n_S = t$ ideas with a total value of $h(t)$ for both firms; with probability $p\,(1-p)$, there will be exactly one further idea after t, so the standard comprises $t+1$ ideas with a total value of $h(t+1)$; with probability $p^2\,(1-p)$ there are exactly two further ideas, and so forth. Observe that $H(t)$ is increasing in p:

$$\frac{\partial H(t)}{\partial p} = \sum_{k=0}^{\infty} p^k \left(\frac{k(1-p)}{p} - 1\right) h(t+k),$$

which, after some manipulation, can be rewritten as

$$\frac{\partial H(t)}{\partial p} = \sum_{k=0}^{\infty} (1+k)\,p^k\,[h(t+k+1) - h(t+k)] > 0$$

for all $p > 0$.

If at stage t, firm i decides to stop, its product market profits are $h(n_S + 1) = h(t)$, whereas firm j's product market profits are $h(n_S) = h(t-1)$. Firm i's payoffs, accounting for license fees, are equal to $U_i(S@t|\tau_i, \tau_j) = (1 - \sigma_j(\tau_j))\,h(t) + \sigma_i(\tau_i)h(t-1)$. Firm i has no incentive to deviate from its equilibrium strategy (given firm j does not deviate) if, and only if, $\mathrm{E}_t U_i(C@t|\tau_i, \tau_j) \geq U_i(S@t|\tau_i, \tau_j)$ for all $t > \max\{\tau_i, \tau_j\}$. This condition can be rearranged to read

$$\left(1 + \frac{\sigma_i(\tau_i)}{1 - \sigma_j(\tau_j)}\right) \frac{H(t) - h(t-1)}{h(t) - h(t-1)} \geq 1. \tag{A.1}$$

Since

$$\begin{aligned} H(t) - h(t) &= \sum_{k=0}^{\infty} p^k\,(1-p)\,h(t+k) - \sum_{k=0}^{\infty} p^k\,(1-p)\,h(t) \\ &= \sum_{k=0}^{\infty} p^k\,(1-p)\,[h(t+k) - h(t)] \;\geq\; 0 \end{aligned}$$

holds for all t, the condition (A.1) holds for all $t > \max\{\tau_i, \tau_j\}$, for all $\sigma_i(\tau_i) \in [0,1)$, and for all $\sigma_j(\tau_j) \in [0,1)$, establishing the proof. Q.E.D.

Proof of Proposition 2

Proof. Before showing the proof of the claim, we derive equations (9) and (10). Let us start with the derivation of (9). By assumption, neither firm stops the process. Hence, when firm i discloses in t it expects product market profits of $H(t)$, license payments of $\sigma_i(t)H(t)$ from firm j, and license payments of Λ_t^j to firm j. The derivation of (10) goes along the same lines. When firm i decides to delay disclosure one round, then she expects with a probability of $1-p$ a new idea does not arrive in $t+1$. The product market profits are $h(t)$, and firm i discloses in $t+1$ so that $\sigma_i(t+1)h(t)$ is the license payment from firm j. With a probability of $p(1-p)$ a new idea arrives in $t+1$ but not in $t+2$. The product market profits are $h(t+1)$, and firm i discloses in $t+2$ so that $\sigma_i(t+2)h(t+1)$ is the license payment from firm j. At last, with probablity p^2 new ideas arrive in both $t+1$ and $t+2$. When firm i discloses, the expected product market profits are $H(t+2)$ and the expected license payments from firm j are $\sigma_i(t+2)H(t+2)$. We collect terms and obtain

$$\begin{aligned}
\mathrm{E}_t U_i(D@t+2) \quad = \quad & (1-p)\left[h(t)+\sigma_i(t+1)h(t)\right] + \\
& p\,(1-p)\left[h(t+1)+\sigma_i(t+2)h(t+1)\right] + \\
& p^2\left[H(t+2)+\sigma_i(t+2)H(t+2)\right] - \pi_t^i \Lambda_t^j(\tau_j^a).
\end{aligned}$$

Note that $H(t) = (1-p)\,h(t) + p\,(1-p)\,h(t+1) + p^2 H(t+2)$ and

$$\begin{aligned}
H(t+1) &= \sum_{k=0}^{\infty} p^k\,(1-p)\,h(t+1+k) = (1-p)\,h(t+1) + \sum_{k=1}^{\infty} p^k\,(1-p)\,h(t+1+k) \\
&= (1-p)\,h(t+1) + p\sum_{k=1}^{\infty} p^{k-1}\,(1-p)\,h(t+1+k) \\
&= (1-p)\,h(t+1) + p\sum_{k=0}^{\infty} p^{k}\,(1-p)\,h(t+2+k) \\
&= (1-p)\,h(t+1) + pH(t+2).
\end{aligned}$$

Collecting terms and simplifying yields the expression in (10). It remains to be shown that

$$\mathrm{E}_t U_i(D@t+2) \geq \mathrm{E}_t U_i(D@t)$$

for all t and $i = A, B$. Given $H(t) = (1-p)\,h(t) + pH(t+1)$, we can rearrange to obtain

$$\begin{aligned}
H(t) + (1-p)\,\sigma_i(t+1)h(t) + p\sigma_i(t+2)H(t+1) \quad &= \\
H(t) + \sigma_i(t+1)\left[(1-p)\,h(t) + pH(t+1)\right] \quad & \\
+\, pH(t+1)\left[\sigma_i(t+2)-\sigma_i(t+1)\right] \quad &= \\
H(t) + \sigma_i(t+1)H(t) + pH(t+1)\left[\sigma_i(t+2)-\sigma_i(t+1)\right] \quad &\geq \quad H(t) + \sigma_i(t+1)H(t)
\end{aligned}$$

which holds since $\sigma_i(t+2) > \sigma_i(t+1)$. Hence, firm i will delay disclosure until a new idea fails to arrive. The proof for j is analogous. Q.E.D.

Proof of Proposition 3

Before deriving the equilibria in Lemma A2, we proof five claims made in the text:

LEMMA A1.

1. *Firm j's expected license payment to firm i when firm i is a patent holder and anticipated to disclose in $\tau_i \geq t+2$, denoted by $\Lambda^i_{t+1}(\tau_i)$, is given in equation (13).*
2. *$\Lambda^i_{t+1}(\tau_i)$ is increasing in τ_i.*
3. *$\Lambda^i_{t+1}(\tau_i) > \sigma_i(t+1)h(t+1)$ for all $\tau_i \geq t+2$.*
4. *$\bar{\pi}^j_{t+1}(\tau_i)$ is strictly positive.*
5. *$\Lambda^i_t(\tau_i) > \sigma_i(t)h(t-1)$ for all $\tau_i \geq t+1$.*

Proof. 1. The license payment from firm j to firm i is equal to firm i's product market profits times σ_i. Suppose firm j continues in $t+1$, and let $\tau_i = t+2$. With probability $1-p$ a new idea does not arrive in $t+2$ (when it is firm i's turn), the standard-setting process ends and firm i discloses in $t+2 \leq \tau_i$. Firm j's product market profits are $h(t+1)$ and the license payment to firm i is $\sigma_i(t+2)h(t+1)$ times $1-p$. With probability p a new idea arrives in $t+2$, and by assumption firm i discloses in $\tau_i = t+2$. Given $t+2$ has been reached, with a probability $1-p$ a new idea fails to arrive in $t+3$, and the process ends. Firm j's product market profits are $h(t+2)$ and the license payments to firm i are $\sigma_i(t+2)h(t+2)$, with probability $p^2(1-p)$. With probability p a new idea arrives in $t+2$ and firm i discloses; with probability p a new idea arrives in $t+3$ and firm j continues; with probability $1-p$ a new idea fails to arrive in $t+4$. The license payments to firm i are $\sigma_i(t+2)h(t+3)$. Continuing in this fashion yields

$$\begin{aligned}
\Lambda^i_{t+1}(t+2) &= (1-p)\,\sigma_i(t+2)h(t+1) + p\,(1-p)\,\sigma_i(t+2)h(t+2) + \\
&\quad p^2\,(1-p)\,\sigma_i(t+2)h(t+3) + p^3\,(1-p)\,\sigma_i(t+2)h(t+4) + \ldots \\
&= \sigma_i(t+2)\left[(1-p)\,h(t+1) + pH(t+2)\right] \\
&= \sigma_i(t+2)H(t+1).
\end{aligned}$$

Now, suppose that firm i does not disclose before $\tau_i = t+4$, i.e., it will disclose whenever the process comes to end before $t+4$, or in $t+4$ when this stage is reached. The expected license payments to firm i are

$$\begin{aligned}
\Lambda^i_{t+1}(t+4) &= (1-p)\,\sigma_i(t+2)h(t+1) + p\,(1-p)\,\sigma_i(t+3)h(t+2) + \\
&\quad p^2\,(1-p)\,\sigma_i(t+4)h(t+3) + p^3\,(1-p)\,\sigma_i(t+4)h(t+4) + \\
&\quad p^4\,(1-p)\,\sigma_i(t+4)h(t+5) + \ldots \\
&= \sum_{k=0}^{2} p^k\,(1-p)\,\sigma_i(t+2+k)h(t+1+k) + p^3\sigma_i(t+4)H(t+4).
\end{aligned}$$

The expression in (13) is derived analogously for general τ_i.

2. We compare $\Lambda^i_{t+1}(\tau_i)$ with $\Lambda^i_{t+1}(\tau_i+\omega)$ and show that $\Lambda^i_{t+1}(\tau_i+\omega) > \Lambda^i_{t+1}(\tau_i)$ for all $\omega \geq 1$. From (13),

$$\Lambda^i_{t+1}(\tau_i) = \sum_{k=0}^{\tau_i-(t+2)} p^k(1-p)\sigma_i(t+2+k)h(t+1+k) + p^{\tau_i-(t+1)}\sigma_i(\tau_i)H(\tau_i),$$

hence

$$\begin{aligned}\Lambda^i_{t+1}(\tau_i+\omega) &= \sum_{k=0}^{\tau_i+\omega-(t+2)} p^k(1-p)\sigma_i(t+2+k)h(t+1+k) + \\ &\quad p^{\tau_i+\omega-(t+1)}\sigma_i(\tau_i+\omega)H(\tau_i+\omega). \qquad \text{(A.2)}\end{aligned}$$

This (A.2) can be rewritten as

$$\begin{aligned}\Lambda^i_{t+1}(\tau_i+\omega) &= \sum_{k=0}^{\tau_i-(t+2)} p^k(1-p)\sigma_i(t+2+k)h(t+1+k) + \\ &\quad p^{\tau_i-(t+1)}\sum_{k=0}^{\omega-1} p^k(1-p)\sigma_i(\tau_i+1+k)h(\tau_i+k) + \\ &\quad p^{\tau_i+\omega-(t+1)}\sigma_i(\tau_i+\omega)H(\tau_i+\omega).\end{aligned}$$

It follows that

$$\begin{aligned}\Lambda^i_{t+1}(\tau_i+\omega) - \Lambda^i_{t+1}(\tau_i) &= p^{\tau_i-(t+1)}\sum_{k=0}^{\omega-1} p^k(1-p)h(\tau_i+k)\left[\sigma_i(\tau_i+1+k)-\sigma_i(\tau_i)\right] + \\ &\quad p^{\tau_i+\omega-(t+1)}\left[\sigma_i(\tau_i+\omega)-\sigma_i(\tau_i)\right]H(\tau_i+\omega) > 0,\end{aligned}$$

because $\sigma_i(\tau_i)$ is increasing in τ_i (Assumption 4).

3. Recall that $\Lambda^i_{t+1}(t+2) = \sigma_i(t+2)H(t+1)$ so that $\Lambda^i_{t+1}(t+2) = \sigma_i(t+2)H(t+1) > \sigma_i(t+1)H(t+1)$ with the last inequality because $\sigma_i(t)$ is increasing in t. Then, $\sigma_i(t+1)H(t+1) > \sigma_i(t+1)h(t+1)$ follows from $H(t+1) > h(t+1)$ as shown in Proposition 1 (where $H(t) > h(t)$ for all t implies $H(t+1) > h(t+1)$). $\Lambda^i_{t+1}(\tau_i)$ increasing in τ_i establishes the proof.

4. The numerator of $\bar{\pi}^j_{t+1}(\tau_i)$ in (16) is positive because $h(t+1) > h(t)$ and $H(t+1) > h(t+1)$ (see the proof of Proposition 2). The denominator is positive because $\Lambda^i_{t+1}(\tau_i) > \sigma_i(t+1)h(t+1)$ for all $\tau_i \geq t+2$.

5. See the proof for $\Lambda^i_{t+1}(\tau_i) > \sigma_i(t+1)h(t+1)$. Q.E.D.

In Lemma A2, we derive perfect Bayesian equilibria (PBE) of the game played in t and $t+1$ by firm i and firm j. The two key conditions are: *(1)* Firm j continues in $t+1$ if firm i

continues in t and if j anticipates firm i to disclose in $\tau_i \geq t+2$ (when firm j has continued in $t+1$) if $\pi^j_{t+1} < \bar{\pi}^j_{t+1}(\tau_i)$ or (using (16)),

$$\pi^j_{t+1} \leq \frac{(1+\sigma_j(\tau_j))\,[H(t+1)-h(t+1)] + \sigma_j(\tau_j)\,[h(t+1)-h(t)]}{\Lambda^i_{t+1}(\tau_i) - \sigma_i(t+1)h(t+1)} =: \bar{\pi}^j_{t+1}(\tau_i), \tag{A.3}$$

and stops otherwise. *(2)* When it anticipates firm j to stop in $t+1$, firm i discloses in t if

$$\frac{(1-\sigma_j(\tau_j))\,[H(t)-h(t)] + \sigma_i(t)H(t)}{\sigma_i(t+1)\,[(1-p)h(t)+ph(t+1)]} \geq 1, \tag{A.4}$$

and continues otherwise. Condition (A.4) is condition (19) in the text. The following notation is used:

- $\alpha_{0|t} = Pr(C@t|i_0)$ is the probability with which a non-patent holder $i = i_0$ continues in t; $1-\alpha_{0|t} = Pr(S@t|i_0) = 1 - Pr(C@t|i_0)$ is the probability with which it stops in t.

- $\alpha_{1|t} = Pr(C@t|i_1)$ is the probability with which a patent holder $i = i_1$ continues in t; $1-\alpha_{1|t} = Pr(D@t|i_1) = 1 - Pr(C@t|i_1)$ is the probability with which it discloses in t.

- $\beta_{t+1} = Pr(C@t+1|j_1)$ is the probability with which a patent holder $j = j_1$ continues in $t+1$ if firm i continues in t; $1-\beta_{t+1} = Pr(S@t+1|j_1) = 1 - Pr(C@t+1|j_1)$ is the probability with which it stops in $t+1$.

For the equilibria in Lemma A2 we assume that *before* firm j has disclosed in τ_j, both firm i types have always continued and firm j has not been able to update its beliefs so that $\pi^j_{\tau_j} = \pi^j$. Moreover, off-equilibrium behavior is according to Proposition 2: Firm i continues and discloses once the process has come to an end (so that $\tau_i = \tau_i^a$); firm j continues.

LEMMA A2.

1. *For $\pi^j \leq \bar{\pi}^j_{t+1}(\tau_i^a)$, there is a pooling PBE in which both firm i types continue in t and firm j continues in $t+1$ irrespective of firm i's action; $\alpha_{0|t} = \alpha_{1|t} = \beta_{t+1} = 1$. Firm i's equilibrium disclosure is ex post in $\tau_i^* = \tau_i^a \geq t+1$.*

2. *For $\pi^j > \bar{\pi}^j_{t+1}(\tau_i^a)$ and (A.4) satisfied, there is a separating PBE in which a patent holder $i = i_1$ discloses in t, a non-patent holder $i = i_0$ stops in t, and firm j stops in $t+1$ if firm i continues in t. Firm i's equilibrium disclosure is ex ante in $\tau_i^* = t$.*

3. *For $\pi^j > \bar{\pi}^j_{t+1}(\tau_i^a)$ and (A.4) violated, there is a semi-separating PBE in which a patent holder $i = i_1$ continues in t; a non-patent holder $i = i_0$ continues with probability $\alpha_{0|t} \in [0,1]$ and stops with $1-\alpha_{0|t}$ in t; firm j stops in $t+1$ if firm i continues in t. Firm i's equilibrium disclosure is ex post in $\tau_i^* = t+1$.*

Moreover, by Proposition 1, firm j continues in $t+1$ if firm i discloses in t.

Proof.

1. Suppose (A.3) holds for some τ_i so that firm j continues in $t+1$ if firm i continues in t, $\beta_{t+1} = 1$. Then, by (17) and (18), both firm i types continue, $\alpha_{0|t} = \alpha_{1|t} = 1$. Firm j observes firm i to continue in t, irrespective of firm i's type. In $t+1$, firm j will therefore not be able to update its beliefs. More generally, when up to $t+1$ it has not been able to update its beliefs, then $\pi^j_{t+1} = \pi^j_{t-1} = \ldots = \pi^j_{\tau_j+2} = \pi^j$, and (A.3) is rewritten as $\pi^j \leq \bar{\pi}^j_{t+1}(\tau_i)$ for some τ_i. Because both firms continue in all t and $t+1$ for some τ_i, firm i will disclose when aspired, in $\tau_i = \tau_i^a$, and firm j anticipates this. Condition (A.3) is thus equal to $\pi^j \leq \bar{\pi}^j_{t+1}(\tau_i^a)$.

2. Given j stops in $t+1$ if firm i continues in t, because (A.4) is satisfied a patent holder $i = i_1$ prefers *disclose* to *continue*, $\alpha_{1|t} = 0$. In this case, firm j continues by Proposition 2. Due to its indifference, a non-patent holder $i = i_0$ stops, $\alpha_{0|t} = 0$ in t. In this case, the game ends and firm j does not get to move in $t+1$. In either case, firm j does not need to update its beliefs on the equilibrium path because its information set is a singleton, or the game has ended. Off the equilibrium path, denoting the combination choices of i_1 and i_0 by $\{s_1, s_0\}$, with $s_1 \in \mathcal{S}_{1|t<\tau_i}$ and $s_0 \in \mathcal{S}_{0|t}$, there are five cases to be considered $\{C,C\}$, $\{C,S\}$, $\{D,C\}$, $\{S,C\}$, $\{S,S\}$. Given that $\pi^j_{t-1} = \pi^j$, in cases $\{C,C\}$, $\{C,S\}$ and $\{D,C\}$ firm j's beliefs satisfy

$$\pi^j_{t+1} = \frac{\alpha_{1|t}\pi^j}{\alpha_{1|t}\pi^j + \alpha_{0|t}\left(1-\pi^j\right)} > \bar{\pi}^j_{t+1}(\tau_i)$$

if

$$\alpha_{1|t} > \frac{\bar{\pi}^j_{t+1}(\tau_i)}{\pi^j} \frac{1-\pi^j}{1-\bar{\pi}^j_{t+1}(\tau_i)} \alpha_{0|t}. \tag{A.5}$$

To see this, consider first $\{C,C\}$: (A.5) prescribes $\pi^j_{t+1} = \pi^j$. At $\{C,S\}$, (A.5) prescribes $\pi^j_{t+1} = 1 > \pi^j$. So, in both cases Bayes' rule can be applied and firm j would stop in $t+1$ off the equilibrium path because $\pi^j_{t+1} > \bar{\pi}^j_{t+1}(\tau_i)$. At $\{D,C\}$ firm j stops if $Pr_{t+1}(i = i_1|C) = \pi^j > \bar{\pi}^j_{t+1}(\tau_i)$, which is again consistent with Bays' rule and, consequently, (A.5). Now, take $\{S,S\}$ and $\{S,C\}$. At $\{S,S\}$ both types stop, so firm j does not update off the equilibrium path. Finally, at case $\{S,C\}$ Bayes' rule cannot be applied, thus we assume that firm j's off-equilibrium beliefs are such that $Pr_{t+1}(i = i_1|C) > \bar{\pi}^j_{t+1}(\tau_i)$, implying that it would stop in $t+1$ if firm i_0 continues in t. Summarizing, a sufficient condition for firm j to *stop* in $t+1$ is that $\pi^j > \bar{\pi}^j_{t+1}(\tau_i^a)$.

3. Given j stops in $t+1$ if firm i continues in t, because (A.4) is violated a patent holder $i = i_1$ prefers *continue* to *disclose*, $\alpha_{1|t} = 1$. Given continue in all t, off equilibrium it will eventually disclose in $\tau_i = \tau_i^a$. The non-patent holder $i = i_0$ is indifferent, and continues with probability $\alpha_{0|t} \in [0,1]$. Given $\alpha_{1|t}$ and $\alpha_{0|t}$ and $\pi^j_{t-1} = \pi^j$, firm j in $t+1$ updates its beliefs according to Bayes' rule. Condition (A.3) is violated if

$$\pi^j_{t+1} = \frac{\pi^j}{\pi^j + \alpha_{0|t}\left(1-\pi^j\right)} > \bar{\pi}^j_{t+1}(\tau_i^a)$$

or

$$1 > \frac{\bar{\pi}^j_{t+1}(\tau^a_i)}{\pi^j} \frac{1-\pi^j}{1-\bar{\pi}^j_{t+1}(\tau^a_i)} \alpha_{0|t},$$

which indeed holds for all $\alpha_{0|t} \in [0,1]$, because $\bar{\pi}^j_{t+1}(\tau^a_i) < \pi^j$. A patent holder $i = i_1$ does not have an incentive to mimic a non-patent holder (and induce firm j to belief it is a non-patent holder, $\pi^j_{t+1} \leq \bar{\pi}^j_{t+1}(\tau_i)$) because (A.4) is violated and because *stop* is strictly dominated as it ends the process and will not allow firm j to update its beliefs on the equilibrium path. Off the equilibrium path, firm i has disclosed and firm j's information set is a singleton. Q.E.D.

Proof of Proposition 4

Proof. At the candidate equilibrium of Proposition 4, firm j_1 discloses and firm j_0 stops in $t-1$, both firm i types continue after disclosure in t, and both firm j types continue in $t+1$. We show that under the conditions provided in the proof, this is indeed an equilibrium. The three key conditions from the main text are (28)=(A.6), (27)=(A.7), and (24)=(A.8):

- Patent holder j_1 discloses in $t-1$ when firm i is anticipated to stop in t if

$$\pi^j_{t-1} \leq \tilde{\pi}^j_{t-1}(\tau_i) := \frac{(1+\sigma_j(t-1))\,H(t-1) - p\sigma_j(t)h(t) - (1-p)\,h(t-1)}{\Lambda^i_{t-1}(\tau_i) - \sigma_i(t)h(t-1)} > 0. \quad \text{(A.6)}$$

  Note that *continue* is dominated by *stop* for non-patent holder j_0 in $t-1$.

- Given firm j has continued in $t-1$, both firm i types stop in t when firm j is anticipated to continue in $t+1$ if

$$\pi^i_t > \bar{\pi}^i_t(\tau_j) := \frac{H(t) - h(t) + \Lambda^i_t(\tau_i) - \sigma_i(t)h(t-1)}{\Lambda^j_t(\tau_j) - \sigma_j(t)h(t)}. \quad \text{(A.7)}$$

- Firm j continues in $t+1$ when firm i is anticipated to continue in $t+2$ if

$$\pi^j_{t+1} \leq \hat{\pi}^j_{t+1}(\tau_i) := \frac{H(t+1) - h(t+1)}{\Lambda^i_{t+1}(\tau_i) - \sigma_i(t+1)h(t+1)} > 0. \quad \text{(A.8)}$$

We assume that before firm j takes turn in $t-1$, both firms i and j types have always continued and neither firm j nor firm i has been able to update its beliefs, so that $\pi^j_{t-1} = \pi^j$ and $\pi^i_{t-2} = \pi^i$. Moreover, if $t+2$ is reached firm i continues the process. Finally, off-equilibrium updating is according to Bayes' rule whenever possible. In particular, in t firm i stops off-equilibrium if

$$\pi^i_t = \frac{\alpha^j_{1|t-1}\pi^i}{\alpha^j_{1|t-1}\pi^i + \alpha^j_{0|t-1}\left(1-\pi^i\right)} > \bar{\pi}^i_t(\tau_j),$$

that is,

$$\alpha^j_{1|t-1} > \frac{\bar{\pi}^i_t(\tau_j)}{\pi^i}\frac{1-\pi^i}{1-\bar{\pi}^i_t(\tau_j)}\alpha^j_{0|t-1}, \tag{A.9}$$

where

- $\alpha^j_{0|t-1} = Pr(C@t-1|j_0)$ is the probability with which a non-patent holder $j = j_0$ continues in t; $1 - \alpha^j_{0|t-1} = Pr(S@t-1|j_0) = 1 - Pr(C@t-1|j_0)$ is the probability with which it stops in $t-1$.

- $\alpha^j_{1|t-1} = Pr(C@t-1|j_1)$ is the probability with which a patent holder $j = j_1$ continues in $t-1$; $1 - \alpha^j_{1|t} = Pr(D@t-1|j_1) = 1 - Pr(C@t-1|j_1)$ is the probability with which it discloses in $t-1$.

In $t-1$: By condition (A.6), if $\pi^j_{t-1} = \pi^j \leq \tilde{\pi}^j_{t-1}(\tau_i)$ is satisfied for some τ_i, then patent holder j_1 discloses if it anticipates i to stop in t. Because firm j_1 continues in $t-1$ for some τ_i and, along the equilibrium path, firm i continues in t, firm i will disclose when aspired, in $\tau_i = \tau^a_i$, and firm j anticipates this. Condition (A.6) is thus equal to $\pi^j \leq \bar{\pi}^j_{t-1}(\tau^a_i)$.

In t: Suppose firm j has continued in $t-1$. If firm i continued in t, then firm j would continue in $t+1$, and both firms would continue in $t+2$ and later. Firm j's aspired disclosure date is then τ^a_j. By condition (A.7), a patent holder i_1 would indeed continue in t if $\pi^i_t \leq \bar{\pi}^i_t(\tau^a_j)$; conversely, a patent holder i_1 would stop (had firm j continued in $t-1$) if $\pi^i_t > \bar{\pi}^i_t(\tau^a_j)$ (and so would a non-patent holder i_0 as its condition is less binding; see the discussion in the main text). Off the equilibrium path, a patent holder j_1 then discloses in t. Denote the off-equilibrium combination choice of j_1 and j_0 by $\{s_1, s_0\}$, with $s_1 \in \mathcal{S}_{1|t<\tau_j}$ and $s_0 \in \mathcal{S}_{0|t}$, five (off-equilibrium) cases can arise (the equilibrium combination is $\{D, S\}$): $\{C, C\}$, $\{C, S\}$, $\{D, C\}$, $\{S, C\}$ and $\{S, S\}$. Under $\{C, C\}$ (A.9) prescribes $\pi^i_t = \pi^i$, under $\{C, S\}$ it prescribes $\pi^i_t = 1$, and under $\{D, C\}$ (A.9) is satisfied if $\pi^i \geq \pi^i_t(\tau^a_j)$. Moreover, if firm j stops in $t-1$ ($\{S, S\}$) the game ends. In the remaining combination in which firm j_1 stops and firm j_0 continues in $t-1$ ($\{S, C\}$), Bayes' rule cannot be applied. In this case, firm i stops in t if $Pr_t(j = j_1|C) > \bar{\pi}^j_t(\tau^a_j)$, which is what we assume. Finally, along the equilibrium path firm j discloses in $t-1$, so firm i in t does not need to update its beliefs.

In $t+1$: If i has continued (without disclosure) in t, by condition (A.8), if $\pi^j_{t+1} \leq \hat{\pi}^j_{t+1}(\tau_i)$ firm j continues irrespective of its type. Moreover, both i and j continue in $t+2$ and later. This implies that firm i will disclose when aspired, in $\tau_i = \tau^a_i$. Along the equilibrium path, firm j discloses in $t-1$ so, if post-disclosure firm i communication incentives are satisfied irrespective of its type, firm j in $t+1$ cannot update its beliefs based on i's move in t, therefore $\pi^j_{t+1} = \pi^j_{t-1} = ... = \pi^j$.

Summarizing, if $\pi^j < \min\{\tilde{\pi}^j_{t-1}(\tau^a_i), \hat{\pi}^j_{t+1}(\tau^a_i)\}$ and $\pi^i > \bar{\pi}^i_t(\tau^a_j)$, then, on the equilibrium path, firm $j = j_0$ stops in $t-1$ and the process is over; firm $j = j_1$ discloses in $t-1$. In t firm i continues irrespective of its type and in $t+1$ firm j continues irrespective of its type. Therefore, firm j_1's equilibrium disclosure is *ex ante*, $\tau^*_j = t-1$. Q.E.D.

Proof of Lemma 1

Proof. For the proof of Lemma 1, we distinguish between the case in which firm i discloses before firm j and the case in which firm i discloses after firm j.

Firm i discloses before firm j: At $t = t_i^0$, immediate disclosure by firm i yields expected payoffs of $\mathrm{E}_{t_i^0}\hat{U}_i(D@t_i^0) = H(t_i^0) - \pi^i_{t_i^0}\hat{\Lambda}^j_{t_i^0}(\tau_j)$ because $\sigma_i(t_i^0) = 0$. Delaying disclosure one round, so that i discloses at $t = t_i^0 + 2$, yields expected payoffs (evaluated at $t = t_i^0$) of $\mathrm{E}_{t_i^0}\hat{U}_i(D@t_i^0+2) = H(t_i^0)+p^2\sigma_i(t_i^0+2)H(t_i^0+2)-\pi^i_{t_i^0}\hat{\Lambda}^j_{t_i^0}(\tau_j)$. *Disclose* at $t = t_i^0$ is dominated by *disclose* at $t = t_i^0 + 2$ if, and only if, $\sigma_i(t_i^0 + 2) > 0$ because $p > 0$ and

$$\begin{aligned}\mathrm{E}_{t_i^0}\hat{U}_i(D@t_i^0) &= H(t_i^0) - \pi^i_{t_i^0}\hat{\Lambda}^j_{t_i^0}(\tau_j) \\ &< H(t_i^0) - \pi^i_{t_i^0}\hat{\Lambda}^j_{t_i^0}(\tau_j) + p^2\sigma_i(t_i^0+2)H(t_i^0) \;=\; \mathrm{E}_{t_i^0}\hat{U}_i(D@t_i^0+2)\end{aligned}$$

if, and only if, $\sigma_i(t_i^0 + 2) > 0$.

Firm i discloses after firm j: For $j = B$, by construction of the case, firm $i = A$ will delay disclosure. Instead, let firm $i = B$ (so that $t_B^0 = 2$) and firm $j = A$. The proof is by $\mathrm{E}_2\hat{U}_B(D@4) = H(2) + p^2\sigma_B(4)H(4) > H(2) = \mathrm{E}_2\hat{U}_B(D@2)$ for $\sigma_B(t_B^0 + 2) = \sigma_B(4) > 0$ and $p > 0$, and the arguments presented above. Q.E.D.

Proof of Lemma 2

Proof. As in the proof of Lemma 1 we distinguish between the case in which firm i discloses before firm j and the case in which firm i discloses after firm j.

Firm i discloses before firm j: For simplicity and without loss of generality, we assume that $t \in (t_i^0, \infty) \subset \mathbb{R}_+$. Consider the following properties of the expected payoff functions $\mathrm{E}_t\hat{U}_i(D@t)$ in equation (38a) and $\mathrm{E}_t\hat{U}_i(D@t + 2)$ in equation (38b):

P1. $\mathrm{E}_t\hat{U}_i(D@t)$ lies in a bounded space because $\sigma_i(t)$ and $h(t)$ are bounded and continuous functions, and $H(t) = \sum_{k=0}^{\infty} p^k (1-p) h(t+k)$ and

$$\hat{\Lambda}^j_t(\tau_j) = p^{\tau_j - t}\sigma_j(\tau_j)H(\tau_j)$$

as defined in (39) are bounded sequences.

P2. Because $\lim_{t\to\infty} h(t+k) = 1$ and $\lim_{t\to\infty} \sigma_i(t) = \zeta_i < 1$ for all $k \geq 0$, we get

$$\begin{aligned}\lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t) &= 1 + \zeta_i - p^{\Delta\tau_j}\zeta_j \lim_{t\to\infty} \pi^i_t, \\ \lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t+2) &= 1 + p^2\zeta_i - p^{\Delta\tau_j}\zeta_j \lim_{t\to\infty} \pi^i_t,\end{aligned}$$

with $\Delta\tau_j := \tau_j - t > 0$ and $p^{\Delta\tau_j}\zeta_j \lim_{t\to\infty} \pi^i_t < \infty$ as $\pi^i_t \in [0, 1]$.

If $\zeta_i > 0$, because $p < 1$, in the limit the expected payoffs from delaying disclosure one round are *strictly* smaller than the payoffs from disclosing right away, $\lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t) > \lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t+2)$, and i will not delay disclosure in the limit if, and only if, $\lim_{t\to\infty} \sigma_i(t) = \zeta_i > 0$. Given the results from Lemma 1, by the intermediate value theorem, and if $\mathrm{E}_t\hat{U}_i(D@t)$ and $\mathrm{E}_t\hat{U}_i(D@t + 2)$ intersect at most once, there exists a finite value of $\hat{t}_i > t_i^0$ such that

$\mathrm{E}_t\hat{U}_i(D@t+2) > \mathrm{E}_t\hat{U}_i(D@t)$ for all $t_i^0 < t < \hat{t}_i$ and $\mathrm{E}_t\hat{U}_i(D@t+2) \leq \mathrm{E}_t\hat{U}_i(D@t)$ for all $t \geq \hat{t}_i$. Setting $\hat{\tau}_i^a = \hat{t}_i$ establishes the proof.

If $\mathrm{E}_t\hat{U}_i(D@t)$ and $\mathrm{E}_t\hat{U}_i(D@t+2)$ intersect more than once, there exist multiple finite values of $\hat{t}_i > t_i^0$ such that $\mathrm{E}_t\hat{U}_i(D@t+2) > \mathrm{E}_t\hat{U}_i(D@t)$ for some $t < \hat{t}_i$ and $\mathrm{E}_t\hat{U}_i(D@t+2) \leq \mathrm{E}_t\hat{U}_i(D@t)$ for some $t \geq \hat{t}_i$. Then $\hat{\tau}_i^a$ is the smallest of these $\hat{t}_i$. This is because, by Assumption 1, firm i cannot commit to disclose in $t+k$ for any $k \geq 2$. Once delaying disclosure one round is less profitable than disclosing right away, firm i will disclose because delaying disclosure more than one round (so to disclosure in $t+4$ or $t+6$) is not an option.

Firm i discloses after firm j: The proof for $\hat{\tau}_i^a(\tau_j) > \tau_j$ being finite is by the properties of $\mathrm{E}_t\hat{U}_i$ presented in the case where firm i discloses before firm j, $\lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t|t > \tau_j) = 1+\zeta_i-\sigma_j(\tau_j)$, $\lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t+2|t > \tau_j) = 1+p^2\zeta_i-\sigma_j(\tau_j)$, so that $\lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t|\tau_j) > \lim_{t\to\infty} \mathrm{E}_t\hat{U}_i(D@t+2|\tau_j)$ for $\zeta_i > 0$ because $p < 1$, and by the arguments presented above. Q.E.D.

Proof of Proposition 5

Proof. "ONLY IF:" If both firms are optimistic and $\delta_i > 0$ and $\delta_j > 0$, then (37) is violated and a cross-licensing agreement is not feasible. Both firms pessimistic is not a necessary condition for a feasible cross-licensing agreement. Let i be optimistic and j be pessimistic, then both the LHS and RHS of (37) are positive. A cross-licensing agreement is more likely to be feasible with smaller LHS and greater RHS, i.e., with smaller $\Lambda_0^i(\tau_i^a)$ and greater $\Lambda_0^j(\tau_j^a)$. Because $\Lambda_0^i(\tau_i^a)$ is increasing in $\bar{\sigma}_i(\cdot)$ for both $i = A, B$, lower $\bar{\sigma}_i(\cdot)$ for the optimistic firm or higher $\bar{\sigma}_j(\cdot)$ for the pessimistic firm establishes the result. Q.E.D.

Proof of Proposition 6

Proof. By Lemma 1 and Lemma 2. The proof for the last claim follows from the observation of $\mathrm{E}_t\hat{U}_i(D@t+2|t < \tau_j) - \mathrm{E}_t\hat{U}_i(D@t|t < \tau_j) = \mathrm{E}_t\hat{U}_i(D@t+2|t > \tau_j) - \mathrm{E}_t\hat{U}_i(D@t|t > \tau_j)$. Q.E.D.

Proof of Proposition 7

Proof. If the firms communicate their ideas until a new idea fails to arrive, then both have the same number of ideas, n_S, and their joint payoffs are

$$\tilde{R}_A + \tilde{R}_B = 2\,(1-\theta)\,h(n_S).$$

If firm i at some point decides to stop rather than reveal a new idea, then $n_i = n_j + 1$. Their joint payoffs in this case are

$$\tilde{R}_i + \tilde{R}_j = h(n_i) + (1-2\theta)\,h(n_j).$$

We analyze under which conditions a cooperative equilibrium with communication exists, implying that communication of ideas for improvement takes place at all stages, until a new idea fails to arrive. We show that for sufficiently high θ the joint payoffs from continuing communication are smaller than from not continuing, i.e.,

$$\mathrm{E}_t\tilde{U}^{ce}(C@t) < \tilde{U}^{ce}(S@t) \tag{A.10}$$

for some t. The joint payoffs at t from continuing are

$$\mathrm{E}_t\tilde{U}^{ce}(C@t) = 2\,(1-\theta)\sum_{k=0}^{\infty} p^k\,(1-p)\,h(t+k),$$

the joint payoffs from stopping are $\tilde{U}^{ce}(S@t) = h(t) + (1-2\theta)\,h(t-1)$. By $h(t) > h(t-1)$, $\tilde{U}^{ce}(S@t) > 0$ for all θ; $\mathrm{E}_t\tilde{U}^{ce}(C@t) = 0$ for $\theta = 1$ and strictly positive otherwise. The critical value $\tilde{\theta}^{ce}$ (for which $\mathrm{E}_t\tilde{U}^{ce}(C@t) = U^{ce}(S@t)$) is strictly smaller than unity so that there are some $\theta > \tilde{\theta}^{ce}$ for which (A.10) holds. Note, also, that this critical value is strictly larger than $1/2$. Suppose for a moment that

$$\mathrm{E}_t\bar{U}^{ce}(C@t) = 2\,(1-\theta)\sum_{k=0}^{\infty} p^k\,(1-p)\,h(t) = 2\,(1-\theta)\,h(t).$$

$\mathrm{E}_t\bar{U}^{ce}(C@t) = \tilde{U}^{ce}(S@t)$ for $\theta = 1/2$, and the condition in equation (A.10) holds for $\theta > 1/2$. Because $h(t) < h(t+k)$ for all $k > 0$, $\mathrm{E}_t\tilde{U}^{ce}(C@t) > \mathrm{E}_t\bar{U}^{ce}(C@t)$ and $\tilde{\theta}^{ce} > 1/2$. Q.E.D.

Proof of Proposition 8

Proof. We proceed in four steps: We show *(1)* that post-disclosure communication incentives are more binding, *(2)* aspired disclosure is not affect by competition, and, *(3)* and *(4)*, the conditions underpinning the equilibrium in Propositions 3 and 4 become more binding under competition.

1. Suppose all patents have been disclosed, i.e., consider $t > \max\{\tau_i, \tau_j\}$. If a new idea arrives, firm i in t either continues or stops. Suppose both firms always continue until a new idea fails to arrive, then firm i's expected payoffs are

$$\mathrm{E}_t\tilde{U}_i(C@t|\tau_i,\tau_j) = (1-\theta)\,[1-\sigma_j(\tau_j)+\sigma_i(\tau_i)]\,H(t)$$

   That is, firm i obtains the profits from continuing the process over its monopoly segment of size $(1-\theta)$. Instead, suppose that firm i chooses to stop at stage t, its payoffs are equal to

$$\tilde{U}_i(S@t|\tau_i,\tau_j) = (1-\sigma_j(\tau_j))\,[h(t)-\theta h(t-1)] + \sigma_i(\tau_i)(1-\theta)h(t-1). \tag{A.11}$$

   For firm i to always continue the standard-setting process until a new idea fails to arrive, $\mathrm{E}_t\tilde{U}_i(C@t|\tau_i,\tau_j) \geq \tilde{U}_i(S@t|\tau_i,\tau_j)$ must hold for all values of $t > \max\{\tau_i,\tau_j\}$. This condition can be rearranged to read

$$\left(1+\frac{\sigma_i(\tau_i)}{1-\sigma_j(\tau_j)}\right)\frac{H(t)-h(t-1)}{h(t)-h(t-1)} \geq \frac{1}{1-\theta}. \tag{A.12}$$

Condition (A.12) is clearly more binding than (A.1), because the LHS is the same in both expressions and the RHS in (A.12) is strictly larger than 1. This implies that post-disclosure communication is not granted with product market competition.

2. We now turn to the analysis of the impact of competition on aspired disclosure. The condition that determines aspired disclosure timing compares the profits from disclosure in t,
$$\mathrm{E}_t\tilde{U}_i(D@t) = (1-\theta)\left[\,(1+\sigma_i(t))\,H(t) - \pi_t^i\Lambda_t^j(\tau_j)\right], \tag{A.13}$$
and the profits from disclosure in $t+2$,
$$\begin{aligned}\mathrm{E}_t\tilde{U}_i(D@t+2) \quad &= \quad (1-\theta)\left[H(t) + (1-p)\,\sigma_i(t+1)h(t) + \right.\\ &\left. \qquad p\sigma_i(t+2)H(t+1) - \pi_t^i\Lambda_t^j(\tau_j)\right].\end{aligned} \tag{A.14}$$
It is easy to see that whether (A.14) is larger than (A.13) does not depend on the size of the monopolistic segment, $(1-\theta)$.

3. For the analysis of pre-disclosure communication under competition, first we consider the case in which firm j has disclosed its patent in τ_j and a patent holder firm i_1 has to decide when to disclose depending on firm j's communication incentives. In Proposition 3 we show that there is a perfect Bayesian equilibrium in which firm i discloses before the end of the process. Here, we discuss how the relevant conditions supporting this equilibrium are affected by the presence of a competitive segment. First, in $t+1$ firm j chooses *continue* or *stop* by comparing the following two expressions:
$$\tilde{U}_{j_1}(S@t+1|\tau_j) = \left(1-\pi_{t+1}^j\sigma_i(t+1)\right)[h(t+1)-\theta h(t)] + \sigma_j(\tau_j)\,(1-\theta)\,h(t) \tag{A.15}$$
and
$$\mathrm{E}_{t+1}\tilde{U}_{j_1}(C@t+1|\tau_j,\neg S) = (1-\theta)\left[\,(1+\sigma_j(\tau_j))\,H(t+1) - \pi_{t+1}^j\Lambda_{t+1}^i(\tau_i)\right], \tag{A.16}$$
where $\Lambda_{t+1}^i(\tau_i)$ is defined in (13). Firm j will continue the process in $t+1$ if $\mathrm{E}_{t+1}\tilde{U}_{j_1}(C@t+1|\tau_j,\neg S) \geq \tilde{U}_{j_1}(S@t+1|\tau_j)$, or
$$\frac{(1+\sigma_j(\tau_j))\,[H(t+1)-h(t)] - \pi_{t+1}^j\left[\Lambda_{t+1}^i(\tau_i) - \sigma_i(t+1)h(t+1)\right]}{\left(1-\pi_{t+1}^j\theta\sigma_i(t+1)\right)[h(t+1)-h(t)]} \geq \frac{1}{1-\theta}. \tag{A.17}$$
In absence of competition, firm j continues if (12a) is larger than (12b), that is if
$$\frac{(1+\sigma_j(\tau_j))\,[H(t+1)-h(t)] - \pi_{t+1}^j\left[\Lambda_{t+1}^i(\tau_i) - \sigma_i(t+1)h(t+1)\right]}{h(t+1)-h(t)} \geq 1. \tag{A.18}$$
Comparing (A.17) with (A.18), communication under competition is more difficult to sustain if
$$\frac{1-\theta}{1-\pi_{t+1}^j\theta\sigma_i(t+1)} \leq 1,$$
which holds true for all $\pi_{t+1}^j\sigma_i(t+1) < 1$. Therefore, competition renders communica-

tion incentives more binding. This implies that the relevant threshold for π^j_{t+1} below which firm j stops the process is lower than in absence of competition.

In Proposition 3, we show that the perfect Bayesian equilibrium that involves firm i disclosing in t, requires the following two additional conditions to be satisfied: firm i_1 prefers *disclose* to *continue* in t (that is, (19) holds true) and firm i_0 stops in t when it anticipates firm j to stop in $t+1$. Note that, under competition, $\mathrm{E}_t U_{i_1}(D@t|\tau_j, C)$ and $\mathrm{E}_t U_{i_1}(C@t|\tau_j, S)$ can be rewritten as

$$\begin{aligned}
\mathrm{E}_t\tilde{U}_{i_1}(D@t|\tau_j, C) &= (1-\theta)\left[1+\sigma_i(t)-\sigma_j(\tau_j)\right]H(t), \\
\mathrm{E}_t\tilde{U}_{i_1}(C@t|\tau_j, S) &= (1-\theta)\big[\left(1+\sigma_i(t+1)-\sigma_j(\tau_j)\right)h(t) + \\
&\quad p\sigma_i(t+1)\left(h(t+1)-h(t)\right)\big],
\end{aligned}$$

thus whether (19) holds true under competition does not depend on θ. Finally, if firms compete on the product market, a non-patent holder i, anticipating that j stops in $t+1$, strictly prefers to *stop* over *continue*

$$\begin{aligned}
\mathrm{E}_t\tilde{U}_{i_0}(C@t|\tau_j, S) &= (1-\theta)\left(1-\sigma_j(\tau_j)\right)h(t) \; < \\
\tilde{U}_{i_0}(S@t|\tau_j) &= \left(1-\sigma_j(\tau_j)\right)\left[(1-\theta)h(t)+\theta\left(h(t)-h(t-1)\right)\right],
\end{aligned}$$

whereas it would be indifferent in the absence of competition.

We can conclude that two out of the three constraints on pre-disclosure communication incentives that support the separating equilibrium in Proposition 3 become more binding under competition, whereas the third is not affected by competition.

4. Finally, we consider the case in which both firms j_1 and i_1 have not disclosed their patents. In Proposition 4 we show that there is a perfect Bayesian equilibrium in which firm j discloses before the end of the process. Here, we analyze how the constraints supporting this equilibrium change in the presence of a competitive segment. The first relevant condition regards firm j_0 incentives to continue in $t+1$, which gives rise to the threshold $\hat{\pi}^j_{t+1}(\tau_i)$ in (24). Uncer competition, firm j_0 compares

$$E_{t+1}\tilde{U}_{j_0}(S@t+1) = \left(1-\pi^j_{t+1}\sigma_i(t+1)\right)\left(h(t+1)-\theta h(t)\right)$$

with

$$\mathrm{E}_{t+1}\tilde{U}_{j_0}(C@t+1|\neg S) = (1-\theta)\left[H(t+1)-\pi^j_{t+1}\Lambda^i_{t+1}(\tau_i)\right].$$

Therefore, *continue* is preferred to *stop* if

$$\begin{aligned}
H(t+1)-h(t+1)-\pi^j_{t+1}\left[\Lambda^i_{t+1}(\tau_i)-\sigma_i(t+1)h(t+1)\right] &\geq \\
\frac{\theta}{1-\theta}\left(1-\pi^j_{t+1}\sigma_i(t+1)\right)\left(h(t+1)-h(t)\right) &> 0.
\end{aligned}$$

It is easy to see that if $\theta = 0$ (no competition) the RHS of the expression above is zero and the condition less binding. This means that the critical value for π^j_{t+1} such that firm j continues in $t+1$ is lower than in absence of competition.

The second relevant condition concerns firm i_1's incentives in t, from which we compute the threshold $\bar{\pi}_t^i(\tau_j)$ in (27). In particular, under competition firm i_1 compares

$$E_t\tilde{U}_{i_1}(S@t) = \left(1 - \pi_t^i \sigma_j(t)\right)[h(t) - \theta h(t-1)]$$

with

$$\mathrm{E}_t\tilde{U}_{i_1}(C@t|\neg S) = (1-\theta)\left[H(t) - \pi_t^i \Lambda_t^j(\tau_j) + \Lambda_t^i(\tau_i)\right].$$

The resulting condition reads

$$\begin{aligned} H(t) - h(t) - \pi_t^i(\Lambda_t^j(\tau_j) - \sigma_j(t)h(t)) + \Lambda_t^i(\tau_i) - \sigma_i(t)h(t-1) \quad &\geq \\ \frac{\theta}{1-\theta}\left(1 - \pi_t^i\sigma_j(t)\right)(h(t) - h(t-1)) \quad &> \quad 0. \end{aligned}$$

Again, the RHS of the expression is zero if $\theta = 0$ and the less binding. This means that the threshold of π_t^i above which firm i stops the process is lower.

In the third, and last, condition, regards firm j_1's decision to disclose in $t-1$, from which we derive $\tilde{\pi}_{t-1}^i(\tau_i)$ in (28). If firms compete on θ, this condition results from the comparison between

$$E_{t-1}\tilde{U}_{j_1}(D@t-1|\neg S) = (1-\theta)\left[\,(1 + \sigma_j(t-1))\,H(t-1) - \pi_{t-1}^j \Lambda_{t-1}^i(\tau_i)\right]$$

and

$$\mathrm{E}_{t-1}\tilde{U}_{j_1}(C@t-1|S) = (1-\theta)\left[\left(1 - \pi_{t-1}^j\sigma_i(t) + \sigma_j(t)\right)h(t-1) + p\sigma_j(t)\,(h(t) - h(t-1))\,\right],$$

which is not affected by θ. Also in this case as for the conditions underpinning the equilibrium in Proposition 3, we can conclude that two out of the three communication constraints that support the equilibrium in Proposition 4 become more binding under competition, whereas the third is independent of the degree of product market competition. Q.E.D.