THE JOURNAL OF INDUSTRIAL ECONOMICS 0022-1821
Volume LXXII March 2024 No. 1

PRICE COMMITMENTS IN STANDARD SETTING UNDER ASYMMETRIC INFORMATION*

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Standards may create market power for the holders of standard essential patents (SEPs). To address these concerns, the literature advocates price commitments, whereby SEP holders commit to the maximum royalty they would charge were their technology included in the standard. We consider a setting in which a technology implementer holds private information about profitability. In this setting, price commitments increase efficiency not only by curbing SEP holders' market power, but also by alleviating distortions in the design of the royalty scheme. We derive conditions under which price commitments can be implemented using a simple royalty cap as used in practice.

I. INTRODUCTION

THERE IS A LIVELY DEBATE CONCERNING the possibility that standards create essentiality and thus monopoly power for the holders of standard essential patents (SEPs) (Farrell *et al.* [2007]; Schmalensee [2009]; Ganglmair *et al.* [2012]; Dewatripont and Legros [2013]; Lerner and Tirole [2015]; Spulber [2019]). This is said to cause at least two inefficiencies. First, SEP holders can charge higher royalties than under hypothetical ex ante licensing. Second, anticipating such opportunistic behavior, standard setting organizations (SSOs) may select technologically inferior functionalities that are available at

*For useful comments and suggestions, we thank Cédric Argenton, Amedeo Piolatto, David Perez-Castrillo, Johannes Schneider, and Bert Willems, as well as conference and seminar participants at Tilburg University, EARIE 2019 (Barcelona), and the Barcelona Summer Forum Workshop on the Economics of Science and Innovation 2022 (Barcelona). All three authors are affiliated with the Tilburg Law and Economics Center (TILEC). For its research on competition, standardization, and innovation, TILEC received funding from Qualcomm Inc. The research on which this article is based was conducted in accordance with the rules set out in the Royal Dutch Academy of Sciences (KNAW) Declaration of Scientific Independence. All errors are our own.

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lower royalties, for example because there is within-functionality competition or the patents have expired.

To address these concerns, SSOs typically impose the requirement that technology contributors commit to license their patents on fair, reasonable and nondiscriminatory (FRAND) terms. But these are thought to be vague, and some SSOs have gone a step further and adopted policies allowing for ex ante price commitments (e.g., ETSI, an SSO setting telecommunications standards, and VITA, an SSO setting standards for computer architecture).[1] In the Rambus case, responding to the European Commission's statement of objections, the company proposed to put a cap on its royalties. Likewise, there is evidence of firms participating in standard setting and patent pools emerging from the works on a new standard which offer nonlinear pricing schemes that cap the royalties they levy on patent holders.

In this article, we study the impact of licensors' commitments to royalty caps on standardization decisions and product-market outcomes in the presence of asymmetric information. In the model, the licensee (the downstream firm) holds superior information vis-à-vis the patent holder (the upstream firm). Absent the cap, as is standard in screening models, the patent holder inefficiently distorts the optimal contract offered to the licensee to reduce the latter's information rent. Rent extraction by the patent holder may also lead the SSO to choose an inferior technology as the standard. Royalty caps reduce the contractual inefficiency. By constraining its ability to extract surplus from the downstream firm, the cap allows the upstream firm to ensure that the SSO selects its technology, and leaving an information rent is an efficient way of transferring surplus.

The merits of caps have been established by the theoretical literature on standard setting in models with complete information. Lerner and Tirole [2015] advocate structured price commitments, whereby SEP holders commit to the maximum royalty they would charge were their technology included in the standard. In Lerner and Tirole's setting, price commitments restore the competitive benchmark royalty rates and ensure that the SSO selects the efficient standard. In a similar vein, Llanes and Poblete [2014] study various alternative standard-setting and patent pool-formation rules and show that welfare is maximized by ex ante agreements about participation in, and the distribution of dividends from, a patent pool for technologies selected into the standard.[2]

In practice, however, there is often considerable uncertainty about the benefits of including certain functionalities in the standard. In the case of

[1] Note that price commitments are voluntary at ETSI whereas they are mandatory at VITA. This distinction turns out not to matter for our purposes, as patent holders in our model have a demand for commitment.

[2] Layne-Farrar *et al.* [2014] analyze the impact of price caps imposed by regulation on innovators' incentives to participate in standard setting.

mobile telephony, for instance, it may not be clear how much consumers are willing to pay for increased transmission speeds. Such uncertainty is typically resolved only after the standard has been set. Moreover, technology contributors (SEP holders) tend to be less well informed about demand parameters than implementers of the standard (in the mobile telephony example, the handset makers).

We consider a setting in which the downstream firm holds private information about the profitability of the final product incorporating the standard. In such a setting, the upstream firm will design its royalty scheme to screen the downstream firm's type and elicit its private information (Macho-Stadler and Perez-Castrillo [1991]).[3] We assume that the uncertainty about profitability is resolved after the SSO sets the standard but before royalty negotiations between upstream and downstream firm take place.

In the absence of price commitments, the upstream firm screens the downstream firm by means of a nonlinear royalty scheme. As usual, the optimal contract involves no output distortion for the type with the highest profitability ('no distortion at the top'). For lower-profitability types, output is distorted downward to make it less attractive for the higher types to mimic the lower types. This is done in an effort to reduce the downstream firm's information rent. Except for the information rent, the optimal contract extracts the downstream firm's entire surplus. Even though an alternative, albeit inferior, technology is available ex ante, once the standard is set the downstream firm can no longer turn to this alternative technology if it wants to comply with the standard. Because the SSO anticipates the upstream firm's behavior, it often selects the inferior alternative technology as the standard.

In the presence of price commitments, the upstream firm can indirectly control the contract that it will offer to the downstream firm after the standard is set by appropriately choosing the royalty cap to which it commits prior to standardization. Essentially, thus, the need to ensure inclusion in the standard adds an additional constraint to the upstream firm's problem. This forces the upstream firm to leave enough rent to the downstream firm to beat out the alternative technology. We show that this is done by proportionally reducing rent extraction for all types. Intuitively, because the upstream firm cannot extract so much downstream surplus anymore, there is less of a need to reduce the information rent; in fact, giving an information rent is an efficient way of transferring some surplus to the downstream firm. This objective can be achieved with an output-dependent royalty cap: if the upstream firm cannot extract more than a certain royalty payment, it has no incentive to distort output further than to the degree the reduced information rent can be extracted.

In our setting, the inefficiency in technology adoption could also be eliminated by tilting the SSO's focus away from users and toward technology

[3] Gallini and Wright [1990] address similar issues in a setting where the innovator, rather than the implementer, holds private information, so that there is signaling rather than screening.

developers. We show, however, that a user-friendly SSO with a policy requiring price commitments leads to higher welfare than a joint profit-maximizing SSO. This is because a joint profit-maximizing SSO always adopts the superior technology and thus does not force U to make concessions to D in order to ensure SSO selection. A user-friendly SSO induces U to leave rents to D, which not only solves the inefficiency in technology adoption but comes with the additional benefit of reducing the output distortion from screening.

Nonlinear royalty schemes are a key feature of our model. Although asymmetric information naturally gives rise to such schemes in theory, finding systematic evidence on their use in practice is notoriously difficult due to the confidential nature of license agreements. Nevertheless, there is both anecdotal and survey evidence suggesting they are common. There are many examples of nonlinear royalties being offered by patent pool administrators in the digital industry. These patent pools license technologies that are tied to technology standards, like MPEG, Wi-Fi or Advanced Audio Coding (AAC). The relevant licensing arrangements take the form of quantity discounts with or without entrance fees,[4] simple caps on the total royalties paid per enterprise or product per year,[5] quantity discounts up to a cap on the total royalties paid per enterprise or product,[6] and two-part tariffs.[7] Moreover, publicly available documents from the decision of the Court of the Northern District of California in *Federal Trade Commission v. Qualcomm* (Case No. 17-CV-00220-LHK) establish the use of caps by Nokia and Qualcomm, both major SEP holders. On top of this anecdotal evidence, industry surveys tend to show that the use of two-part tariffs is widespread.[8]

The article is related to the growing literature on the economics of standard setting. Within that literature, Llanes and Poblete [2014] and Lerner and Tirole [2015] share our focus on ex ante commitments. Llanes [2019] studies

[4] See the AAC license fees at VIA (*https://www.via-corp.com/aac-license-fees-structures/*) or the DVB-T2 license fees at Sisvel (*https://www.sisvel.com/licensing-programs/digital-video-display-technology/dvb-t2/license-terms*).

[5] See the MPEG surround PC software license fees at VIA (*https://www.via-corp.com/licensing/mpeg-surround/mpeg-surround-license-fees/*) or the AGORA-C one-time payment on free-to-air broadcast services at VIA (*https://www.via-corp.com/licensing/agora-c/agora-c-license-fees/*).

[6] See the MPEG-4SLS consumer PC software license fees at VIA (*https://www.via-corp.com/licensing/mpeg-4-sls/mpeg4-sls-license-fees/*).

[7] See the DVB-SIS license fees at Sisvel (*https://www.sisvel.com/licensing-programs/digital-video-display-technology/dvb-sis/license-terms*). For example, the two-part tariffs of the DVB-SIS portfolio license have a nonrefundable entrance fee of € 1000.00 and royalty rates of up to € 220 based on the number of transmitting functionalities and receiving functionalities of products.

[8] For example, Rostoker [1984] reports that two-tariffs, consisting of fixed upfront payments and running royalties, are the most frequently chosen method of compensation among the firms he surveys. In a more recent survey commissioned by the European Commission, Radauer and Dudenbostel [2013] find that 81% of firms use upfront fees and 78% use per-unit royalties, implying that a sizeable fraction uses a combination of both (i.e., a two-part tariff).

a game of repeated standard setting and shows that commitments to license on fair, reasonable, and nondiscriminatory (FRAND) terms can outperform price commitments when technologies are hard to describe ex ante. Llanes and Poblete [2020] show that, when there is more than one possible standard so that a standards war may emerge, the optimality of ex ante agreements is no longer assured. Bekkers *et al.* [2017] model the disclosure process and show that, when there is competition for inclusion in the standard, vertically integrated firms can find it optimal to commit to royalty-free licensing.

For the most part, the literature has ignored asymmetric information about the benefits and costs of technologies vying for inclusion in a standard, which is the focus of our paper. The exceptions—though different in focus from us—are Farrell and Simcoe [2012], Lerner *et al.* [2016], Bonatti and Rantakari [2016] and Balzer and Schneider [2021]. Farrell and Simcoe [2012] and Bonatti and Rantakari [2016] model standard setting as a war of attrition. Lerner *et al.* [2016] study SEP holders' decision whether to make generic or specific disclosures to the SSO. These papers assume that the quality of technologies, or the patents that cover them, is innovators' private information. By contrast, in our model it is the implementer that holds private information about the profitability of a technology. Finally, Balzer and Schneider [2021] model coordination among competitors in standard setting, in the shadow of a market mechanism, under private information about each innovator's chances in a standards war.

Our paper also differs from much of the rest of the literature by considering nonlinear royalties. In a similar spirit, Schmidt [2014] allows for two-part tariffs and shows that, in the context of licensing complementary technologies, they eliminate royalty stacking. In our paper, royalties can be part of the optimal contract despite the fact that we allow for nonlinear tariffs because they are used for screening purposes.

The remainder of the article is organized as follows. Section II sets out the model. Section III presents the general problem of the upstream firm (the licensor). Section IV solves the case without price commitments, while Section V turns to the case in which price commitments, in the form of a royalty cap, are possible. Section VI examines the implications of our analysis for the objective SSOs should pursue. Section VII concludes.

II. MODEL

Consider the following setup. There is a single upstream firm U, a single downstream firm D, and an SSO. U owns a patent on a feature that the SSO considers for inclusion in a standard. The product-market profit generated by U's technology ($\tilde{\pi}(q,\theta)$) is uncertain and governed by output q and a profitability parameter $\theta \in [\theta_0, \theta_1]$, with $\theta_1 > \theta_0 > 0$. Parameter θ is distributed according to an atomless cumulative distribution function F that has density function f and a strictly decreasing hazard rate ($d[(1-F(\theta))/f(\theta)]/d\theta < 0$).

The value of parameter θ is initially unknown to all parties but is revealed to D prior to the implementation of the standard (in a final product). There also exists an alternative (backstop) technology that is available royalty free and generates a known profit $\tilde{\pi}(q,0)$.

Equilibrium profit with the backstop technology is denoted $\pi_0 = \max_q \tilde{\pi}(q,0)$. If, instead of the backstop technology, U's superior technology is implemented by D, we use the following notation for D's equilibrium profit:

$$\pi(\theta) = \max_q \ \tilde{\pi}(q,\theta) - R(q), \tag{1}$$

where $R(q)$ denotes the royalty scheme chosen by U.

Maximizing the joint profits of D and U yields

$$\pi^*(\theta) = \max_q \ \tilde{\pi}(q,\theta). \tag{2}$$

Accordingly,

$$q^*(\theta) = \arg\max_q \ \tilde{\pi}(q,\theta).$$

We impose the following assumptions on our profit function:

Assumption 1.

i. The profit is concave in output q ($\tilde{\pi}_{qq} < 0$).
ii. The profit $\tilde{\pi}$ increases in θ ($\tilde{\pi}_\theta \geq 0$, with strict inequality for $q > 0$).
iii. The marginal profit $\tilde{\pi}_q$ increases in θ ($\tilde{\pi}_{q\theta} > 0$).
iv. The innovation yields higher profit than the backstop technology ($\tilde{\pi}(q,\theta) > \tilde{\pi}(q,0)$).

Assumption 1(i) helps ensure that the first-order condition is sufficient for profit maximization. Assumption 1(ii) means that a higher value of parameter θ leads to higher profit. Assumption 1(iii) says that the change in profit resulting from a marginal expansion of output is larger for larger values of the profitability parameter θ; it also gives us single crossing for the downstream firm. Finally, Assumption 1(iv) implies that, absent any distortion caused by U's pricing, U's technology generates larger product-market profit for the downstream firm than the backstop technology.

Example. Suppose inverse demand is given by $p(q,\theta) = 1 + \theta - q$ and the downstream firm's cost function is independent of θ and equal to $c(q) = cq$, where $0 \leq c < 1$. Assume $\theta_0 > 0$. Then the profit function is $\tilde{\pi}(q,\theta) = (1 + \theta - q - c)q$, which satisfies Assumption 1.[9] This example corresponds to a situation in which θ is a parameter that shifts out the demand

[9] We have: (i) $\tilde{\pi}_{qq} = -2 < 0$; (ii) $\tilde{\pi}_\theta = q \geq 0$ (with strict inequality for $q > 0$); (iii) $\tilde{\pi}_{q\theta} = 1 > 0$, and (iv) $\tilde{\pi}(q,\theta) > \tilde{\pi}(q,0) \Leftrightarrow \theta > 0$, which holds for any $\theta \in [\theta_0, \theta_1]$ since by assumption $\theta_0 > 0$.

curve. We believe this to be a particularly plausible scenario in the context of standard setting, where implementers are closer to consumers and thus tend to be better informed about demand than innovators. Nevertheless, the analysis that follows is more general and can accommodate other explanations for why the downstream firm would have private information about its profits as well as other functional forms.

In the analysis below, we distinguish between the cases with and without commitment on the royalty scheme. Absent commitment, the upstream firm U solves a standard screening problem. With commitment, U commits to a royalty cap $\overline{R}(q)$ prior to standardization. The timing is as follows: .

1. In the presence of price commitments, U announces the maximum royalty it will charge $\overline{R}(q)$.
2. The SSO selects between U's technology and the alternative one. Assume the SSO is "user-driven" and thus selects the technology that maximizes D's expected profit.
3. If U's technology is selected, D learns θ. Otherwise, D produces using the backstop technology and earns π_0.
4. U proposes a royalty scheme $R(q)$. If a price commitment is in place, U is subject to the constraint $R(q) \leq \overline{R}(q)$.
5. D accepts or rejects. If it accepts, it chooses its output q to maximize $\tilde{\pi}(q, \theta) - R(q)$.

III. GENERAL PROBLEM

We now have all the ingredients to set up the optimization problem of the upstream firm. We find it useful to first solve a general version of the problem, which embeds the cases with and without commitment. We then zoom in on each of the two cases to discuss the features of the ensuing solutions.

The upstream firm's problem, in its general version, is to choose the royalty scheme that maximizes U's expected revenue, $\int_{\theta_0}^{\theta_1} R(q(\theta))f(\theta)d\theta$, subject to individual rationality (IR), incentive compatibility (IC), and (under commitment) SSO selection. As usual, this problem can be rewritten as choosing a menu of quantities and royalty payments $(q(\theta), R(\theta))$, where $R(\theta) = R(q(\theta))$. Individual rationality requires $\pi(\theta) \geq 0$ for all θ. Incentive compatibility requires that, for all θ, $q(\theta)$ solves the maximization problem in equation (1), that is,

$$q(\theta) = \arg\max_{q} \ \tilde{\pi}(q, \theta) - R(q).$$

An equivalent way of writing the IC constraint can be obtained by noticing that, because $q(\theta)$ solves D's maximization problem, the envelope theorem implies that the derivative of equation (1) with respect to θ is

$$\pi_\theta(\theta) = \tilde{\pi}_\theta(q(\theta), \theta), \tag{3}$$

where π_θ denotes the derivative of function π. In what follows, we use equation (3) to define our IC constraints. We also have

$$R(\theta) = \tilde{\pi}(q(\theta), \theta) - \pi(\theta),$$

which we can use to replace $R(\theta)$ in U's optimization problem and instead maximize with respect to $q(\theta)$ and $\pi(\theta)$.

Finally, in the case of commitment, the SSO selection constraint is

$$\int_{\theta_0}^{\theta_1} \pi(\theta) f(\theta) d\theta \geq \pi_0. \tag{4}$$

The left-hand side is the downstream firm's expected profit if U's technology is chosen as the standard, while the right-hand side is D's profit if the backstop technology is chosen. The constraint in (4) guarantees that, when U can commit to a royalty scheme—and thus to the rents $\pi(\cdot)$ it leaves to D—before standard selection, the SSO selects U's technology instead of the backstop technology.

Putting everything together, and ignoring IR for the moment (later we show the IR constraint can be binding only for the lowest type, θ_0, if at all), U's problem is to choose the menu of output $q(.)$ and downstream profit $\pi(.)$ to maximize

$$\max_{q(.),\pi(.)} \int_{\theta_0}^{\theta_1} \left([\tilde{\pi}(q(\theta), \theta) - \pi(\theta) + \zeta(\pi(\theta) - \pi_0)] f(\theta) + \mu(\theta)[\pi_\theta(\theta) - \tilde{\pi}_\theta(q(\theta), \theta)] \right) d\theta,$$

where $\mu(\theta)$ denotes the Lagrange multiplier on the IC in equation (3), with $\mu(\theta) > 0$, and ζ is the Lagrange multiplier on the SSO selection constraint in (4). Without commitment, constraint (4) is slack, so that $\zeta = 0$. With commitment, the constraint may or may not be binding; if SSO selection imposes an actual constraint, then $\zeta > 0$. In the remainder of this section, we present the solution to the maximization problem above. We will later discuss the two cases with and without commitment by distinguishing between $\zeta = 0$ and $\zeta > 0$.

The first order condition for $q(.)$ can be written as:

$$f(\theta)\tilde{\pi}_q(q(\theta), \theta) = \mu(\theta)\tilde{\pi}_{q\theta}(q(\theta), \theta) \tag{5}$$

and for $\pi(.)$, the Euler equation implies:

$$\mu_\theta(\theta) = -f(\theta)(1 - \zeta).$$

Since $\pi(\theta_1)$ is free to choose, we obtain the following transversality condition:

$$\mu(\theta_1) = 0.$$

We then have a differential equation with an end-point condition that can be solved as:

$$\mu(\theta) = (1 - F(\theta))(1 - \zeta).$$

Substituting this value of $\mu(\theta)$ into equation (5), we find

$$\tilde{\pi}_q(q(\theta), \theta) = (1 - \zeta)\frac{1 - F(\theta)}{f(\theta)}\tilde{\pi}_{q\theta}(q(\theta), \theta). \tag{6}$$

Below, we discuss the intuition for this equation for both the case with and without commitment. Beforehand, in Lemma 1 we do two things. First, we derive a sufficient condition under which $q(\theta)$ is increasing in θ. Together with the concavity of the profit function (Assumption 1(i)), single crossing (Assumption 1(iii)), and the monotone hazard rate, an increasing $q(\theta)$ ensures that the second order condition for D's optimization problem is satisfied and that local IC implies global IC (Fudenberg and Tirole [1991, Chapter 7]). Second, we derive a condition under which U does not want to shut down downstream types with low values of θ:

Lemma 1.

i. If, in addition to the conditions in Assumption 1, it holds true that

$$\tilde{\pi}_{qq\theta} \geq 0 \text{ and } \tilde{\pi}_{q\theta\theta} \leq 0,$$

then $dq(\theta)/d\theta > 0$.

ii. If

$$\tilde{\pi}_q(0, \theta_0) > \frac{1}{f(\theta_0)}\tilde{\pi}_{q\theta}(0, \theta_0) \tag{7}$$

then all downstream types participate actively ($q(\theta) > 0$) in U's optimal allocation.

Proof. Differentiating equation (6) with respect to θ gives:

$$\left[\tilde{\pi}_{qq} - (1 - \zeta)\frac{1 - F(\theta)}{f(\theta)}\tilde{\pi}_{qq\theta}\right]\frac{dq(\theta)}{d\theta} = -\tilde{\pi}_{q\theta} + (1 - \zeta)\frac{d\left(\frac{1 - F(\theta)}{f(\theta)}\right)}{d\theta}\tilde{\pi}_{q\theta} + (1 - \zeta)\frac{1 - F(\theta)}{f(\theta)}\tilde{\pi}_{q\theta\theta}. \tag{8}$$

It follows that $dq(\theta)/d\theta > 0$ because the expression between brackets on the left-hand side is negative and the three terms on the right-hand side are also negative under our Assumption 1 and the conditions in the first claim of the lemma.

The condition in the second claim of the lemma is derived as follows. If at $q(\theta_0) = 0$ it is the case that U's marginal profit for $q(\theta_0)$ is strictly positive (taking the information rent into account), then it is optimal for U to have type θ_0 active. Because $dq(\theta)/d\theta > 0$, this implies that all downstream types θ are active. ■

The example with linear demand and constant returns to scale we introduced above satisfies the conditions in the first claim of Lemma 1, as in that case $\tilde{\pi}_{qq\theta} = \tilde{\pi}_{q\theta\theta} = 0$. It satisfies condition (7) provided $1 + \theta_0 - c > 1/f(\theta_0)$, a sufficient condition for which is that $\theta_0 f(\theta_0) \geq 1$. That is, θ_0 and the probability density at θ_0 must not be too small. In what follows, we assume that the conditions in the lemma are satisfied. We proceed by considering the cases with and without commitment.

IV. NO PRICE COMMITMENTS

Let us first consider the case where U cannot commit to a menu $(q(\theta), R(\theta))$ before the standard-setting stage. We solve the model backwards, starting from stage 4.

Royalty setting stage. Suppose that the SSO has selected U's technology as the standard, so that D cannot use the alternative technology. The following proposition applies the results from the previous section to characterize the solution to U's problem.

Proposition 1. In the absence of price commitments, U chooses the royalty scheme to implement an allocation $q^{NC}(\theta)$ such that $q^{NC}(\theta) = q^*(\theta)$ if and only if $\theta = \theta_1$, and $q^{NC}(\theta) < q^*(\theta)$ otherwise (i.e., for all $\theta \in [\theta_0, \theta_1\rangle$).

Proof. Technically, the absence of commitment implies that $\zeta = 0$ in the general version of U's optimization problem studied in Section III. Consider equation (6). The first best allocation $q^*(\theta)$ for the upstream and downstream firms combined requires that the left-hand side of equation (6) equals zero. However, since $F(\theta) \in [0, 1\rangle$ for all $\theta \in [\theta_0, \theta_1\rangle$, the quantity $q(\theta) = q^{NC}(\theta)$ that solves the equation is strictly less than $q^*(\theta)$ for each type $\theta < \theta_1$. ■

The allocation in Proposition 1 features the familiar "no distortion at the top" result—the highest type, θ_1, produces the efficient output—and a downward distortion of the output of all types lower than θ_1, that is, the lower types produce less than the efficient quantity (characterized by $\tilde{\pi}_q(q^*(\theta), \theta) = 0$). The intuition is as follows. U can extract D's surplus through the royalty scheme $R(q)$, and thus has an interest in inducing the profit-maximizing output level. High levels of $q(\theta)$, however, make it attractive for high types to mimic low types. To prevent this from happening and get truthful revelation, U offers the high types information rents: $\pi_\theta(\theta)$ increases with $q(\theta)$ in equation (3). To reduce these rents, U distorts $q(\theta)$ downwards for all types $\theta \in [\theta_0, \theta_1\rangle$. This generates first-order gains in terms of rent extraction, while (initially) causing only second-order losses in terms of efficiency. Since no one tries to mimic type θ_1, its output level is not distorted.

The royalty payments associated with the quantities $q^{NC}(\theta)$ derived in Proposition 1 can be determined as follows. Because IC implies that $\pi^{NC}(\theta)$ is increasing, U will optimally set $\pi^{NC}(\theta_0) = 0$, extracting all rents from the lowest type (i.e., IR binds for type θ_0). For the remaining types, we have

$$\pi^{NC}(\theta) = \underbrace{\pi^{NC}(\theta_0)}_{=0} + \int_{\theta_0}^{\theta} \pi_\theta^{NC}(x)dx = \int_{\theta_0}^{\theta} \tilde{\pi}_\theta(q(x), x)dx.$$

Using (1), we obtain

$$R^{NC}(\theta) = \tilde{\pi}(q^{NC}(\theta), \theta) - \int_{\theta_0}^{\theta} \tilde{\pi}_\theta(q^{NC}(x), x)dx. \tag{9}$$

Standard setting stage. Anticipating the outcome at the royalty-setting stage without price commitments, the SSO selects U's technology if and only if it yields D a greater expected profit than the alternative technology:

$$\int_{\theta_0}^{\theta_1} \pi^{NC}(\theta) f(\theta) d\theta \geq \pi_0. \tag{10}$$

In the absence of commitment, there are two inefficiencies that arise. First, although U's technology always generates larger profit than the backstop technology (Assumption 1(iv)), nothing guarantees that equation (10) is satisfied. This is only the case if the expected *information rent* that D obtains—which amounts to only a fraction of the expected downstream profits—is larger than the profit from the backstop technology. Thus, U's technology will sometimes not be selected by the SSO. This inefficiency is due to U's lack of commitment power: because royalties are negotiated after the standard is set, U cannot credibly promise not to extract (most of) D's surplus after being selected as the standard. Second, the contract designed by the upstream firm introduces an output distortion for all types except the highest one. This second inefficiency exacerbates the first one, as it reduces the range of parameters for which the SSO adopts U's superior technology compared to a situation without output distortions. That is, if U asked all types to produce the efficient quantity $q^*(\theta)$ and left them the information rents required to achieve IC, given that allocation, the expected information rent would be larger than with U's optimal allocation characterized in Proposition 1 and equation (9); hence, U's technology would be selected more often (i.e., for a larger range of values of the backstop technology).

V. PRICE COMMITMENTS

We now consider the case where U can commit to a menu $(q(\theta), R(\theta))$ at stage 1, before the standard-setting stage. We first derive the optimal menu of quantities and royalty payments under commitment. We then determine conditions under which the optimal allocation can be implemented by allowing U to commit to a simple output-independent cap on the total royalty payment, rather than to the full schedule of royalties.

Standard setting stage. Let $(q^C(\theta), R^C(\theta))$ denote the quantities and royalty payments that the SSO anticipates will be implemented at the royalty setting stage if U is selected as the standard when price commitments are in place. Let $\pi^C(\theta)$ denote D's payoff with that allocation. The SSO selects U's technology if and only if

$$\int_{\theta_0}^{\theta_1} \pi^C(\theta) f(\theta) d\theta \geq \pi_0.$$

Under commitment, the upstream firm will always choose its royalty scheme in such a way that the SSO selection constraint in satisfied; otherwise it makes zero profits. Price commitments thus—not surprisingly—solve the inefficiency in technology selection we identified above. In what follows, we study their effects on output distortions.

Price commitment stage. If the upstream firm can commit to a menu $(q^C(\cdot), R^C(\cdot))$, it solves the full problem described in Section III; in particular, it is subject to the SSO selection constraint (4). We thus have $\zeta \geq 0$, with strict inequality when the constraint is binding.

Proposition 2. Suppose $\int_{\theta_0}^{\theta_1} \pi^{NC}(\theta) f(\theta) d\theta < \pi_0$. Then, allowing the upstream firm to commit to an allocation $(q^C(\theta), R^C(\theta))$ before the standard is set strictly reduces output distortions: $q^{NC}(\theta) < q^C(\theta) \leq q^*(\theta)$ for all $\theta < \theta_1$.

Proof. The condition $\int_{\theta_0}^{\theta_1} \pi^{NC}(\theta) f(\theta) d\theta < \pi_0$ implies that the no-commitment solution $(q^{NC}(\theta), R^{NC}(\theta))$ does not satisfy the SSO selection constraint (4), so the constraint must be binding at the commitment solution $(q^C(\theta), R^C(\theta))$. It follows that $\zeta > 0$, and hence that, for all $\theta < \theta_1$, the right-hand side of the first-order condition characterizing the optimal allocation in equation

(6) is strictly lower than absent commitment, where $\zeta = 0$. Noticing that, by Assumption 1(i), the left-hand side of (6) is strictly decreasing establishes the claim. ■

It is immediate from equation (6) that, for each type $\theta < \theta_1$, the distortion on $q(\theta)$ is reduced, and strictly so for $\zeta > 0$. The proposition states the condition under which the SSO selection constraint is binding, so that $\zeta > 0$, which is true if the no-commitment solution does not leave enough rents to D for the SSO to select U's technology as the standard. The proposition shows that the optimal quantity $q(\theta)$ gets closer to the first-best value of $q^*(\theta)$ as defined in equation (2). Intuitively, since U must leave rents to D, there is less of an incentive to keep information rents low, reducing the need to distort output. Note also that distortions are reduced "proportionally" for all types (except the highest type where there was no distortion), since the distortion term on the right hand side of equation (6) is multiplied by $1 - \zeta \leq 1$.

As more rents are left to D due to U's commitment, the royalties $R(q)$ are reduced for all levels of q. It follows that, in general, the cap $\overline{R}(q)$ needed to implement the royalty scheme that U would like to commit to is not a simple function. However, as the next proposition shows, when the backstop technology is sufficiently attractive, the optimal cap on $R(q)$ takes the simple form of a uniform royalty cap $\overline{R}$.

Proposition 3. If the profit levels satisfy

$$\pi_0 \geq \int_{\theta_0}^{\theta_1} \pi^*(\theta) f(\theta) d\theta - \pi^*(\theta_0) \tag{11}$$

the optimal royalty cap is $R(q) = \overline{R}$ for all q.

Proof. Note that with $\zeta = 1$, equation (6) implies that $q(\theta) = q^*(\theta)$ for each θ. It is only possible to implement $q^*(\theta)$ if $R_q(q) = 0$ for all q; that is, $R(q) = \overline{R}$. This is optimal to implement for U if two conditions are satisfied. First, every type is willing to participate if they have to pay $\overline{R}$:

$$\pi^*(\theta_0) \geq \overline{R}. \tag{12}$$

Second, it is not possible for U to earn more rents than $\overline{R}$:

$$\int_{\theta_0}^{\theta_1} \pi^*(\theta) f(\theta) d\theta - \overline{R} = \pi_0.$$

Intuitively, if the left hand side were strictly greater than π_0, then you could either raise $\overline{R}$ for all types (as long as condition (12) is not violated), or you could raise royalties for some high types, which means you'd have an incentive to distort output to extract information rents. With the inequality in the proposition both conditions are satisfied. ■

Summarizing, we get the following results. For π_0 low enough, the rents in the no commitment case exceed π_0. In this case, $\zeta = 0$ and the commitment and no commitment solutions coincide. For an intermediate range of values of π_0, equation (4) is binding and $\zeta > 0$. As U has to leave enough rents to D, there is less of a need to minimize the information rents. Hence, the output distortion $q^*(\theta) - q(\theta)$ is reduced for all types. This can be achieved with an output-dependent cap $\overline{R}(q)$ on the royalty rate: if U cannot extract more than a certain royalty payment, it has no incentive to distort output further than to the degree the reduced information rent can be extracted. If π_0 is increased further, the royalty cap becomes a uniform cap $\overline{R}$ that applies to all types. As R no longer varies with q, the optimal menu then implements first-best output levels for all types.

Note that $\pi_0 < \pi^*(\theta_0)$ implies

$$\pi^*(\theta_0) \geq \int_{\theta_0}^{\theta_1} \pi^*(\theta) f(\theta) d\theta - \pi_0 > \int_{\theta_0}^{\theta_1} \pi^*(\theta) f(\theta) d\theta - \pi^*(\theta_0). \tag{13}$$

Hence, we can find values for π_0 that satisfy equation (11) if the following inequality is satisfied: $\pi^*(\theta_0) > 1/2 \int_{\theta_0}^{\theta_1} \pi^*(\theta) f(\theta) d\theta$.

VI. WHAT OBJECTIVE SHOULD SSOS PURSUE?

We have assumed that the SSO is only concerned with the downstream firm's surplus and does not take into account the upstream firm's surplus when selecting a standard. This assumption can be justified by the fact that many real-world SSOs are indeed "user friendly," to use the terminology of Chiao *et al.* [2007], and seek to promote the widest possible adoption of the standard. Nevertheless, a natural question is whether, from the perspective of social welfare, the SSO should be user friendly or instead maximize the firms' joint surplus, taking into account both upstream and downstream profits. In this section, we address that question by examining how a joint profit-maximizing SSO chooses between technologies. We then draw conclusions about the welfare comparison and discuss policy implications.

Proposition 4. A joint profit-maximizing SSO always selects U's technology as the standard.

Proof. The joint profit-maximizing adoption rule (for a given $q(\cdot)$) would be to select U's technology if and only if

$$\int_{\theta_0}^{\theta_1} \tilde{\pi}(q(\theta), \theta) f(\theta) d\theta \geq \pi_0. \tag{14}$$

We now show that it is always joint profit maximizing to adopt U's technology, even if there are no price commitments so that U chooses the contract derived in Proposition 1. Notice first that Assumption 1(ii) and the envelope theorem imply $d\tilde{\pi}(q^*(\theta),\theta)/d\theta = \partial\tilde{\pi}(q^*(\theta),\theta)/\partial\theta > 0$, and hence that $\tilde{\pi}(q^*(\theta_0),\theta_0) > \pi_0$. Next, observe that U could propose a unique contract $(q,R) = (q^*(\theta_0),\pi^*(\theta_0))$, which all types would accept because, for all $\theta \in [\theta_0,\theta_1]$,

$$\tilde{\pi}(q^*(\theta_0),\theta) - \pi^*(\theta_0) \geq 0 \quad \Leftrightarrow \quad \tilde{\pi}(q^*(\theta_0),\theta) \geq \tilde{\pi}(q^*(\theta_0),\theta_0),$$

which holds due to Assumption 1(ii). By revealed preference, if U instead proposes the menu of contracts $(q^{NC}(\theta), R^{NC}(\theta))$ characterized in Proposition 1 and Equation (9), it must be that this yields a higher profit:

$$\int_{\theta_0}^{\theta_1} R^{NC}(\theta) f(\theta) d\theta \geq \pi^*(\theta_0).$$

But since we must have $R^{NC}(\theta) \leq \tilde{\pi}(q^{NC}(\theta),\theta)$ for all θ, this, together with $\pi^*(\theta_0) > \pi_0$, implies (14) when evaluated at $q(\theta) = q^{NC}(\theta)$. ■

As Proposition 4 shows, a joint profit-maximizing SSO always selects U (even in the absence of price commitments). Thus, whether a joint profit-maximizing SSO asks the upstream firm to make price commitments is immaterial: if it did, U could choose a nonbinding royalty cap and would be selected anyway. A user-friendly SSO does not always select U in the absence of price commitments, but as our analysis shows, would similarly lead to selection of U's technology when it asks for price commitments.

Thus, both regimes eliminate the inefficiency in technology adoption. The difference is that in the case of a joint profit-maximizing SSO, U does not have to make any concessions in order to be selected. By contrast, a user-friendly SSO with price commitments forces U to leave rents to D, with the side effect of inducing U to decrease output distortions. Our analysis therefore suggests that a regime featuring an SSO with a pure user focus combined with price commitments is welfare superior to a regime with an SSO that takes into account the surplus of both technology users and developers.[10]

Of course, the SSO's objective function is not a policy variable. SSOs are typically private organizations that choose their own statutes. Public policy may be able to indirectly influence SSOs' objectives, however. Antitrust rules often impose openness requirements on SSOs. For example, the standardization-related provisions of the European Commission's [2011]

[10] This result is reminiscent of the competition-policy literature on optimal welfare standards, which shows that a consumer-welfare standard can dominate a total-welfare standard (see, e.g., Lyons [2002]; Armstrong and Vickers [2010]).

guidelines on horizontal agreements call for the standardization process to be open and transparent, and for voting rights to be attributed in a nondiscriminatory fashion. To the extent that implementers outnumber technology developers, openness requirements arguably tilt SSOs' decisions in favor of implementers and users of the standard. Our results lend support to such rules.

VII. CONCLUSION

This article analyzes the role of price commitments in the standard-setting process when there is asymmetric information between upstream and downstream firms. Specifically, we assume that the downstream firm is privately informed about the profitability of a final product incorporating the upstream firm's technology. In the absence of price commitments, the upstream firm designs its royalty scheme to elicit the downstream firm's private information. To reduce the downstream firm's information rent, the upstream firm distorts output away from the efficient level for all except the highest type. Moreover, because royalties are negotiated after the standard has been set, the upstream firm cannot commit to leave the downstream firm better off than with an inferior alternative technology that is available royalty free. Anticipating this opportunistic behavior, a user-friendly SSO often refrains from selecting the upstream firm's technology despite its technological superiority.

Price commitments allow the upstream firm to commit not to behave opportunistically after being selected as the standard. An interesting side effect of this is that it curbs the incentive for the upstream firm to distort the downstream firm's output. In fact, convincing the SSO to select the upstream firm's technology requires leaving enough surplus to the downstream firm, and giving information rents to the high type is a relatively cheap way of doing so. As a result, price commitments reduce output distortions and ensure that the superior technology is selected as the standard.

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