Standard-essential patents and incentives for innovation

Chayanin Wipusanawan*

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Abstract

This paper presents a model of innovation incentives with multiple innovators, whose inventions may be (imperfect) complements or substitutes, and derives the value-sharing rules that maximise the expected social value of innovation. Under this framework, the paper examines an influential policy in the context of standard setting, royalties for standard-essential patents should reflect the outcome of a hypothetical competition prior to standard setting, and shows that in the presence of both potential complements and substitutes, the competitive outcome provides suboptimal incentives for innovation.

Keywords: innovation, standardisation, standard-essential patents, FRAND, complements

JEL classification: L15, O31, O34, O38

* Tilburg University, Department of Economics, TILEC. Email: c.wipusanawan@tilburguniversity.edu. I am grateful to my supervisors Florian Schuett and Bert Willems for their tremendous guidance and support. I also thank Gerard Llobet, Eric van Damme, Cédric Argenton, Jens Prüfer, and participants at Tilburg University, Toulouse Applied Theory Workshop, EARIE 2021, and TILEC Workshop on the Economics of Patents and Standards for their helpful comments.

1 Introduction

Technical standards, such as Wi-Fi or LTE for wireless communication, often combine many inventions that are patented. If a patented invention is needed to implement the standard, the patent becomes a *standard-essential patent* (SEP) and the implementer needs to obtain a licence to market their products. A complex standard can involve a large number of patents. For example, over 10,000 patents are claimed as essential to the LTE standard (Baron and Pohlmann 2018).

While patent laws generally allow patent holders to exclude others from using their inventions, standard-setting organisations (SSOs) typically require SEP holders to license their patents under *fair, reasonable, and non-discriminatory* (FRAND) terms.[1] Determining whether a licensing term is FRAND has been a contentious issue both in patent litigations as well as competition law enforcement. For example, in the case *Microsoft v Motorola* in the US, the court ruled that the royalties that Motorola demanded for every Wi-Fi-enabled device were excessive and in breach of Motorola's FRAND licensing commitment. The court set the appropriate royalties that were substantially lower than the initial offer.[2]

One problem that FRAND licensing requirement purports to alleviate is the *patent hold-up* problem. Before a standard is codified, multiple substitute technologies may provide similar functionalities, and the bargaining power of a particular patent holder at this stage is restricted by competition. However, once the SSO chooses a particular technology as the standard, other technologies are no longer viable alternatives for implementers. Without restrictions on licensing, an SEP holder could capture the value of being included in the standard, which is higher than its prior underlying value among competitors (Shapiro 2001; Farrell et al. 2007). An influential interpretation of 'fair and reasonable' part of FRAND is that royalties should reflect the outcome of a hypothetical competition before the standard is set, which should equal the *incremental value* over the next best alternative (Swanson and Baumol 2005; Farrell et al. 2007).[3] This interpretation has been endorsed in the United States by the Federal Trade Commission (2011) and courts in SEP-related cases.[4] Given that

[1] Lemley (2002) studies the policies of forty-three SSOs in telecommunications and computer networking industries and finds that the majority of them requires FRAND licensing.

[2] *Microsoft Corp v Motorola, Inc*, 696 F3d 872 (9th Cir 2012). See also Pentheroudakis and Baron (2017) and Siebrasse and Cotter (2017*a*) for summaries of cases from multiple jurisdictions in which the court determines the FRAND royalty rate.

[3] This is often called *ex ante* competition in the literature, since it reflects the situation before the standard is chosen. I do not use this terminology in the paper to avoid confusion, since such competition occurs *after* the innovation process, which is the focus of this paper.

[4] For example, in *Ericsson, Inc v D-Link Sys, Inc*, 773 F3d 1201 (Fed Cir 2014) the court notes that 'the patentee's

patents are meant to provide incentives for innovation, some scholars express concerns that a policy that is essentially a price cap will excessively restricts the incentives for innovators (see e.g. Geradin and Rato 2007; Sidak 2013; Siebrasse and Cotter 2017*b*). From the perspective of economic welfare, the pertinent question is what the optimal innovation incentives should look like and whether the prevalent interpretation of reasonable royalties is optimal.

In this paper, I study the incentive to innovate when there are multiple technologies and the incremental value of each technology depends on which other technologies are available. Technologies from different innovators may be competing with each other, with the extreme case being that they are perfect substitutes, or they may complement each other meaning that the whole is greater than the sum of its parts, with the extreme case being the perfect complements. Using this framework, I consider the problem of choosing the incentive scheme to induce research investments that maximise the expected value of the technologies net of the research costs. The incentive scheme is restricted by a budget constraint that the revenues given to innovators come from the values that they jointly create; in other words, external subsidies are not allowed and the incentive scheme can be thought of as a sharing rule. Then, I define the competitive benchmark that represents the prevalent policy interpretation of FRAND and evaluate the benchmark compared to the optimal incentive scheme.

In the 'first-best' case, if each innovator is paid the incremental value of the technology, then the innovation efforts would be socially optimal. This follows the conventional economic wisdom that decisions are efficient if the marginal private incentive aligns with the marginal social contribution.[5] However, paying every innovator the incremental value is not always feasible given the budget constraint. With complementary technologies, the sum of individual incremental values could exceed the total value of the technologies, as discussed by, for example, Shapiro (2007). With the binding budget constraint, the 'second-best' incentives mirrors the Ramsey pricing solution from the budget-balanced multi-product pricing problem (Baumol and Bradford 1970).

The competitive royalty that a patent holder can command, according to the idea of

royalty must be premised on the value of the patented feature, not any value added by the standard's adoption of the patented technology ... to ensure that the royalty award is based on the incremental value that the patented invention adds to the product, not any value added by the standardization of that technology'.

[5] Pigouvian taxes (or subsidies) for externalities are one of the best-known applications of this wisdom. In the work that introduces this concept, Pigou (1920: 161) uses patent laws as an example of a tool for 'bringing marginal trade net product and marginal social net product more closely together'.

pre-standardisation competition, is restricted by the incremental value of the technology. However, the idea also applies to any arbitrary group of technologies. Their combined competitive royalties are restricted by their joint incremental value over the best alternative that does not contain any of their technologies. This means when there are complements, the competitive royalties will be strictly smaller than the individual incremental values. When there are possibilities of both complements and substitutes, then the incentives given by competitive royalties are not second-best, and allowing royalties greater than the competitive level can improve the expected social welfare. By imposing competitive royalties within a specific realised state of innovation, it is possible that an inventor has a competing substitute that drives down its competitive royalty (justifiably in isolation) in one state of the world, but receives a competitive royalty smaller than its incremental value in another state due to complementarities. By allowing supra-competitive royalties in the former state, the marginal incentive in expectation over different states moves closer to the marginal social contribution when the incentives are considered in expectation over multiple possible outcomes.

This paper contributes to the analysis of how innovation should be incentivised in the standardisation context. The model adds a preceding stage to models of the standard-setting process that begin after the technologies have been invented (i.e. no innovation stage). The most relevant work of this nature is by Lerner and Tirole (2015), who formally model standard selection and the notion of the pre-standardisation competition. The competitive benchmark in this paper follows the definition of competitive equilibrium in Lerner and Tirole (2015).

A similar model of innovation incentives is used by Layne-Farrar, Llobet, and Padilla (2014) to show that competitive royalties are not sufficient to attract innovating firms to participate in standardisation efforts when the choice of participation is endogenous. Other papers study different aspects of innovation incentives under FRAND licensing commitments. Ganglmair, Froeb, and Werden (2012) study the enforcement of FRAND commitments through competition law and argue that damage remedies against SEP holders suboptimally restrict innovation. Dewatripont and Legros (2013) show that FRAND licensing requirements may lead to firms claiming SEPs that are not really 'essential' to the standard.

More broadly, the paper is related to models of incentives for complementary innovations. Gilbert and Katz (2011) study the question of dividing the value of multiple perfectly complementary technologies among inventors. Their paper uses a dynamic model in which multiple inventors compete to discover each component sequentially. In contrast to their work, my model does not feature a 'winner-takes-all' race to discover a technology, but allows each invention to potentially have complementary as well as substitute innovations. The set-up of a static innovation game under a pre-determined incentive scheme is similar to the literature on research contests and procurement, e.g. Taylor (1995) and Che and Gale (2003), but these papers focus on competing (substitute) firms and do not include complements.

The structure of innovation efforts in this paper can also be compared to the standard problem of incentives for teams, in which multiple agents contribute to a common goal. The model of multiple innovators contributing to the expected social welfare corresponds to the team incentive model of Holmström (1982), with the key difference being that, instead of contracting solely on the joint outcome, the principal can also contract upon individual signals (i.e. research outcomes), even though actions of individual agents remain non-contractible.

The rest of the paper is structured as follows. To set the stage, Section 2 presents a simplified example that highlights the intuition presented in this paper. Section 3 describes the model set-up for the rest of the paper, while Section 4 explains the result that the competitive benchmark is not necessarily optimal. Section 5 concludes with discussions on the policy implications and possible caveats.

2 Example

Consider a standard that requires two perfectly complementary parts A and B and has a value of 1 for the consumer. For each part A or B, there are two firms who independently try to invent a technology for the part. Let $\{A_1, A_2\}$ be the set of firms working on part A and $\{B_1, B_2\}$ the set of firms working on part B. The two firms who work on the same part pursue different but equally good technologies. The innovation process is probabilistic: the probability that firm i successfully invents its technology depends on its costly innovation efforts. There are therefore sixteen possible states of the world depending on whether each of the four firm's technology is invented. A standard can be created if at least one technology is invented for each part. Otherwise, the technologies have zero value on their own. The value of the technologies in each state of the world can be described as a function of the set S of successful technologies

$$v(S) = \begin{cases} 1 & \text{if } S \cap \{A_1, A_2\} \neq \emptyset \text{ and } S \cap \{B_1, B_2\} \neq \emptyset \\ 0 & \text{otherwise.} \end{cases}$$

We are interested in setting the incentives for the firms to maximise the expected social welfare, defined as the expected value of the technologies net of total cost of efforts. The firms' efforts are not contractible, but an incentive scheme can condition the payment to each firm on the state of the world. In addition, assume that there is no possibility of subsidies, so the incentives must be provided by distributing the values created by the technologies. Firms choose their efforts to maximise their expected profit given the incentive scheme.

For this section, the effort costs of the firms are not modelled explicitly. However, we will take as given that firms choose the unconstrained welfare-maximising efforts if each of them is paid the incremental value of its technology in each state, where the incremental value of a technology is defined as the difference between the value of the standard in that state and the value in the state that the technology does not exist: $v(S) - v(S \setminus \{i\})$. This follows the economic intuition that an economic agent behaves optimally if they fully internalise their marginal social contributions.

Given the assumption of no subsidies, it is not necessarily possible to pay each firm its incremental value in each state. The incremental value of a technology in a particular state is either 1 or 0, depending on whether the technology is pivotal for the standard or not. The middle column of Table 1 summarises the incremental values in different types of states of the world in which the standard is created. For example, if all firms but A_2 successfully invent their technologies, then A_1's technology is pivotal since the standard cannot be created without it. Its incremental value is therefore the whole value 1, whereas the incremental value for each of B_1 and B_2's technologies is 0. If instead exactly one technology is invented for each part, for example A_1 and B_1's, then both invented technologies are pivotal, meaning that the incremental value of each technology is the full value of 1. In this case, it would not be possible for our incentive mechanism to pay each firm its incremental value with the value of the technologies in that state.

One mechanism that we consider is one whereby the payments the firms receive are determined by the price competition after the state of the world is realised, which is the economic interpretation of 'reasonable' royalties as proposed by Swanson and Baumol (2005) and formalised by Lerner and Tirole (2015). In this competitive process, each

Table 1: The incremental values and the competitive prices in different states of the world

Invented technologies	Incremental values					Competitive prices				
	A_1	A_2	B_1	B_2	Total	A_1	A_2	B_1	B_2	Total
A_1 A_2 B_1 B_2	0	0	0	0	0	0	0	0	0	0
A_1 B_1 B_2	1		0	0	1	1		0	0	1
A_1 B_1	1		1		2	½		½		1

successful firm simultaneously announces a price for its technology to the user. The user then observes the prices and chooses the set of technologies to buy. The competitive prices are shown in the right column of Table 1. Through the usual Bertrand argument, if two firms working on the same part, A or B, are both successful, perfect substitutability will drive the equilibrium price down to zero. If there is one pivotal firm in the realised state of the world, then with the take-it-or-leave-it offer the firm who owns the pivotal technology can command the whole value of the standard. In this case, the competitive prices coincide with the incremental values of the technologies. However, when there are two pivotal technologies, for example when only A_1 and B_1 are invented, the total payment that these two firms can jointly command is the value of the standard, since the user will not be willing to pay in total more than the value. In this case, the symmetric competitive price is ½ for each technology.

Can a social planner who wishes to maximise the expected social welfare do better than the competitive prices given the budget constraints? Although firms are paid less than the incremental values of their technologies in the states of the world in which two technologies are pivotal, it is not possible to pay more in those states without breaking the budget constraints. However, the planner can bring the *expected* incentives closer to the ideal case of paying incremental values. In the state of the world in which all firms successfully invent their technologies, the competitive price for each technology is zero, so the budget is not used up in this state. By increasing the payment for each firm in this state by $\varepsilon > 0$, the planner brings the expected payment that each firm receives when its innovation succeeds closer to the ideal level that is given by the incremental value. Paying more than the incremental value in the state where it is possible compensates for the insufficient payment in other states.

We can contrast this example to simpler cases of two technologies that are either only

Table 2: The competitive prices in different states of the world in cases of perfect substitutes and perfect complements

Invented technologies	Substitutes				Complements			
	C	D	Total	Value	C	D	Total	Value
C D	0	0	0	1	½	½	1	1
C	1		1	1	0		0	0

perfect complements or perfect substitutes, as shown in Table 2. Suppose there are two firms C and D, similarly working on their own technologies. If the two technologies are perfect substitutes, such that only one is needed for the standard, then the competitive price is the full value 1 if only one firm successfully invents and 0 if both firms succeeds. This is perfectly in line with the incremental values, so the competitive prices lead to the socially optimal efforts. On the other hand, if C and D are perfect complements, such that the standard has value only if both firms succeed, then we have again the problem of two pivotal technologies and the competitive price for each technology is ½, which is smaller than the incremental value. However, in this case the social planner cannot increase the incentives, since there is no longer leftover budget in any states of the world.

3 The model

Consider the following model of innovation in which multiple technologies can be invented. There is a set $N = \{1, \dots, n\}$ of risk-neutral firms. Each firm is endowed with an idea for a single technology. Firm i successfully invents its technology with probability x_i if it invests $c_i(x_i)$. Assume that each function c_i is increasing and convex with $c_i(0) = 0$ and $c_i'(0) = 0$. Let x denote the vector of *research efforts* $(x_1, \dots, x_n)$. All firms choose their research efforts simultaneously.

Given the binary outcome of each technology, there are 2^n possible states of the world, each state characterised by the set of successfully invented technologies. I will refer to the state of the world in which S is the set of successfully invented technologies as state S. The set of all possible states is the power set of N, denoted $\mathcal{P}(N)$.

If S is the set of available technologies, the technologies jointly create a value of $v(S)$ to the user. The value function v is assumed to be monotonic, meaning for any sets S and T, we have $v(T) \leq v(S)$ if $T \subseteq S$, and normalised such that $v(\emptyset) = 0$.[6]

Let $\bar{v}(x)$ denote the expected value of $v(S)$ given the research efforts x,

$$\bar{v}(x) = \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x)\, v(S),$$

where

$$\Pr(S \mid x) = \prod_{i \in S} x_i \prod_{j \in N \setminus S} (1 - x_j)$$

is the probability that state S is realised given the research efforts x. The social objective function is the expected net value of innovation

$$w(x) = \bar{v}(x) - \sum_{i \in N} c_i(x_i).$$

As the *first-best* benchmark, let x^* be the research efforts that maximise the expected social surplus $w(x)$. Assume that x^* is the unique local and global maximum that is an interior point of $[0, 1]^n$. The first-best research efforts x^* must be a solution to the first-order conditions

$$\frac{\partial \bar{v}(x^*)}{\partial x_i} = c_i'(x_i^*) \tag{1}$$

for all $i \in N$. The marginal contribution of the effort is the expected incremental value

$$\frac{\partial \bar{v}(x)}{\partial x_i} = \sum_{S \in \mathcal{P}(N)} \Pr(S \setminus \{i\} \mid x_{-i}) \left[v(S) - v(S \setminus \{i\})\right]$$

where $x_{-i} = (x_1, \dots, x_{i-1}, 0, x_{i+1}, \dots, x_n)$. For S such that $i \in S$, the probability $\Pr(S \setminus \{i\} \mid x_{-i})$ can be interpreted as the probability that other firms in set S—and only them—succeed independently of firm i's effort, and we have

$$\Pr(S \mid x) = x_i \Pr(S \setminus \{i\} \mid x_{-i}). \tag{2}$$

Throughout this paper, the research efforts x are assumed to be unobservable, but it is possible to specify how much each firm is paid in a particular state of the world. Let $r_i(S) \geq 0$ denote the revenue that firm i receives in state S. A full schedule of revenues for all i and S is referred to as a *revenue scheme*. I will also use $r(S)$ and r to denote the

[6] It is conceivable that including more technologies into a standard may reduce the value of the standard, meaning that the value function of the standard is not monotonic (see Lerner and Tirole 2015). Since the standard selection process is not modelled in this paper, the monotonicity of v can be justified by interpreting $v(S)$ as the value of the best standard that can be chosen in state S. In other words, invented technologies can be ex post freely disposed.

revenues for firms in state S and the entire revenue scheme. Given a revenue scheme, the innovation decisions can then be characterised as a strategic game with n firms, in which each firm i chooses its research effort x_i to maximise its expected profit

$$\sum_{S \in \mathcal{P}(N)} \Pr(S \mid x)\, r_i(S) - c_i(x_i).$$

Assume that if the game has multiple Nash equilibria, the equilibrium that produces the highest welfare $w(x)$ is chosen. In a Nash equilibrium of this game, the equilibrium investment $\hat{x}$ satisfies the first-order condition

$$\sum_{S \in \mathcal{P}(N)} \Pr(S \setminus \{i\} \mid \hat{x}_{-i}) \left[r_i(S) - r_i(S \setminus \{i\}) \right] = c_i'(\hat{x}_i) \tag{3}$$

for all $i \in N$. From this equation, we see that any revenue schemes that feature the same value of the difference $r_i(S) - r_i(S \setminus \{i\})$ across all i and S will induce identical equilibrium research efforts. Therefore, for the rest of the paper, I will restrict attention to revenue schemes that pay the firms only if they succeed: $r_i(S) = 0$ if $i \notin S$. Comparing (3) with the first-best efforts (1) also shows that if the revenue $r_i(S)$ equals the incremental value $v(S) - v(S \setminus \{i\})$ for all i and S, then the system of equations characterised by (3) coincides with the welfare-maximising first-order conditions. This correspondence reflects the notion that paying the incremental value aligns the social and private incentives.

However, it is not necessarily possible to pay the incremental values to all firms. In this paper, I consider a principal who sets a feasible revenue scheme to maximise the expected social surplus $w(x)$, given that the research efforts are the equilibrium (3) under the condition that external subsidies are not possible and the revenues that firms receive can only come from the value created by the technologies. A revenue scheme can then be thought off as a sharing rule for a joint project. In particular, I consider two types of such budget constraints. Under the *ex ante budget constraint*, the expected revenue given to firms must not exceed the expected value

$$\sum_{S \in \mathcal{P}(N)} \Pr(S \mid \hat{x}) \sum_{i \in S} r_i(S) \leq \sum_{S \in \mathcal{P}(N)} \Pr(S \mid \hat{x})\, v(S) \tag{4}$$

given the firms' equilibrium efforts $\hat{x}$ determined by the revenue scheme. Under the *ex post budget constraint*, the budget constraint exists in every possible state of the world:

$$\sum_{i \in N} r_i(S) \leq v(S) \tag{5}$$

for all $S \subseteq N$.

4 Analysis

4.1 Optimal revenue scheme under the ex ante budget constraint

To simplify the exposition, let $\bar{r}_i$ denote the expected revenue that firm i receives *if its research succeeds* given other firms' research efforts x_{-i},

$$\bar{r}_i = \sum_{S \in \mathcal{P}(N)} \Pr\left(S \setminus \{i\} \mid x_{-i}\right) r_i(S), \tag{6}$$

and let $\bar{r}$ denote the vector $(\bar{r}_1, \ldots, \bar{r}_n)$. Given (2), firm i's expected profit can then be rewritten as $x_i \bar{r}_i - c(x_i)$ and the condition (3) for the equilibrium research efforts can be rewritten as

$$\bar{r}_i = c_i'(\hat{x}_i) \tag{7}$$

for all $i \in N$. The effort $\hat{x}_i$ that satisfies (7) is unique for each $\bar{r}_i$ and increasing in $\bar{r}_i$.

With the formulation, the principal's problem under the ex ante budget constraint becomes choosing $\bar{r}$ to to maximise $w(x)$ subject to (7) and

$$\sum_{i \in N} \hat{x}_i \bar{r}_i \leq \bar{v}(\hat{x}).$$

This simplifies the problem to a standard contracting problem with one budget constraint.[7] Since (7) defines a one-to-one mapping between $\bar{r}_i$ and x_i, the problem can be further rewritten as

$$\begin{aligned} &\max_{x} \; w(x) \\ \text{subject to } &\sum_{i \in N} x_i c_i'(x_i) \leq \bar{v}(x). \end{aligned} \tag{8}$$

Proposition 1 below describes a condition for the solution of this constrained maximisation problem.

[7] The structure in this model is similar to that of Holmström (1982), which can be characterised as follows. Given a vector of agents' actions x, a joint value of $w(x)$ is created. A principal specifies a sharing rule $s_i(w)$ such that $\sum_i s_i(w) \leq w$ for all w. Agent i's pay-off given the action profile x is $s_i(w(x)) - c(x_i)$. Comparing the constraints with $s_i(w(x))$ and $x_i\bar{r}_i$, the sharing rule $s_i(w(x))$ is not necessarily linear in x, while in this paper $x_i\bar{r}_i$ must be.

Proposition 1. *Under the ex ante budget constraint, the optimal expected revenue scheme $\bar{r}$ satisfies, for all $i \in N$,*

$$\frac{\partial \bar{v}(x)/\partial x_i - \bar{r}_i}{\bar{r}_i} = \frac{m}{e_i} \tag{9}$$

with some constant $m \geq 0$ and

$$e_i = \frac{c_i'(x_i)}{x_i c_i''(x_i)}.$$

Proof. The Kuhn–Tucker necessary conditions imply that the solution to the maximisation problem satisfies

$$\frac{\partial \bar{v}(x)}{\partial x_i} - c_i'(x_i) + \lambda \left[\frac{\partial \bar{v}(x)}{\partial x_i} - c_i'(x_i) - x_i c_i''(x_i) \right] = 0 \tag{10}$$

for all $i \in N$, and the complementary slackness condition

$$\lambda \left[\sum_{i \in N} x_i c_i'(x_i) - \bar{v}(x) \right] = 0,$$

with $\lambda \geq 0$ being the Lagrange multiplier for the budget constraint. If the first-best efforts x^* are not feasible, then in the solution we have $\lambda > 0$ and $\partial \bar{v}(x)/\partial x_i - c'(x_i) > 0$. Rearranging equation (10) yields

$$\frac{\partial \bar{v}(x)/\partial x_i - c'(x_i)}{c'(x_i)} = \frac{\lambda}{1+\lambda} \cdot \frac{x_i c''(x_i)}{c'(x_i)}.$$

Letting $m = \lambda/(1+\lambda)$ and $c'(x_i) = \bar{r}_i$ we arrive at equation (9).

If the first-best efforts are feasible, then $\partial \bar{v}(x^*)/\partial x_i - c_i'(x_i^*) = 0$ and equation (9) holds with $m = 0$. □

The result from this maximisation problem is analogous to the Ramsey pricing formula, which in the simplest case is usually presented with a monopolist who supplies n independent goods (Baumol and Bradford 1970). The Ramsey pricing formula for good i, determining the deviation from the first-best marginal-cost pricing, is given by $(p_i - mc_i)/p_i = \mu/\varepsilon_i$, where p_i denotes the price of good i, mc_i its marginal cost, ε_i its price elasticity of demand, and μ a constant that is identical for all i. Equation (9) is the flip side of this formula with a monopsonist and n suppliers of research efforts. For all firms, the deviation of their marginal revenues $\bar{r}_i$ from their marginal contributions $\partial \bar{v}(x)/\partial x_i$ is inversely proportional to the 'elasticity' of effort that measures the change of effort x_i in response to the change in the expected revenue $\bar{r}_i$.

4.2 Competitive benchmark

In this section, I define the competitive benchmark that captures the notion that royalties should reflect the hypothetical competition before the industry has committed to a standard. Then I present the conditions under which the research efforts induced by the benchmark are neither first-best nor second-best under the ex ante budget constraint.

Suppose that the revenue scheme is determined through the following competitive process after the innovation outcome is realised. The firms that have successfully invented their technologies engage in a Bertrand-like pricing game with a single user who values the technologies according to the function v. In state S, each firm $i \in S$ simultaneously proposes a price $r_i(S)$ to the user. The user then chooses a subset of technologies T to maximise the net value

$$\max_{T \in \mathcal{P}(S)} v(T) - \sum_{i \in T} r_i(S).$$

Each firm i's pay-off is the price $r_i(S)$ if its technology is in the set chosen by the buyer and zero otherwise.

A competitive benchmark for state S is defined as a price vector $r^c(S)$ that is part of a subgame-perfect equilibrium of the pricing game in which the buyer buys from all firms in the set S.[8] This definition of the competitive benchmark in this paper aligns with that of Lerner and Tirole (2015).[9]

The following Lemma 1 characterises the competitive benchmark.

Lemma 1. *A price vector $r^c(S)$ is a competitive benchmark for state S if and only if*

$$\sum_{i \in T} r_i^c(S) \leq v(S) - v(S \setminus T) \tag{11}$$

for all $T \subseteq S$, and for every firm $i \in S$, there exists a subset $T \subseteq S$ such that $i \in T$ and condition (11) holds with equality.

Proof. Given a price vector $r^c(S)$, buying the entire set S is optimal for the user if and only if (11) holds, since (11) is equivalent to

$$v(S \setminus T) - \sum_{i \in S \setminus T} r_i^c(S) \leq v(S) - \sum_{i \in S} r_i^c(S)$$

[8] This condition rules out equilibria with coordination failure, in which firms with complementary technologies both choose too high prices. Alternatively, Lerner and Tirole (2015) impose that the competitive prices of technologies not bought by the user must be zero.

[9] In particular, the description given of the competitive prices in Lemma 1 is identical to equation (1) of Lerner and Tirole (2015) when there is no distinction between 'within-' and 'across-functionality' substitution and the demand is perfectly inelastic.

for all $T \subseteq S$.

The next step is to show that the price vector is a competitive benchmark if and only if each firm faces at least one binding constraint in (11).

Suppose that in the equilibrium that constitutes a competitive benchmark, the condition (11) holds with equality for a subset T. If firm $i \in T$ increases its price by $\varepsilon > 0$, then for the subset T we have

$$\sum_{i \in T} r_i^c(S) + \varepsilon > v(S) - v(S \setminus T).$$

Rearranging this yields

$$v(S \setminus T) - \sum_{i \in S \setminus T} r_i^c(S) > v(S) - \sum_{i \in S} r_i^c(S) - \varepsilon.$$

Since in this equilibrium, buying from the set S is optimal for the user, it follows that

$$v(S \setminus T) - \sum_{i \in S \setminus T} r_i^c(S) > v(T') - \sum_{i \in T'} r_i^c(S) - \varepsilon$$

for any subset T' such that $i \in T'$. This means if firm i unilaterally increases its price, the user will no longer buy technology i and it is not profitable for firm i to raise the price. Therefore, all firms face at least one such binding constraint, it is not possible for any firm to gain by unilaterally increasing its price.

For the other direction, if there exists $i \in S$ that faces no binding constraint, then there exists $\varepsilon > 0$ by which firm i can increase its price and not be dropped from the user's basket. □

Remark — The competitive benchmark as defined is not necessarily unique. Take for example the four-firm setting described in Section 2. In the state $\{A_1, B_1\}$ in which there are two perfect complements, any split of the full value to these two firms is a competitive benchmark, not just the symmetric one. We can impose further restrictions to narrow down the set of competitive benchmark, for example an assumption on symmetry or proportionality, but they are not necessary for the results that follow.

The inequality (11) represents the notion that the royalties that the firms can command for their technologies must be restricted by their incremental values. This incremental value rule applies not only to individual technologies but also to any subsets of technologies in that state. This means the competitive price for firm i may be strictly less than its *individual* incremental value $v(S) - v(S \setminus \{i\})$.

From (1) and (3), the efforts induced by the competitive benchmark are first-best if $\bar{r}_i^c$ equals the expected incremental value (1). Since Lemma 1 shows that $r_i^c(S)$ never exceeds the incremental value, the efforts induced by the competitive benchmark deviate from the first-best if $r_i^c(S) < v(S) - v(S \setminus \{i\})$ for some state S. Let $\hat{x}^c$ denote the equilibrium efforts given the competitive benchmark. Proposition 2 provides a sufficient condition for the competitive benchmark not to lead to first-best efforts.

Proposition 2. *If there exists a state S such that $\Pr(S \mid \hat{x}^c) > 0$ and for a subset $T \subseteq S$*

$$\sum_{i \in T} \left[v(S) - v(S \setminus \{i\})\right] > v(S) - v(S \setminus T), \tag{12}$$

then the first-best research efforts are not implemented by the competitive benchmark.

Proof. From (1) and (7), the first-best efforts x^* must satisfy

$$x_i^* \bar{r}_i = \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x^*) \left[v(S) - v(S \setminus \{i\})\right] \quad \text{for all } i \in N.$$

If there is a state S such that for $T \subseteq S$,

$$v(S) - v(S \setminus T) < \sum_{i \in T} \left[v(S) - v(S \setminus \{i\})\right],$$

then by (11) we have

$$\sum_{i \in T} r_i^c(S) < \sum_{i \in T} \left[v(S) - v(S \setminus \{i\})\right].$$

Define $\bar{r}^c$ analogously to (6). Multiplying both sides by $\Pr(S \mid \hat{x}^c)$ and sum over all states yields, with $\Pr(S \mid \hat{x}^c) > 0$,

$$\sum_{i \in T} \hat{x}_i^c \bar{r}_i^c < \sum_{S \in \mathcal{P}(N)} \Pr(S \mid \hat{x}^c) \sum_{i \in T} \left[v(S) - v(S \setminus \{i\})\right].$$

This cannot be the case with the first-best efforts x^*, therefore $\hat{x}^c \neq x^*$ and the first-best efforts are not implemented by the competitive benchmark. □

The inequality (12) means that for the firms in the subset T, the sum of their individual contributions in state S exceeds their joint contribution. The restriction imposed by the joint incremental value means that at least some firms in the set T must get paid strictly less than their individual incremental value in the competitive benchmark for state S. Note that this result only requires this relationship in a single state.

Even in the case that the competitive benchmark does not achieve the first best, it may still implement the second-best efforts if the first-best efforts are not feasible. The following Proposition 3 provides the necessary condition that the competitive benchmark does not lead to the second-best efforts under the ex ante budget constraint. If the competitive benchmark is not on the boundary of the set of efforts that can be induced by a permissible revenue scheme. Loosely speaking, there is 'money' left on the table that can still be distributed, then increasing the revenues over the competitive benchmark can improve welfare.

Proposition 3. *If the first-best efforts are not implemented by the competitive benchmark and there exists a state S such that $\Pr(S \mid \hat{x}^c) > 0$ and for a partition $\mathcal{T}$ of S*

$$\sum_{T \in \mathcal{T}} [v(S) - v(S \setminus T)] < v(S), \tag{13}$$

then the second-best efforts under the ex ante budget constraint are not implemented by the competitive benchmark.

Proof. If the first-best efforts are feasible under the budget constraint, then they are also second-best and the proposition holds trivially.

Suppose that the first-best efforts are not feasible. From the assumption that there is a unique local and global maximum in $[0, 1]^n$, if the first-best efforts are not in the feasible set, then there is no local maximum in the interior of the feasible set. Since a maximum must exist in the compact feasible set, the maximum is located on the boundary of the set. If the competitive benchmark corresponds to an interior point, it must not induce welfare-maximising efforts in the feasible set, i.e. it does not implement the second-best research efforts. From the constraint (8), the efforts are interior if

$$\sum_{S \in \mathcal{P}(N)} \Pr(S \mid x) \sum_{i \in N} r_i^c(S) < \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x)\, v(S).$$

I will now show that the efforts induced by a competitive benchmark are interior under the condition described in this proposition. Since the sum of competitive prices in any state S does not exceed the value $v(S)$, the above strict inequality is true if and only if there exists a state S such that $\sum_i r_i^c(S) < v(S)$. If there exists a partition $\mathcal{T}$ of the set S such that (13) is true, then we have

$$\sum_{i \in S} r_i^c(S) \leq \sum_{T \in \mathcal{T}} \big[v(S) - v(S \setminus T)\big] < v(S)$$

where the first weak inequality follows from the condition of the competitive benchmark (11). □

With Proposition 2 and Proposition 3, we see that with complementary technologies, it is possible that there is room to improve welfare without breaking the budget. This happens if in some states the full value is not paid out in the competitive benchmark.

4.3 Ex post budget constraints

The previous sections consider the problem of providing innovation incentives under the single ex ante budget constraint (8) that is formulated in expectation across all states. Implementing a revenue scheme that only satisfies the ex ante constraint may require a principal who can absorb the risk. However, if such a mechanism does not exist and the principal is only allowed to distribute the available value within each state, then we need to consider the more stringent ex post constraints (5).

In Section 4.1 it is possible to simplify the problem to choosing the efforts x from the feasible set of efforts, since there is a one-to-one mapping between x_i and $\bar{r}_i$. However, the correspondence between a revenue scheme and the vector $\bar{r}$ is not unique, so multiple multiple revenue schemes can be mapped to the same equilibrium efforts $\hat{x}$.

It should also be noted that even if the ex post budget constraints hold with equality for some states, it does not necessarily mean the budget is really 'binding' in the sense it is not feasible to increase every firm's equilibrium effort. In the example in Section 2, Table 1 shows that the competitive prices use up the budget in all states except the state in which all firms are successful, but it is still possible to increase the expected revenue (and equilibrium efforts) for every firm by paying more than the competitive price of zero when all firms are successful.

The following result means that the problem with ex post budget constraints can be similarly converted to a similar problem with the set of feasible $\bar{r}$ (and thus x). The lemma restates the constraints (5) into a set of constraints on $\bar{r}$. This means the problem of choosing a revenue scheme that satisfies (5) can still be reduced to that of choosing the expected revenues $\bar{r}$ subject to the following set of constraints (14), without specifying the (not necessarily unique) implementation of the revenue scheme.

Lemma 2. *Given research efforts x and expected revenues $\bar{r}$, there exists a revenue scheme that implements $\bar{r}$ according to (6) and satisfies the constraints (5) for all states, if and only if $\bar{r}$*

satisfies

$$\sum_{i \in T} x_i \bar{r}_i \leq \sum_{S \in \mathcal{Q}(T)} \Pr(S \mid x)\, v(S), \tag{14}$$

for any subset $S \subseteq N$, where

$$\mathcal{Q}(T) = \{S \in \mathcal{P}(N) \mid S \cap T \neq \emptyset\}$$

is the set of states that has at least one of the firms in set S.

Proof. First, I will show that a revenue scheme that represents $\bar{r}$ and satisfies the ex post budget constraints (5) exists only if $\bar{r}$ and the corresponding x satisfy (14) for all S. From (6) and (2), a revenue scheme representing $\bar{r}$ implies

$$\sum_{i \in T} x_i \bar{r}_i = \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x) \sum_{i \in T} r_i(S)$$

for all $T \subseteq N$. The imposition $r_i(S) = 0$ if $i \notin S$ implies that

$$\sum_{i \in T} r_i(S) \leq \sum_{i \in S} r_i(S)$$

for any S and T, and it also means we can safely ignore the states that do not intersect with T, yielding

$$\sum_{i \in T} x_i \bar{r}_i \leq \sum_{S \in \mathcal{Q}(T)} \Pr(S \mid x) \sum_{i \in S} r_i(S)$$

for all $T \subseteq N$. If the revenue scheme satisfies the ex post budget constraint (5), then

$$\sum_{i \in T} x_i \bar{r}_i \leq \sum_{S \in \mathcal{Q}(T)} \Pr(S \mid x)\, v(S)$$

for all $T \subseteq N$. Therefore, a scheme represents $\bar{r}$ and satisfies (5) only if $\bar{r}$ and x satisfy (14).

Next, I will show that there exists a revenue scheme that satisfies the ex post budget constraints if $\bar{r}$ and x satisfy (14). The existence of a revenue scheme that represents $\bar{r}$ and satisfies the ex post constraint (5) for all states means the minimum in the following constrained minimisation problem is zero:

$$\min_{r} \sum_{i \in N} \left[x_i \bar{r}_i - \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x)\, r_i(S) \right]^2$$

subject to (5) for all $S \subseteq N$

and $r_i(S) \geq 0$ for all $i \in N$ and $S \subseteq N$.

I will show by contrapositive that if the constrained minimum is not zero, then condition (14) is violated.

Suppose the constrained minimum is strictly greater than zero and is attained at r^0. The Kuhn–Tucker necessary conditions for this minimisation problem are

$$2 \Pr(T \mid x) \left[x_i \bar{r}_i - \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x)\, r_i(S) \right] + \lambda_{iT} = \mu_T \qquad \text{for all } i \in N \text{ and } T \subseteq N \tag{15}$$

$$\mu_T \left[\sum_{i \in T} r_i(T) - v(T) \right] = 0 \qquad \text{for all } T \subseteq N \tag{16}$$

$$\lambda_{iT} r_i(T) = 0 \qquad \text{for all } i \in N \text{ and } T \subseteq N \tag{17}$$

with the multipliers $\mu_T \geq 0$ for each ex post budget constraint and $\lambda_{iT} \geq 0$ for each non-negativity constraint.

Since $x_i \bar{r}_i \geq 0$ and we can always decrease $r_i(S)$ down to zero, we can focus on the case that

$$x_i \bar{r}_i > \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x)\, r_i^0(S)$$

for some $i \in N$. Let A be the set of every such i,

$$A = \left\{ i \in N \mid x_i \bar{r}_i > \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x)\, r_i^0(S) \right\}.$$

Equation (15) implies $\mu_T > 0$ for every T such that $T \cap A \neq \varnothing$. By (16), the ex post budget constraints must be binding for all such sets T. Given $\mu_T > 0$, we have that $\lambda_{jT} > 0$ for $j \notin A$ since the first term in (15) is zero, which then implies through (17) that $r_j(T) = 0$. This means, for $j \in A$ and T such that $T \cap A \neq \varnothing$,

$$\sum_{j \in A} r_j^0(T) = v(T)$$

and

$$\sum_{S \in \mathcal{P}(N)} \Pr(S \mid x) \sum_{j \in A} r_j^0(S) = \sum_{T \in \mathcal{Q}(A)} \Pr(T \mid x)\, v(T).$$

From the definition of set A, we then have

$$\sum_{j \in A} x_j \bar{r}_j > \sum_{T \in \mathcal{Q}(A)} \Pr(T \mid x)\, v(T)$$

which contradicts condition (14). Therefore, if $\bar{r}$ satisfies (14), the minimum must be zero, which means there exists a feasible revenue scheme that represents $\bar{r}$. $\square$

Applying $S = N$ to inequality (14) yields the relaxed budget constraint (8), so the constraints on other subsets of N restrict the share of $\bar{v}(x)$ that can be given to firms in those subsets. The intuition of Lemma 2 is that the maximum expected payment a principal can assign to a group of firms is the portion of the available expected value $\bar{v}(x)$ that comes from states that have at least some firms in that group. If all the value in any states with at least one firm from set S is used, then it is not possible to pay more to firms in S without taking it from another firm in the set.[10] When the values of x and $\bar{r}$ satisfy the whole stack of such conditions, it is possible to find a revenue scheme that requires no transfers across different states, as prescribed by (5).

With constraints defined by expected revenues, the problem is now in a form similar to the problem considered in previous sections. A principal chooses expected revenues $\bar{r}$, subject to the constraints (14), to maximise the surplus $w(x)$ given the investment equilibrium (7). It is still the case that if the efforts not first-best and is interior in the feasible set, then the efforts are also not the constrained optimal or second-best efforts.

Proposition 3 still directly applies in this case, with the constraint (8) replaced by the set of constraints (14); the expected surplus from the competitive benchmark is not optimal, neither in the first-best nor second-best senses, if some technologies are complementary and the benchmark research efforts are interior in the feasible set defined by (14). The proof of Proposition 3 applies to a compact feasible set, it holds for the feasible set defined by these budget constraints.

However, given that the feasible set defined by (14) is more restricted than (8), it remain to be seen whether the efforts that are interior under the laxer constraint are also interior in the set defined by (14). The following Proposition 4 shows that a competitive benchmark that is interior in the feasible set defined by (8) is also interior in the feasible set defined by (14). Thus, Proposition 3 still holds.

Proposition 4. *Given x such that $x_i > 0$ for all i, if the expected revenue from a competitive benchmark is interior in the feasible region defined by the constraint* (8)*, it is also interior in the feasible region defined by the constraints* (14)*.*

Proof. Consider the research efforts induced by competitive benchmark $r_i^c(S)$ that are interior in the feasible region defined by (8). The following steps show that the efforts

[10] Note that the formulation of $\bar{r}_i$ works only under the assumption that firm i does not receive any reward when it fails. Paying firm i when it fails does not increase its incentive to invest as shown by (3).

induced by a competitive benchmark cannot be interior in the feasible region of (8) but not interior in the feasible region of (14).

From the definition of expected revenue, the competitive benchmark being interior under constraint (8) means

$$\sum_{T \in \mathcal{P}(N)} \Pr(T \mid \hat{x}^c) \sum_{i \in N} r_i^c(T) < \sum_{T \in \mathcal{P}(N)} \Pr(T \mid \hat{x}^c)\, v(T), \tag{18}$$

while not being interior in (14) means, given that the competitive benchmark satisfies (11), the inequality (14) holds with equality for some state $S \in \mathcal{P}(N)$ such that $S \neq N$, that is

$$\sum_{T \in \mathcal{Q}(S)} \Pr(T \mid x) \sum_{i \in S} r_i^c(T) = \sum_{T \in \mathcal{Q}(S)} \Pr(T \mid x)\, v(T). \tag{19}$$

From Lemma 1, equation (19) is true only if

$$\sum_{i \in S \cap T} r_i^c(T) = v(T) \tag{20}$$

for all $T \in \mathcal{Q}(S)$. That is, only firms in set S can receive a positive revenue in any states in the set $\mathcal{Q}(S)$ and the value in those states are fully distributed. Subtracting (19) from (18) yields

$$\sum_{T \in \mathcal{P}(N) \setminus \mathcal{Q}(S)} \Pr(T \mid x) \sum_{i \in N \setminus S} r_i^c(T) < \sum_{T \in \mathcal{P}(N) \setminus \mathcal{Q}(S)} \Pr(T \mid x)\, v(T).$$

This is true only if there exists a set T such that $T \cap S = \emptyset$ and

$$0 \leq \sum_{i \in T} r_i^c(T) < v(T).$$

Consider a set U such that $T \subseteq U$ and $U \cap S \neq \emptyset$. From Lemma 1, the competitive benchmark satisfies, given that $v(T) > 0$,

$$\sum_{i \in U \setminus T} r_i^c(U) \leq v(U) - v(T) < v(U).$$

But since $U \in \mathcal{Q}(S)$, then by (20) we should have

$$\sum_{i \in S \cap U} r_i^c(U) = v(U)$$

with $S \cap U$ being disjoint from T. Therefore, it is not possible that the expected revenue from a competitive benchmark is interior under (8), but not under (14). □

The idea of the proof is that for a constraint (14) to be binding for a set of firms S, the values in all states that contain at least one firm in S must be fully paid only to the firms in set S. However, some of the states also include firms outside of set S that have positive values by themselves. Since the revenues in the competitive benchmark is limited by (joint) incremental values, it cannot be the case that the full values in those states are distributed to only the firms in set S.

Proposition 4 means that while the extra state-based budget constraints considered in this section potentially reduce the feasible set, they do not affect the main results on the competitive benchmark described in Proposition 2 and Proposition 3. It is possible that, with complementary technologies, the competitive benchmark does not lead to the welfare-maximising research efforts under the condition that the incentives given to the firms can only be from the values created by the available technologies in a particular state.

4.4 Generalising the competitive benchmark

The results on the competitive benchmark only use the incremental value condition (11). Therefore, they apply to a broader set of allocation rules than the competitive benchmark. Given the nature of the function v, it is also reasonable to consider the problem from the perspective of cooperative game theory. Consider a coalitional game with the set of players $S' = S \cup \{0\}$, where player 0 is the buyer, and the characteristic function u such that for any subset $T \subseteq S$, $u(T) = 0$ and $u(T \cup \{i\}) = v(T)$. This means the buyer also holds an indispensable mean of utilising the technologies (compare to the Bertrand pricing game where the technologies also have no value without the user). Let

$$r_0(S) = v(S) - \sum_{i \in S} r_i(S)$$

be the residual value retained by the buyer. The following proposition shows that the competitive benchmark is part of the core of this coalitional game.

Proposition 5. *If the price vector $r^c(S)$ is a competitive benchmark, it is an imputation in the core of the coalitional game.*

Proof. The core of the coalitional game in state S is the set of vectors $(r_i(S))_{i \in S'}$ that satisfy

$$\sum_{i \in S'} r_i(S) = u(S') = v(S)$$

and

$$\sum_{i\in T'} r_i(S) \geq u(T')$$

for all $T' \subseteq S'$. The first condition follows directly from the definition of $r_0(S)$, so we focus on the second condition.

If $\{0\} \notin T'$, then $u(T') = 0$ and the inequality is satisfied. Now we consider the set $T \cup \{0\}$ for $T \in \mathcal{P}(S)$, where the condition can be rewritten as

$$r_0(S) + \sum_{i\in T} r_i(S) \geq v(T)$$

for all $T \subseteq S$. In the competitive benchmark, the buyer receives the maximum surplus by choosing the whole set S:

$$r_0^c(S) = v(S) - \sum_{i\in S} r_i^c(S) \geq v(T) - \sum_{i\in T} r_i^c(S)$$

for all $T \subseteq S$. Rearranging the inequality yields

$$r_0^c(S) + \sum_{i\in T} r_i^c(S) \geq v(T)$$

for all $T \subseteq S$. □

5 Concluding remarks

In this paper, I analyse innovation incentives in the context of standardisation. The model introduces the research stage for multiple interacting inventions that precedes the standardisation process. It allows us to study how the value jointly created by the inventions should optimally be appropriated by their inventors and how the competitive outcome, as commonly defined, performs compared to the optimal rule.

The paper shows that allowing supra-competitive royalties for innovators may enhance economic welfare. Specifically, it increases welfare in expectation by allowing innovators to reap more benefits when there are competing substitutes that drive the royalties down in order to compensate the suboptimal incentives that arise from complementarities. This result provides a caveat to the attractive notion that patent holders should be restricted to charging pre-standardisation competitive prices. Given that a standard often comprises multiple complementary technologies, the results in this paper suggest allowing such supra-competitive royalties may be justified.

However, the effects illustrated in this paper should be interpreted as one of many relevant factors that affect innovation incentives. Since the model assumes that the technologies generate fixed welfare unaffected by royalties, it shuts down effects associated with non-perfectly-inelastic demand such as the deadweight loss from royalties and the multiple marginalisation problem (also known as royalty stacking in patent licensing) whereby the cumulative royalties demanded by multiple patent holders exceed even the monopoly level. The model also assumes that firms pursue distinct, independently patentable inventions, which follows from how the notion of pre-standardisation incremental value is discussed. If multiple firms pursue the same technology with only one 'winner', known as a patent race, this could lead to over-investment in research as shown by Tandon (1983).

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