Ideas-Driven Endogenous Growth and Standard-Essential Patents

Andrei Kirilenko

Center for Global Finance and Technology

Imperial College Business School

Albina Neklyudova-Khairullina

École Polytechnique Fédérale de Lausanne

Artem Neklyudov

University of Lausanne and SFI

Christopher Tucci

École Polytechnique Fédérale de Lausanne

February 22, 2019

Abstract

In this paper, we study how the regulator expands production possibilities of the economy by assigning a standard-essential status to patents. Firstly, we show that productivity-enhancing standards tend to adversely affect the endogenous economic growth. This is due to the pace of discovery of new technologies is generally smaller than the rate of discounting of monopoly profits in equilibrium. We also demonstrate that the zero-sum redistribution of market share due to standardization by itself plays no role on an aggregate level. Secondly, standards may strengthen incentives to innovate when there are additional complementarities between standards and patents. When discovered, new additional technologies dampen incentive to engage in final good production relative to patents production—and relatively more human capital moves to the innovative sector of the economy, which enhances endogenous economic growth. Our results have significant policy implications. Regulators impose FRAND pricing on standard-essential technologies to compensate for the larger market-share the innovators get. As we show, the innovators' risk of losing the standard-setting game ex-ante attenuates the anticipation of a higher market share. Thus FRAND regulation of mark-ups on top of that can easily have growth-destroying consequences.

1 Introduction

In this paper, we study how standards-essential patents impact the long-term economic growth. Standards-essential patents (SEPs), where patent holders apply "essential" intellectual property (IP) to an emerging standard as explained in more detail below, is a phenomenon that has been taking on increasing importance over the last two decades (see Figure 1). This growth is likely related to the growing complexity of high-tech devices, hardware, and telecommunications products/services. They incorporate more and more technologies to make them work well, miniaturization of components in technological systems, as well as industry "deconstruction" where firms become less vertically integrated and produce fewer parts of a more modular system, relying on interfaces developed with partners. In this article, we will analyze the economics of SEPs from a macroeconomic point of view, the incentives for participating in the production of technology with standards versus the final good production, under what circumstances standards enhance economic growth, and the consequences of special IP licensing terms for economic growth.

A standard is a description of an interface (e.g., a plug and socket for electricity or audio component connection), a technical specification (e.g., wifi connectivity), a "dominant design" in a marketplace (e.g., DVD format, or historically, internal combustion engine automobile), or a way of doing things (e.g., driving on the right side of the road).

These are not mutually exclusive, and there can be different ways of developing and commercializing them. In this article, we will focus primarily on the first three, with an emphasis on the established norms in a technical system.

How do standards come into force? Standards are normally classified as de facto and de jure. De facto standards are usually developed and commercialized by private parties, for example, firms, either in a private consortium or even individually, introduced into the market and then accepted by the market. The firm may or may not coordinate the development of the standard with other parties, what is important is that the de facto standard is a standard in use and its claim to legitimacy is that the market finds it useful. A de jure standard, on the other hand, is something that is intentionally negotiated by a third party, which is often called a "standards-setting organization" (SSO) or a "standards committee." Examples of SSOs include the IEEE (Institute of Electrical and Electronics Engineers), ISO (International Organization for Standardization), or ITU (International Telecommunications Union). These bodies coordinate the development of standards by managing the various parties to determine the functionality of the standard, the technical specifications, and the interfaces needed to comply with and use the standard.

One apparent complication of the standard-setting process described above is that with increasing complexity, there are more parties involved in setting the standards, and these parties may or may not bring IP that is owned by them and that will be crucial for complying with the standard. If a third party would like to adopt the standard, the third party would have to negotiate a license agreement with every IP holder involved in the standard; otherwise, the third party would be an infringement of some IP in the standard. In some cases, there are dozens or even hundreds of IP owners staking some claim to the IP of the standard and this negotiation process would become lengthy and expensive. Furthermore, it is not clear that an IP holder would even grant a license at any price, or threaten to withhold a license. Therefore, in such a situation, potential adopters would be highly unlikely to adopt the standard and thus in the extreme case none of the IP holders would receive royalties for their technologies.

The policy of treating standard-essential patents (also called "essential patents") was thus developed in recent years to deal with this specific situation. SEPs are patents that are required for a third party to comply with a given standard (Tucci [2013]). The IP holders promise to charge "fair and reasonable" license fees, and to do so in a "non-discriminatory" way; in other words, to not deny anyone who wants a license to have one. Such pricing is called "FRAND" terms for Fair, Reasonable, And Non-Discriminatory. The argument goes that an IP holder trades off FRAND terms in exchange for a higher likelihood of adoption of the standard since if no-one adheres to FRAND, the standard ends up in a prisoners-dilemma-type problem and no-one profits from the adoption of the standard as described above. In practice, the details of FRAND terms are not negotiated in advance and are only solved by negotiation and litigation. There has been attempts to make the price setting mechanism for SEPs more efficient, for example see Lemley and Shapiro [2013].

There has a growing research interest in the process of standardization and standard-essential patents. Lerner and Tirole [2015] develop a seminal theoretical framework to study the optimal standard composition and incentives of end-users to implement a standard technology. In particular, they show how standards are often are inefficiently small (under-inclusive) and how the SSOs create competition among owners of technology and lower licensing fees. Our paper takes the composition of a standard as given and focuses on the long-term growth dynamics of the economy, where standards reduce production costs in the final goods sector. In this sense, we complement the analysis in Lerner and Tirole [2015] with a macroeconomic view on standards and the regulation of licensing fees. Kung and Schmid [2015] study the asset-pricing consequences of innovation and patenting in a general equilibrium macroeconomic setting. We complement their analysis by bringing standardization process of patents into the relatively standard macro environment and focusing on long-term growth rather than short-term business cycle. We model the endogenous technological change as in Romer [1990] and extend it to talk about standardization of technologies and standard-essential patents.

Standardization and SEPs received a relatively broader coverage in the empirical studies. In Blind and Thumm [2004] authors model the probability of a patent holder joining the standardization processes. They demonstrate that companies with higher patenting intensities are less likely to join standardization race. The intuition behind these results is that a company with a high patenting intensity possesses a strong technological advantage that yields market success without the support of formal standardization. Blind and Thumm [2004] discuss incentives and deterrents of firms to join standardization process. On the one hand, the decision to apply for a standard might be driven by the economies of scales (diffusion of well-protected know-how) and positive network externalities. On the other hand, companies may be reluctant to spread their technologies as they seek a dominant position in the market and exclude others from having access to their unique technologies. The results suggest that the positive economic effects of standards will not be fully exploited because big technological companies are still reluctant to participate in standardization.

In a comprehensive report, OECD [2013] describes SSOs, how they work to develop new knowledge, and how standards can contribute to innovation. According to OECD, SSOs have to strike a delicate balance between what we are calling the IP holders or the "supply-side" of technology and the "demand side" of potential adopters. FRAND terms are seen as a potential solution to hold-up problems, although the authors acknowledge the lack of commitment once IP holders pledge to adhere to FRAND terms and the problems this can cause. Hold-up is only one problem associated with "thicketed" technology spaces such as technology standards, and the other is "royalty stacking." Both of these may lead to costs that greatly outweigh the benefit from adopting or commercializing the standard OECD [2013].

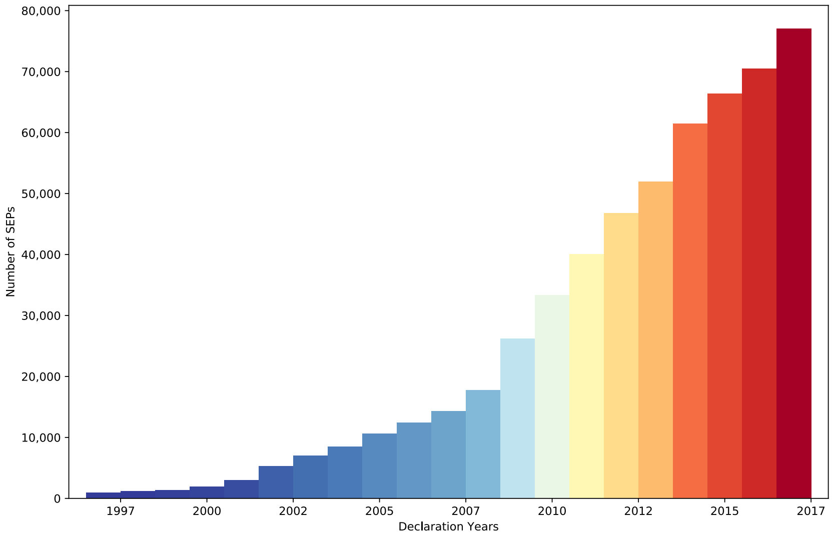
Bekkers and Updegrove [2012] provide an extensive treatment of the interrelations between IP and standards and the challenges of IP rights in standards. The authors describe the workings of several well-known SSOs and the difficulties of combining different IP claims in a standard. They stay at the level of "IP" because patents may be only one form of IP critical to conform to a standard without infringing on it. The definition of what "essential" means varies widely from SSO to SSO, with large variation in practices across many areas. Relevant practices are whether to include copyrights and other non-patent IP, whether the "essentiality" includes commercial or purely technical, whether the timing of essentiality is defined, whether pending applications are included, whether expired or invalid patents are included, and several more.

In this paper, we examine some of the macroeconomic implications of this process. In the next section, we explore some trends in SEPs to illustrate the major areas that use SEPs. Then we develop a model to examine SEPs and endogenous economic growth based on "innovator" agents who may give up some of their monopoly IP exclusion rights in favor of participating in a broader market based on a standard built partly on their IP. We examine the conditions required for standards to be growth-enhancing at the level of the economy. We then discuss the policy implications of SEPs with FRAND in a balanced growth equilibrium before concluding the paper.

2 Trends in Standard-Essential Patents

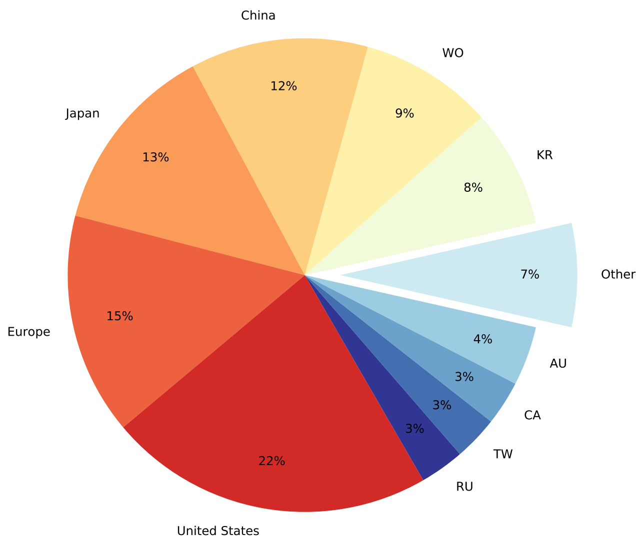
Our data on standard-essential patents (SEPs) covers 80,935 patents with application years spanning 1995 to 2017 provided by the Iplytics. Out of all patents published Figure 1 shows the distribution of patents applied for in different years. As seen in that figure, SEPs represent a phenomenon of growing importance for the economy. The distribution of SEPs by patent office countries is shown in Figure 2. 22% of patents were published by the US patent office, 15% of patents were published by the European patent office, these are the two biggest patent offices in our data. All the SEPs in our data belong to electrical engineering sector and cover a variety of industry fields shown in Figure 3. Digital communication, telecommunication, and computer technology are the three most populated industry fields in our data.

Figure 1: Stock of SEPs by declaration year



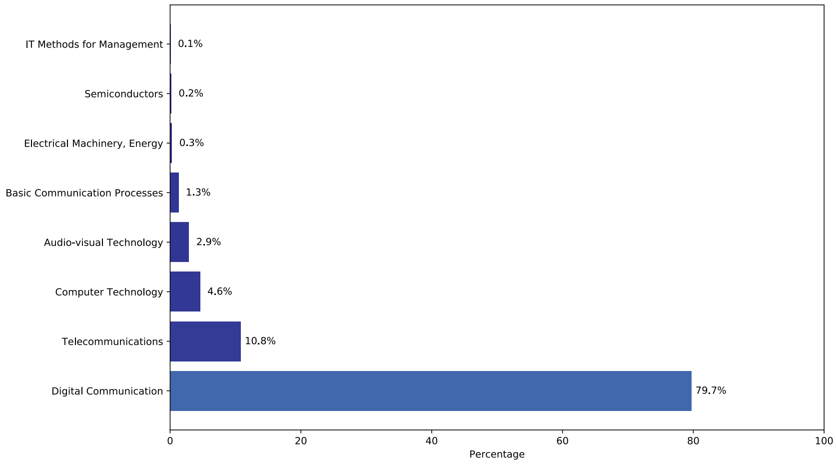
The figure shows the total number of declared standard-essential patents grouped by the declaration year.

Figure 2: Distribution of SEPs by patent offices of countries



The figure shows the ratio of standard-essential patents granted by patent offices of different countries. The "other" category includes: DE, ES, HK, AT, BR, GB, SG, MX—accounting for 1% of SEPs each.

Figure 3: Distribution of industry types of SEPs



The figure shows the percentage of different industry types among the SEPs.

3 The Model

In this section, we describe our theoretical framework to study the effect of standardization on innovation and economic growth. We describe agents who produce innovation—innovators, the process of technological change and formalize the notion of technological standardization. Standardization of a technology results in a substantial increase in the economy-wide demand for that technology. For example, when JPEG became a standard image format, most producers of photo cameras moved to JPEG and abandoned alternative formats of image encoding. Our idea, in brief, is that technologies become standard-essential over time at some rate and standardization of one technology crowds-out demand for a set of rival technologies. Innovators are running a risk of their patents becoming irrelevant for the production process if a competing technology is standardized. We model the endogenous technological change as in Romer [1990] and extend it to talk about standardization of technologies and standard-essential patents.

3.1 Innovators and technological change

In our model, the economy is populated by a fixed number of agents $H = 1$, which represents the stock of human capital. A subset of agents H_A decide to be innovators and the remaining $1 - H_A$ agents contribute their human capital to final good production. Economic growth is endogenously driven by decisions of agents to become innovators—as more agents choose to be among H_A in equilibrium, economy grows at a higher rate. Our model of innovation is different from Gârleanu and Panageas [2017], who use labor instead of human capital as the main factor to pin down the growth rate of the economy. Standards will not play much role in a setting like Gârleanu and Panageas [2017] because the trade-off for suppliers of labor does not fully take into account the present value of monopoly profits coming from patents, like in the original Romer [1990] setting.

Time runs continuously and at every point in time $t \geq 0$ there is a stock of discovered technologies A_t. A patentable idea arrives to an innovator as a random event with a Poisson rate $\kappa \cdot A_t$. The larger is the current stock of discovered ideas in the economy, the higher is the rate of arrival of new ideas. In this sense, the production of ideas does not exhibit diminishing returns to scale, a key assumption behind the endogenous growth of the economy. The growth in the stock of discovered technologies A_t over time is:

$$\frac{dA_t}{dt} = \kappa \cdot A_t \cdot H_A \tag{1}$$

At some point in time an individual technology may be included in a standard. We denote all technologies that has not yet been included in a standard by $B_t < A_t$. We denote industry standards by $A_{sep,t}$ and, as we discuss later, each standard includes $N > 1$ individual technologies in it. The accounting identity for all types of technologies is:

$$A_t = N \cdot A_{sep,t} + B_t \tag{2}$$

The stock of discovered technologies A_t enhances the production of the final good Y, which is consumed by households. To focus our analysis of economic growth on the role of human capital H_A and productive technologies A_t we use a parsimonious production function of the final good Y:

$$Y_t = (1 - H_A)^{\alpha} \left(\int_{i \in B_t} x_{i,t}^{1-\alpha} \, di + (1 + \epsilon_{sep}) \cdot \int_{j \in N \cdot A_{sep,t}} x_{j,t}^{1-\alpha} \, dj \right) \tag{3}$$

We assume away physical capital and labor to keep our analysis focused. Each individual technology in B_t is used to produce an intermediate good x_i, which enters the production function as an input and has diminishing returns to it. Each industry standard in $A_{sep,t}$ is used to produce N intermediate goods x_j, which all enter the production function as inputs with diminishing returns. Further, we assume standardization itself has some additional effect on the total factor productivity, so we put an extra $(1 + \epsilon_{sep})$ term for all the inputs which are produced under standards. The marginal productivity of standardized technology is:

$$\frac{\partial Y}{\partial x_{j \in N \cdot A_{sep,t}}} = (1 + \epsilon_{sep}) \frac{\partial Y}{\partial x_{i \in B_t}}$$

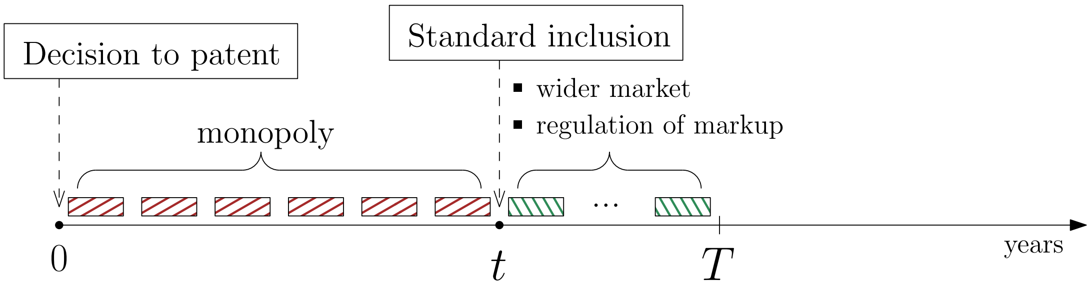
We assume standardization has a non-negative effect on the total factor productivity, $\epsilon_{jpeg} \geq 0$ and the marginal product of standardized technology is weakly higher. This effect possibly pertains to a greater maturity of the underlying technology, positive spillovers associated with implementing standardized technology in the production process, etc.

3.2 Patents

The patent expires after $T = +\infty$ years, which is a normalization—a finite patent life would not affect our qualitative results, but make calculations more cumbersome. A successfully granted patent gives the innovator a monopoly right in production of an intermediate good, which is valuable in the final good production process.

Each patent has value P_B and it allows to produce an input x_i. In the future life of a patent two events may happen: A new relevant standard may encapsulate a patent, or

Figure 4: The lifetime of a patent in the model



a new standard may make it obsolete. Before either of these events happen, the inventor enjoys a monopoly right to produce x_i. The inverse demand for x_i from the final good production sector has a constant price-elasticity and a scaling factor $\chi > 0$:

$$
\begin{aligned}
p(x_i) &= \chi \cdot x_i^{-\alpha} \qquad (4)\\
\text{where:} \quad & \chi = (1-\alpha)(1-H_A)^{\alpha}
\end{aligned}
$$

The unit cost of production of input x_i is the cost of capital $r(t)$ times the amount of capital needed η. The optimal monopolistic price $p^M(t)$ and the monopolistic output of the input $\overline{x}_i$ every period is:

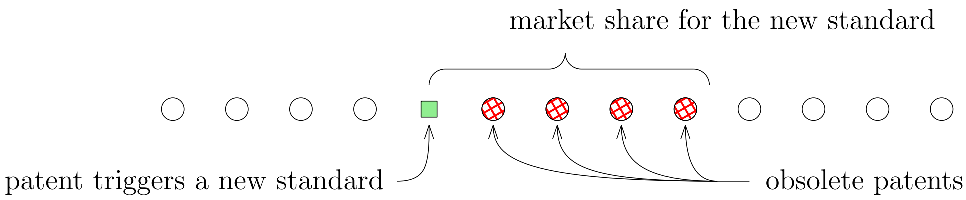
$$
\begin{aligned}
p^M(t) &= \frac{r(t)\cdot\eta}{(1-\alpha)} \qquad (5)\\
\overline{x}_i &= (1-H_A)\cdot\left(\frac{r(t)\cdot\eta}{(1-\alpha)^2}\right)^{-\frac{1}{\alpha}}
\end{aligned}
$$

The monopoly profit per unit of time is:

$$
\pi^M(t) = \alpha\cdot(1-\alpha)(1-H_A)\left(\frac{(1-\alpha)^2}{r(t)\cdot\eta}\right)^{\frac{1}{\alpha}-1} \qquad (6)
$$

This expression is the monopoly profit of a patent that has been successfully granted, and has not been included in any standard. Moreover, no existing standard replaced the productive role of this patent. What happens with standardization we describe in the next subsection.

Figure 5: Standardization of patents



Legend: The event with rate γ_{jpeg} has occurred to the patent marked by a green box. The scope of a new standard is $N = 5$, so the winning patent eats the market share of the $N - 1 = 4$ other patents that used to protect a sufficiently similar technology.

3.3 Standards

At an exogenous rate γ_{sep} an individual patent wins a standardization race with the standard-setting organization. In our model, γ_{sep} is the i.i.d. Poisson intensity of this event happening to an individual patent. Once it becomes a standard, it consumes the market share of $N-1$ other technologies. We refer to N as the scope of a standard in the economy: One standardized technology substitutes $N - 1$ individual rival technologies, which become obsolete when a standard is approved by the standard-setting organization. For example, in case of JPEG the scope N would equal one plus the number of alternative image encoding technologies that lose their market share in favor of JPEG when it becomes an industry standard.

The growth in the stock of standard technologies $A_{sep,t}$ over time is:

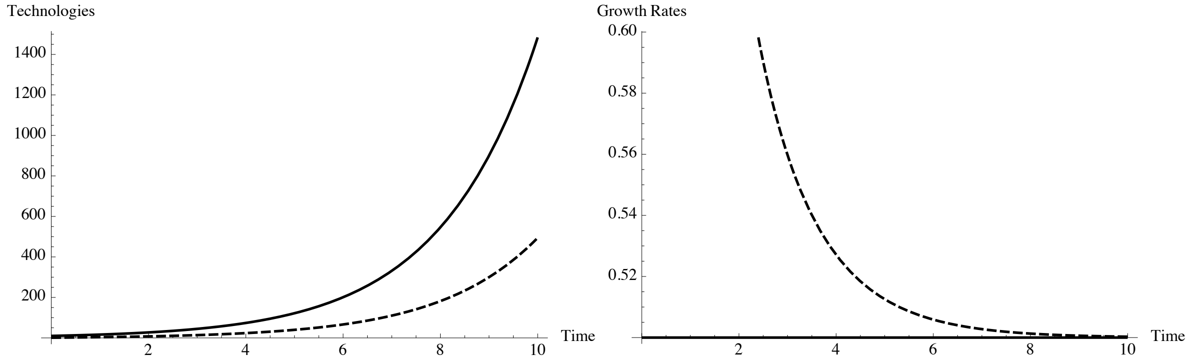
$$\frac{dA_{sep,t}}{dt} = \gamma_{sep} \cdot B_t \tag{7}$$

This results in the dynamics for individual patents with no standard:

$$\frac{dB_t}{dt} = \kappa \cdot A_t \cdot H_A - N \cdot \gamma_{sep} \cdot B_t \tag{8}$$

When there are no standards yet and $A_{sep,t} = 0$ we have $A_t = B_t$ and the growth in newly set standards is $\dot{A}_{sep,t}/A_{sep,t} = \gamma_{sep}$. As standards cover all discovered technologies so that $A_{sep,t} = A_t/N$ we have no individual patents remaining $B_t = 0$ and the growth

Figure 6: Growth in standards: Example



Legend: Dashed line shows standard-essential patents $N \cdot A_{sep,t}$, solid line shows the stock of discovered technologies A_t. In the beginning there are $A_0 = 10$ technologies and $B_0 = 9$ individual patents. The rate of standardization $\gamma_{sep} = 0.05$, the scope of standards is $N = 5$ and the parameters of technological growth are $\kappa = 0.5$ and $H_A = 1$. The figures show how the growth rates in technologies, standards and individual patents all converge to $\kappa \cdot H_A = 0.5$.

in standards stops $\dot{A}_{sep,t}/A_{sep,t} = 0$. In the balanced growth equilibrium there would be a steady-state situation when the growth in standards is equal to the growth in patents and is equal to the overall growth of technological discovery $\kappa \cdot H_A$. Note that H_A would be endogenous in equilibrium.

Now we explore how standardization affects the value of a patent P_B. Suppose the standardization event occurs and the owner of the patent enjoys the extended market share $N > 1$ and the standardization gain in productivity $(1 + \epsilon_{sep})$. The per-unit demand for the resulting input x_j is:

$$p(x_j) = \overline{\chi} \cdot x_j^{-\alpha} \tag{9}$$

$$\text{where:} \qquad \overline{\chi} = (1 + \epsilon_{sep})(1 - \alpha)(1 - H_A)^{\alpha}$$

The unit cost of production of input x_j is the cost of capital $r(t)$ times the amount of capital needed η. The optimal monopolistic price is still the same because we assume there is no change in the demand elasticity, however the monopolistic output of the input

$\overline{x}_j$ per unit of time changes to:

$$\overline{x}_j \quad = \quad \overline{x}_i \cdot (1 + \epsilon_{sep})^{\frac{1}{\alpha}}$$

The monopoly profit per unit of time becomes:

$$\pi^M_{sep}(t) = N \cdot (1 + \epsilon_{sep})^{\frac{1}{\alpha}} \pi^M(t) \tag{10}$$

Let the inter-temporal cost of capital be $r(t)$. The HJB equation for the value of an individual patent P_B before standardization implies:

$$(r(t) + N \cdot \gamma_{sep}) \cdot P_B \quad = \quad \pi^M(t) + \underbrace{\gamma_{sep}\left(\frac{N \cdot \pi^M_{sep}(t)}{r(t)}\right)}_{\text{set as a new standard}} + \underbrace{(N-1)\,\gamma_{sep} \cdot 0}_{\text{eaten by a new standard}}$$

$$P_B \quad = \quad \frac{\pi^M(t)}{r(t)} \cdot \left(\rho(t) + (1 - \rho(t))\,(1 + \epsilon_{sep})^{\frac{1}{\alpha}}\right) \tag{11}$$
$$\text{where: } \rho(t) = \frac{r(t)}{r(t) + N \cdot \gamma_{sep}}$$

There are several economic insights that come out of the last equation. First, when there are no productivity gains due to standardization $\epsilon_{sep} = 0$ and what the standard does is reshapes the market shares of the underlying technologies, then the monopolist is getting the same expected profits as if there is no standardization: $P_B = \pi^M(t)/r(t)$. Productivity gains are necessary for standards to have any effect on the endogenous growth of the economy. Only when $\epsilon_{sep} > 0$ standardization changes the incentives that drive technological innovation. Second, the market share effect of standardization alone cannot drive growth. The monopolist ex ante faces $\gamma_{sep}/(N-1)\,\gamma_{sep}$ odds of winning the market N times larger than before, however with the residual chance the monopolist loses his business to some other standard that won the attention of the standard-setting organization. In expectation, when all monopolists are equally talented as in our model, the market share effect alone constitutes a wash.

We are primarily interested in the balanced growth equilibrium of the model, in which all relevant variables describing the economy grow at a constant rate g. The growth rate g in our model is determined by: 1) the relative productivity of human capital in the innovative sector versus the final good production, and 2) the dynamics of standardization of patents and the productivity gains $\epsilon_{sep} \geq 0$ standards create.

3.4 Balanced growth equilibrium

From our previous discussion recall the dynamics of standard-essential patents and all other patents over time:

$$\frac{dA_{sep,t}}{dt} = \gamma_{sep} \cdot B_t \quad \text{and} \quad \frac{dB_t}{dt} = \kappa \cdot A_t \cdot H_A - N \cdot \gamma_{sep} \cdot B_t \tag{12}$$

Substitute for the stock of discovered technologies the total sum of patents and established standards by using the accounting identity in the equation (2). The system of equations below capture the time-dynamics of the stock of patents and the stock of standards:

$$\begin{aligned} \frac{dB_t}{dt} &= (\kappa \cdot H_A - N \cdot \gamma_{sep}) \cdot B_t + \kappa \cdot H_A \cdot N \cdot A_{sep,t} \\ \frac{dA_{sep,t}}{dt} &= \gamma_{sep} \cdot B_t \end{aligned}$$

Lemma 1. *In the long-term the growth rate of the stock of patents B_t and the growth rate of the stock of standards $A_{sep,t}$ converge to the growth rate of discovered technologies A_t. The initial values of patents and standards do not affect the long-term growth rates.*

Proof. The outline of the formal proof follows. The system of the two ODEs that describe the time-dynamics of patents and standards has a closed-form solution. The solution for both standards and patents has the common form $C_1 \cdot \exp^{\lambda_1 \cdot t} + C_2 \cdot \exp^{\lambda_2 \cdot t}$; C_1 and C_2 are constants that differ for patents and standards and depend on the initial values of patents and standards; λ_1 and λ_2 are the two eigenvalues of the matrix of coefficients A

of the system of equations describing the dynamics of patents and standards:

$$A = \begin{pmatrix} \kappa \cdot H_A - N \cdot \gamma_{sep} & \kappa \cdot H_A \cdot N \\ \gamma_{sep} & 0 \end{pmatrix}$$

The eigenvalues of the matrix A are the roots of the equation:

$$(\kappa \cdot H_A - N \cdot \gamma_{sep} - \lambda)(-\lambda) - \gamma_{sep} \cdot \kappa \cdot H_A \cdot N = 0 \tag{13}$$

The equation (13) has two roots, one strictly negative and one strictly positive. This can be seen by plugging in $\lambda = 0$ in the left-hand side of the equation, which is a U-shaped parabola with a strictly negative intercept at $\lambda = 0$. In the long-term as $t \to +\infty$ all terms with a negative eigenvalue disappear from the solution form $C_1 \cdot \exp^{\lambda_1 \cdot t} + C_2 \cdot \exp^{\lambda_2 \cdot t}$ for both standards and patents. This leads to the ratios of standards and patents being asymptotically-constant, and thus the growth rates being identical in the long-term limit. $\square$

When B_t grows at the same rate as A_t in a conjectured balanced growth equilibrium, the standard-essential patents $A_{sep,t}$ grow at that same rate as well. Thus the ratios B_t/A_t and $A_{sep,t}/A_t$ are constant in the balanced growth equilibrium. We solve for these ratios using the dynamics above:

$$\begin{aligned} B_t &= \zeta_B \cdot A_t \\ A_{sep,t} &= \frac{1}{N}(1 - \zeta_B) \cdot A_t \\ & \text{where: } \zeta_B = \frac{\kappa \cdot H_A}{\kappa \cdot H_A + N \cdot \gamma_{sep}} \end{aligned} \tag{14}$$

This result allows us to rewrite the final good production function as:

$$Y_t = (1 - H_A)^{\alpha} A_t \left(\zeta_B + (1 - \zeta_B)(1 + \epsilon_{sep})^{\frac{1}{\alpha}} \right) \cdot \overline{x}_i^{1-\alpha}$$

In this formula everything is constant except the stock of discovered technologies A_t, which grows at an endogenous rate g. Thus the total output Y_t grows at g as well. Both patents and standard-essential patents grow at the same rate $\dot{B}_t/B_t = \dot{A}_{sep,t}/A_{sep,t}$ as the stock of discovered technologies $\kappa \cdot H_A$. This gives the equilibrium condition for the human capital allocation:

$$\alpha \left(1 - H_A\right)^{\alpha-1} \left(\zeta_B + \left(1 - \zeta_B\right)\left(1 + \epsilon_{sep}\right)^{\frac{1}{\alpha}}\right) \cdot \overline{x}_i^{1-\alpha} \quad = \quad P_B \cdot \kappa \tag{15}$$

On the left-hand side of the equation above is the marginal product of human capital employed in the final good production per unit of the discovered technology A_t. On the right-hand side of the equation is the marginal product of human capital in the innovative patent-production sector. Note that to calculate the marginal product of human capital in the innovative patent-production sector we take the growth of newly discovered patents $\kappa \cdot A_t \cdot H_A$ rather than the growth of the patents without standards $\kappa \cdot B_t \cdot H_A$. The latter includes the effect of existing patents being eaten by newly set standards, while to measure productivity of human capital we count only newly discovered patents.

Simplifying the equilibrium condition for the human capital allocation we get the endogenous growth rate g as the solution to the equation:

$$\left(1 - \frac{g}{\kappa}\right) \cdot \frac{\rho + \left(1-\rho\right)\left(1 + \epsilon_{sep}\right)^{\frac{1}{\alpha}}}{\zeta_B + \left(1 - \zeta_B\right)\left(1 + \epsilon_{sep}\right)^{\frac{1}{\alpha}}} \quad = \quad \frac{r}{\kappa} \cdot \frac{1}{\left(1-\alpha\right)} \tag{16}$$

The last term in the equation above captures the effect of standards and standard-essential patents on the endogenous growth rate g. Denote this term as:

$$\begin{aligned} G_{sep} \quad &= \quad \frac{\rho + \left(1-\rho\right)\left(1 + \epsilon_{sep}\right)^{\frac{1}{\alpha}}}{\zeta_B + \left(1 - \zeta_B\right)\left(1 + \epsilon_{sep}\right)^{\frac{1}{\alpha}}} \\ \text{where:} \quad & \rho = \frac{r}{r + N \cdot \gamma_{sep}} \\ & \zeta_B = \frac{g}{g + N \cdot \gamma_{sep}} \end{aligned} \tag{17}$$

Equation (17) demonstrates that when $\epsilon_{sep} = 0$ there is no effect of standards on economic growth and $G_{sep} = 1$. When standards only reallocate market share among technologies, relative incentives of agents to engage in technology production are unchanged. The following condition is required for standards to be growth-enhancing $G_{sep} > 1$:

> **Necessary condition:** Standards have a productivity-enhancing effect so that $\epsilon_{sep} > 0$ and the growth rate of the economy is higher than the cost of capital so that $g > r$.

The economic intuition behind our results is the following. When growth rate of the economy g is relatively high, there are relatively more patents than standards in the technology mix according to the equation (14) in the steady-state. Such dominance of non-standard-essential patents coupled with the productivity-enhancing effect of standards $\epsilon_{sep} > 0$ reduces incentives for the human capital to choose final good production sector, and thus raises H_A in equilibrium and increases the endogenous growth rate of the economy.

As we show the zero-sum redistribution of market share is not enough to reshape incentives to innovate on an aggregate level. Productivity-enhancing standards strengthen incentives to innovate when the discovery of new technologies is faster than discounting of monopoly profits over time. As new technologies are born not yet standardized, they dampen the incentive to engage into final good production relative to patent production—and relatively more human capital moves to the innovative sector of the economy, which enhances economic growth g.

3.5 Standards and growth

As our model demonstrates, the effect of standards on economic growth depends on how g compares to the cost of capital r and whether standards are productivity-enhancing so that $\epsilon_{sep} > 0$. In this section we focus on these features of the model.

As Romer [1990] for simplification we could use Ramsey consumers with CRRA utility function, risk aversion σ and inter-temporal discounting β. Then the interest rate on capital in the balanced growth equilibrium is $r = \sigma \cdot g + \beta$. When risk-aversion of consumers is sufficiently high, the risk-free rate is above the balanced growth rate g: $r > g$.

Now suppose consumers in our model have Epstein-Zin preferences, with the intertemporal discounting β, coefficient of risk-aversion γ, coefficient of the intertemporal substitution ψ, and $\theta = \frac{1-\gamma}{1-\frac{1}{\psi}}$:

$$U_t = \left[\beta C_t^{\frac{1-\gamma}{\theta}} + (1-\beta) E_t \left[U_{t+1}^{1-\gamma}\right]^{\frac{1}{\theta}}\right]^{\frac{\theta}{1-\gamma}}$$

The risk-free rate in the deterministic steady-state is approximately $r = \frac{1}{\psi} g + \beta$. Based on the multi-country estimates of the intertemporal elasticity of substitution in Havranek et al. [2015] the average estimated value of IES is $\psi = 1/2$. So again we get the result that the risk-free rate is above the balanced growth rate g: $r > g$. From now we conclude that, generally, the growth rate of the economy g is lower than the cost of capital r.

In the baseline model standards and patents are perfect substitutes: one standard consumes N patents. We conclude that productivity-enhancing standards result in lower economic growth in equilibrium, because they weaken incentives of human capital to go to the innovative sector of the economy.

3.6 Extension with standards and M new patents

In our baseline model so far patents and standards were perfect substitutes. In this section we consider an extension of our model, in which a successful standardization of one technology occasionally gives birth to additional patentable ideas. This way we allow for an additional complementarity between standards and patents. To capture this technological spillover in this section we assume that with every new standard there are $M > 0$ new patents appearing and extending the stock of technologies in the economy. There are two changes to the equilibrium introduced by this extension: 1) the balanced growth will be affected by the additional dynamics of new patents, and 2) the patent value P_B will take into account the additional value created if we assume the new M patents belong to the same person who owns the standard.

Firstly, the new dynamics describing the balanced growth equilibrium are:

$$\frac{dA_{sep,t}}{dt} = \gamma_{sep} \cdot B_t \quad \text{and} \quad \frac{dB_t}{dt} = \kappa \cdot A_t \cdot H_A - (N - M) \cdot \gamma_{sep} \cdot B_t$$

Solving for the steady-state growth rates of patents and standards, we get:

$$\begin{aligned} B_t &= \zeta_B^M \cdot A_t \\ A_{sep,t} &= \frac{1}{N}\left(1 - \zeta_B^M\right) \cdot A_t \\ & \text{where: } \zeta_B^M > \frac{\kappa \cdot H_A}{\kappa \cdot H_A + N \cdot \gamma_{sep}}, \ \frac{d\zeta_B^M}{dM} > 0 \end{aligned}$$

The new patent value P_B is the same as before if the new patents do not belong to the owner of the standard. The modified equilibrium condition for the human capital allocation is:

$$\alpha \left(1 - H_A\right)^{\alpha-1} \left(\zeta_B^M + \left(1 - \zeta_B^M\right)\left(1 + \epsilon_{sep}\right)^{\frac{1}{\alpha}}\right) \cdot \overline{x}_i^{1-\alpha} = P_B \cdot \kappa \tag{18}$$

Alternatively, if we assume the new M patents belong to the same person who owns the standard, the modified patent value P_B^M is:

$$\begin{aligned} P_B^M &= \delta_M \cdot P_B \\ & \text{where: } \delta_M = \frac{r(t) + N \cdot \gamma_{sep}}{r(t) + (N - M) \cdot \gamma_{sep}} \end{aligned}$$

To avoid bubbles in the patent valuation, we need to make an additional assumption that $M \leq N$. The modified equilibrium condition for the human capital allocation is:

$$\alpha \left(1 - H_A\right)^{\alpha-1} \left(\zeta_B^M + \left(1 - \zeta_B^M\right)\left(1 + \epsilon_{sep}\right)^{\frac{1}{\alpha}}\right) \cdot \overline{x}_i^{1-\alpha} = \delta_M \cdot P_B \cdot \kappa \tag{19}$$

Since $\frac{d\zeta_B^M}{dM} > 0$ we know that the fraction of patents in the population will be higher, the higher is M. This would have a dampening effect on the incentive to produce final good if standards are productivity-enhancing $\epsilon_{sep} > 0$. In addition, if we assume the new M patents belong to the same person who owns the standard, the incentive to join the innovative sector will strengthen. We conclude that for the case when standards are productivity-enhancing $\epsilon_{sep} > 0$, the positive $M > 0$ increases the likelihood of the growth-enhancing outcome in equilibrium. It relaxes the necessary condition $g > r$ for standards to be growth-enhancing. We conclude that complementarities between patents and standards result in a higher economic growth.

4 Policy implications

As our data section on standard-essential patents shows, there are several industry fields for which standards are primarily relevant, including e.g. electrical engineering, telecommunications, software development. Our theoretical framework argues that standards will enhance economic growth only for those industries, for which the very fact of standardization is productive, in other words when technological variety slows down production. Further, our model argues that the growth in these sectors must be above the cost of capital for the standards to be growth-enhancing. We can use our model to prescribe which technological fields should have standard-essential patents implemented first. Our recommendations are largely consistent with the trends we observe in our data: all fields with most of growth in SEPs are likely to have both growth conditions we outline above satisfied.

We are getting more worrying results when we apply our model to study how the FRAND regulation of monopoly mark-ups affects economic growth. It turns our regulators need to be very careful implementing FRAND as it can easily revert the growth-enhancing effect of standards and slow down aggregate innovation.

In the context of our model, FRAND pricing will reduce $\pi_{sep}^{M}(t)$. Suppose that this effect is captured by a coefficient $\delta_{FRAND} < 1$ so that:

$$\pi^M_{sep}(t) = \delta_{FRAND} \cdot N \cdot (1 + \epsilon_{sep})^{\frac{1}{\alpha}} \pi^M(t) \tag{20}$$

and the effect of standard-essential patents on the endogenous growth changes accordingly:

$$G_{sep} = \frac{\rho + \delta_{FRAND} \cdot (1-\rho) \cdot (1+\epsilon_{sep})^{\frac{1}{\alpha}}}{\zeta_B + (1-\zeta_B) \cdot (1+\epsilon_{sep})^{\frac{1}{\alpha}}} \tag{21}$$

There are two benchmark regions for the value of δ_{FRAND} that are useful to develop intuition for the effect of FRAND pricing of standard technology of endogenous growth. For all these cases we assume standards are growth-enhancing in case of no FRAND, so that $\epsilon_{sep} > 0$ and $g > r$ in equilibrium.

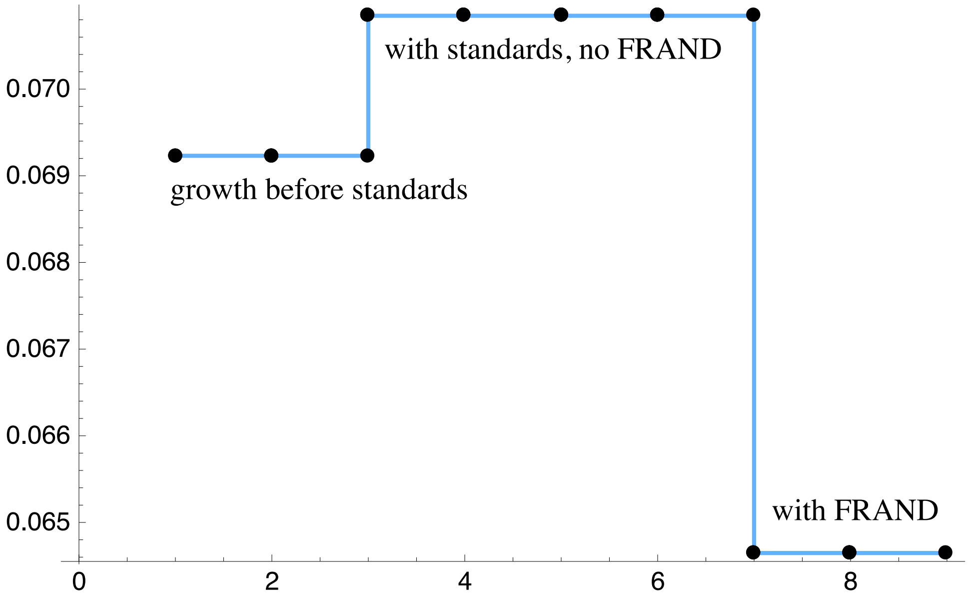
1. When $\delta_{FRAND} > \overline{\delta} > (1+\epsilon_{sep})^{-\frac{1}{\alpha}}$ standards are still growth-enhancing, however the increase in growth due to introduction of standards is lower than when there is no FRAND pricing $\delta_{FRAND} = 1$. The cutoff $\overline{\delta}$ is determined as the solution to the following equation:

$$\begin{aligned} \zeta_B + (1-\zeta_B) \cdot (1+\epsilon_{sep})^{\frac{1}{\alpha}} &= \\ = \rho + \overline{\delta} \cdot (1-\rho) \cdot (1+\epsilon_{sep})^{\frac{1}{\alpha}} \end{aligned} \tag{22}$$

2. When $\delta_{FRAND} \leq (1+\epsilon_{sep})^{-\frac{1}{\alpha}}$ our model implies $\pi^M_{sep}(t) \leq N \cdot \pi^M(t)$ and standards reduce economic growth. FRAND pricing cancels the productivity-enhancing effect of standards and we are back to the scenario when standards constitute a zero-sum market share reshuffling. However standards are still productivity-enhancing in terms of final good production, so incentives to innovate are lowered relative to incentive to produce final goods. The effect of standard-essential patents on the endogenous growth is $G_{sep} < 1$, which makes final good production more promising than innovation production for investment of human capital.

We conclude that FRAND pricing is always growth-reducing in our framework and the

Figure 7: Growth with standards and FRAND: Example



Legend: The figure shows growth rates in the balanced growth equilibrium. First three points on the graph correspond to growth rate in an equilibrium with no standards. Next five points correspond to growth rate in an equilibrium with standards and no FRAND price regulation. The last three points correspond to growth rate in an equilibrium with standards and with FRAND price regulation in which $\delta_{FRAND} = (1+\epsilon_{sep})^{-\frac{1}{\alpha}} < 1$. It can be seen how FRAND can reduce the endogenous growth rate of the economy.

harder is the regulation of mark-ups on standard technologies the more likely such regulation would overturn any benefits of standardization to endogenous growth of the economy.

5 Conclusion

In this paper, we show that for standards to affect endogenous economic growth, they have to be productivity-enhancing. The zero-sum redistribution of market share is not enough to reshape incentives to innovate on an aggregate level. Secondly, when standards and patents are perfect substitutes as in our baseline model, it turns out standards reduce economic growth. As new technologies are discovered, they dampen incentives to engage into the innovative sector—and relatively less human capital moves to the innovative sector of the economy, which dampens endogenous economic growth. When we consider technological complementarities in standard creation process, in other words, when new standards create additional patents, the standards can become growth-enhancing in equilibrium. Complementarities are necessary for standards to be growth-enhancing. As we show, the innovators' risk of losing the standard-setting game ex-ante attenuates the anticipation of a larger market share. Thus FRAND regulation of mark-ups on top of that can easily have growth-destroying consequences.

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