Standard-Setting and the Incentives to Innovate: Evidence from the IEEE Patent Policy Update*

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Abstract

This paper investigates the effects of enforcing licensing requirements on firms' standard-related innovation by empirically analyzing the Institute of Electrical and Electronics Engineers' 2015 patent policy revision. Using a continuous difference-in-differences approach, I find that firms technologically further from the standards increased their patenting activity by 33% after the policy change, compared to an 18% rise for firms closer to the standards. The results reveal distinct effects on standard-essential patent (SEP) holders and non-SEP holders, suggesting that stricter licensing policies can reshape the patenting landscape, offering opportunities for some firms while creating challenges for others.

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1 Introduction

Technology standards play a crucial role in the Information and Communication Technology (ICT) sector, where independently designed innovations need to interoperate. These complex systems demand collaboration among firms to ensure that technologies, products, and services are compatible. Standard setting organizations (SSOs) facilitate this process by coordinating the development of standards with contributions from various stakeholders. One of the SSOs' most critical functions is regulating the licensing of standard-essential patents (SEPs)—intellectual property rights essential for implementing these standards (Bekkers et al., 2014).

Licensing rules for SEPs have long been a controversial topic, drawing attention from both academics and legal experts. Since the early 2000s, concerns have emerged about the potential for anti-competitive behavior by SEP holders, leading SSOs to introduce stricter intellectual property rights (IPR) policies. These changes seek to balance the incentives for developing essential technologies with the goal of promoting widespread adoption of standards. However, the impact of these patent policies on innovation remains unclear. While tighter licensing requirements may discourage firms from contributing to standards, lenient policies could impose higher costs on implementers and deter downstream innovation.

This paper addresses this ambiguity by investigating the effects of licensing requirements on innovation. I focus on a major policy change introduced in 2015 by the Institute of Electrical and Electronics Engineers Standards Association (IEEE SA), which implemented tighter restrictions on SEP royalties. Using a continuous difference-in-differences methodology, I analyze how this policy change affected innovation in standard-related technologies at the firm level. I find that the IEEE's IPR policy revision led to an increase in standard-related patenting among affected firms, with evidence of a negative impact on firms declaring SEPs.

The 2015 IEEE policy aimed to provide greater clarity around the definition of SEPs royalties. In so doing, the revision included two important changes: all entities holding patents that are essential for the standard are strongly recommended to base their royalties on the Smallest Salable Patent Practicing unit, and they are constrained in their right to take injunctions (Prohibitive Orders) against licensees of SEPs.

The updated patent policy affected not only SEP holders, by restricting the royalties for essential patents, but also had broader implications for firms not directly involved in standards development. By putting pressure on the royalties that the holders of SEPs could charge, the policy potentially opened new opportunities for firms to innovate with standardized technologies, even if they had not contributed to the original standard-setting process. This demonstrates the broader influence of standardization on innovation, affecting both contributors to and users of standards.

The theoretical literature has extensively studied how licensing commitments influence firms' incentives to invest in standard's innovation (Layne-Farrar et al., 2014; Lerner and Tirole, 2015; Spulber, 2019). In standard organizations, unfavorable licensing requirements may decrease incentives for SEP holders to invest in standards development and deter their participation. Conversely, strong SEP rights could stifle the adoption of the standard in downstream markets, reducing the returns to innovation. Changes in licensing rules can impact standard-related profits, as royalty fees affect the demand for a standard. Enforcing licensing commitments may promote innovation, particularly among vertically integrated firms that contribute to standards without relying on licensing revenue. Such firms may benefit more from expanding the market for complementary goods and services or from the non-monetary advantages of integrating their technology into standards.(Simcoe and Zhang, 2021)

To analyze the effects of stricter licensing rules, one would need to identify the full range of firms involved in standardization and distinguish their roles between upstream innovators (firms developing technologies incorporated into standards), downstream implementers (firms applying standards to end-user technologies), and vertically integrated firms (engaged in both). However, identifying these types of firms presents challenges due to the complexity of technological overlap across industries [1].

To address these challenges, I employ a novel empirical approach. Using data from the Searle Center Database, PATSTAT, and Compustat, I construct a dataset of companies potentially involved in both upstream and downstream technologies related to IEEE

[1] See Bekkers et al. (2012) for an attempt to identify the business model of firms and the associated limitations.

standards in the ICT sector. My sample includes firms that declared at least one SEP for an IEEE standard before the policy change, along with firms active in the same industries and countries as SEP holders, that did not declare SEPs. This allows me to capture different types of firms and their varying responses to the policy revision: SEP holders, likely upstream innovators or vertically integrated firms, and non-declaring firms, which are potential downstream implementers or vertically integrated firms without declared SEPs. Although I observe firms declaring SEPs, distinguishing between pure upstream innovators and vertically integrated firms remains challenging. Furthermore, it is unclear whether non-declarant firms are entirely uninvolved in standards development or participate through other channels.

An additional empirical challenge arises from the fact that licensing requirements affect all firms, though in different directions. To identify the causal effect of enforcing licensing requirements on firms' standard-related innovation, I need to define an appropriate control group of similar firms unaffected by the policy revision. However, due to the widespread diffusion of technology standards across industries, finding an unaffected sample of firms is difficult.

My approach addresses this by considering firms' proximity to the technological domain of the standard to define continuous treatment groups. I use the cosine similarity to compute the technological similarity between each firm's patent portfolio and all standards issued by IEEE. This allows me to assess the effects of the policy change on firms with varying degrees of involvement in standardization. I empirically show that firms declaring to hold standard-essential patents are the ones closer to the standards' technology space. This suggests that firms owning standard-essential technologies have been the most involved in developing innovation for those standards. I also show that firms that invested less in standard-related technologies in the pre-period increased their relative number of patents filed in standards' technologies classes after the policy revision compared to firms that are closer to the standards.

My identification strategy relies on the assumption that firms closer to the standards' technology space provide a good counterfactual for firms that are technologically further away. The identification strategy is motived by a theoretical result and empirical facts. The empirical fact is that firms with similar technological ties to the standard behaved similarly before the policy change, but diverged afterward. Specifically, firms closely aligned with the standard did not change their innovation investments post-2015. My theoretical results show that firms less aligned with the standard's technology space exhibit a greater sensitivity to fluctuations in SEPs royalties. This relationship is consistent across different firm types. The results hold regardless of whether firms are pure upstream innovators, vertically integrated firms, or downstream implementers.

I, therefore, employ a difference-in-differences approach with continuous treatment, allowing me to assess the intensity of the policy change's effects on different groups exposed to varying levels of treatment. I define this continuous treatment based on technological similarity, clustering firms into quartiles. To account for potential spillovers across standards and avoid biases from technological overlap, I control for the technological distance between firms and all IEEE standards. I also adjust for the relative importance of each technology class within a standard when measuring standard-related patenting.

The results of the econometric analysis provide causal evidence that the IEEE policy change increased standard-related patenting among affected firms. Firms further from the standards showed the largest increases, filing 33.4% more patents on average in standard-related technologies. Firms in the second and third quartiles also experienced increases, though to a lesser extent, of 18.2% and 18.4% respectively. This non-linear relationship suggests a threshold effect regarding how licensing rules impact standard-related patenting. To further investigate this mechanism, I computed the distances across firms in the different groups, accounting for both standard-related and non standard-related technology classes. I find that firms in the second quartile are technologically closer to firms in the fourth group than firms in the third. This empirical fact indicates positive spillovers from the supply side on standard-related innovation. I then tested for the effect of the policy revision on patents filed in technology classes unrelated to standards. The findings support the spillover hypothesis. I observe significant positive effects in the second and fourth quartiles, but no effect on firms in the third group. When I test for an effect on SEP holders, I find evidence of a decline in standard-related patenting.

Taken together, my findings suggest that enforcing licensing requirements can stimulate innovation in standard-related technologies at the firm level. Although SEP holders experience a decline in patenting, the overall increase in innovation among other firms outweighs this effect.

Contribution to the literature. This paper contributes to the literature on licensing and innovation in the context of standardization. Prior economic research has extensively examined the relationship between standardization and patenting, with notable focus on the economic impact of standard-essential patents (Rysman and Simcoe, 2008; Lerner and Tirole, 2015) and the strategic considerations behind firms' decisions to declare ownership of intellectual property to standard organizations (DeLacey et al., 2006; Bekkers et al., 2011; Hussinger and Schwiebacher, 2013; Layne-Farrar et al., 2014). I contribute to this literature by adopting a broader definition of standard-related patenting and emphasizing the roles of both upstream innovation and downstream standard-related technologies.

Further research has extended this literature by exploring the role of firms' technological positioning in their involvement in standards development. This literature has examined the technological distance between firms, focusing on their membership in standard consortia (Baron and Pohlmann, 2013), committees (Bar and Leiponen, 2014), and submission of technical contributions (Rosa, 2019) as indicators of participation in standard setting. However, these studies have not specifically addressed how the alignment between a firm's technological capabilities and the standard's technological domain influences its decisions to invest in standard-related patenting.

Despite the growing literature on technology standards and declared essential patents, empirical evidence of the effect of the SSOs' patent policy on innovation is limited (Gandal et al., 2004; Chiao et al., 2007; Bekkers et al., 2017). Gandal et al. (2004) empirically examine the interaction between intellectual property and participation in standardization committee meetings in the modem industry. Chiao et al. (2007) theoretically and empirically explore standard setting organizations' policy choices. Bekkers et al. (2017) develop a model to study the link between SSO patent policies and firms' disclosure commitments. In contrast to my work, these papers focus solely on the effect of patent policies on firm participation in standard organizations and the declaration of SEPs. My research extends this literature by estimating the causal correlation between enforcing licensing rules and the behaviors of developers and implementers of standard-essential technologies.

In addition to this broader focus, my study addresses the IEEE policy revision, a topic explored in only a few prior papers, which have yielded mixed results regarding its impact on standard-related innovation (IPlytics, 2017, 2018; Gupta and Effraimidis, 2018; Simcoe and Zhang, 2021). Simcoe and Zhang (2021), the most comprehensive analysis to date, found little evidence that the IEEE policy change reduced participation in SSOs or innovation by SEP holders. However, their analysis was limited to unweighted patent counts and specific committees, focusing primarily on participation through standards' contributions. In contrast, my research introduces a novel identification strategy that allows for a more complete assessment of the policy's net impact on standard-related innovation, accounting for both upstream and downstream activities. I also employ a class-weighted patent count to reflect the relative importance of each technology class for the standard, offering a more nuanced view of standard-related innovation. By providing new insights into the effects of licensing commitments on innovation incentives, my research contributes to the longstanding debate among policymakers, specialists, and SSOs on how technology standards and standard-essential patents should be regulated.

The paper proceeds as follows. Section 2 provides an overview of IEEE and its patent policy revision. In Section 3, I present a stylized model motivating my identification strategy. Section 4 presents the database creation and the estimation procedure is presented in Section 5. The results of the empirical analysis and robustness checks are discussed in Section 6. Section 7 concludes.

2 Institutional Setting

The Institute for Electrical and Electronics Engineers Standards Association is a globally recognized private standards development organization affiliated with the IEEE. Founded in the United States in 1890, it has since expanded its global reach and influence. IEEE SA specializes in creating standards in the fields of electricity, electronics, and telecommunications.[2] Participation in standards development requires the payment of a fee, and IEEE SA members enjoy various benefits, such as eligibility to hold working group positions, vote on standards, assume leadership roles, and participate in elections for IEEE SA governance. However, membership does not obligate contributions to standards development,

[2] Appendix A.1 provides a detailed explanation of the process followed by IEEE for standards development.

and, in fact, most members do not actively participate in this process.[3]

To address potential opportunistic behavior by SEP holders, IEEE SA requires that they declare essential patents and commit to licensing them on fair, reasonable, and non-discriminatory (FRAND) terms. This policy ensures that implementers can access these patents at reasonable costs while fairly compensating the patent holders. IEEE SA also allows blanket declarations, whereby a contributor can declare the existence of essential patents without specifying individual patent numbers.[4]

In 2015, IEEE SA introduced controversial changes to its patent policy, aiming to address concerns about the potential strategic use of SEPs by their holders. Although the changes became effective in February 2015, the revision process began two years earlier.[5] While the policy revision was not publicly disclosed until 2015, it is likely that members and stakeholders were aware of the organization's intention to amend the policy before its official release.[6] A legal debate has since emerged about whether the revisions constitute substantive changes, applying only to licensing commitments made after the policy's implementation, or clarifications addressing ambiguities surrounding the definition of FRAND royalties in prior commitments.

Two central amendments were at the heart of the policy revision. First, firms declaring essential patents were encouraged to base royalty calculations on the Smallest Salable Patent Practicing (SSPP) unit rather than the value of the end product. Critics argue that this recommendation effectively reduces the maximum royalties firms can demand for their SEPs (Layne-Farrar et al., 2014; Llobet and Padilla, 2016).[7] Second, SEP holders were restricted from seeking injunctions against licensees of SEPs, limiting their ability to prevent patent infringement. This limitation potentially incentivizes patent infringement, as implementers may believe that the worst consequence they face is paying a reasonable royalty (Contreras and Gilbert, 2015), thereby weakening the innovation incentives for firms

[3] For more information, see IEEE SA Standard Association.

[4] For a detailed discussion of standard setting organization patent policies, see Bekkers et al. (2017) and Baron and Spulber (2018).

[5] IEEE Website, News Releases Section, 2015, https://www.ieee.org/about/news/2015/patent-policy.html.

[6] See subsection 8.1 in the Appendix for a detailed description of the process followed for the patent policy revision at IEEE.

[7] Although using SSPPU as the baseline is only a recommendation, the absence of alternative methods in the policy increases the likelihood that SSPPU will be the primary approach in SEP licensing negotiations. See Sidak (2014); Gautier and Petit (2019) for more details on the Smallest Salable Patent Practicing Unit.

reliant on SEP royalties to recoup their investments in standard-related technologies.[8]

The policy update was highly controversial, both for its content and the process leading to its adoption. Following the revision, several major contributors to IEEE standards, including Qualcomm, Alcatel-Lucent, Ericsson, General Electric, and InterDigital, refused to submit Letters of Assurance (LoAs) under the new policy. These firms, prominent players in the ICT sector, argued that the changes would disrupt the balance of power between upstream innovators and downstream implementers of ICT technologies (Teece, 2015). Conversely, some participants in IEEE standards development, including Apple, Broadcom, Dell, Hewlett Packard, Intel, and Samsung, supported the changes. The existence of standards contributors who do not monetize their SEPs indicates that licensing revenue is not always necessary to induce upstream innovation. A supporting factor is that some SEP holders were actually in favor of the new patent policy.

A second major criticism of the policy revision concerned the process itself. The drafting was largely driven by major standard implementers, who pursued changes that aligned with their interests (Hoffinger et al., 2015; Zingales and Kanevskaia, 2016), while standard-related technology developers, who should have provided a counterbalance to manufacturers, were only involved in the final stages of the revision process (Zingales and Kanevskaia, 2016). This imbalance prompted discontent among some stakeholders. Following the policy revisions, Qualcomm stated that over 15 major technology companies, whose engineers contribute to IEEE standards, objected to the changes but were excluded from the rule-making process. They criticized the lack of open debate on the revisions' merits, consequences, and rationale.[9] InterDigital shared similar concerns in an open letter to the IEEE and a public article, highlighting dissatisfaction with the process's lack of transparency and inclusivity.[10]

[8] Appendix A.2 provides a detailed description of the process undertaken by IEEE for the policy revision. See also Zingales and Kanevskaia (2016) for a comprehensive explanation of the IEEE SA policy update.

[9] *Qualcomm Responds to Updated IEEE Standards-Related Patent Policy*, Qualcomm, February 2015.

[10] *Re: Licensing Assurances and IEEE's 2015 Patent Policy*, InterDigital, March 2015. See also *Why We Disagree with the IEEE's Patent Policy*, March 2015, available at https://www.eetimes.com/why-we-disagree-with-the-ieees-patent-policy/.

3 Analytical Framework

This section presents a stylized theoretical model that explores how changes in royalty rates for SEPs affect firms' incentives to invest in standard-related technologies. By focusing on firms' technological proximity to the standard, the model predicts how optimal innovation at the firm level adjusts in response to shifts in royalty policies. The analysis provides theoretical results that I can take to the data.

Building on the framework developed by Baron et al. (2014), I adapt the model to incorporate firms' technology proximity to the standard and to account for both upstream and downstream innovations. I consider a standard that is developed and deployed within an industry. The standard generates aggregate profits $v(x, y)$ that increase with the number of inventions included in the standard, x, and the inventions deploying the standard, y. For tractability, I assume a linear functional form of the aggregate profits defined as $v(x, y) = x + \beta y$, where β captures the contribution of downstream innovation to the standard's profit.

The industry consists of n firms that can participate in standard development as upstream innovators, implement the standard in their inventions as downstream implementers, or engage in both activities as vertically integrated firms. For firm $i = 1, \ldots, n$, x_i denotes the number of patented inventions included in the standard, with $x = \sum_{i=1}^{n} x_i$ representing the total amount of upstream standard-related innovation. Similarly, y_i represents the number of patented inventions by firm i that deploy the standard, with $y = \sum_{i=1}^{n} y_i$.

I denote $r \in [0, 1]$ as the share of profits accruing to upstream inventions. The aggregate licensing revenues $rv(x, y)$ are distributed among firms in proportion to their essential patents, represented as $\frac{x_i}{x}$. I treat r as an exogenous parameter determined by the licensing policies of standard-setting organizations. By assuming r as exogenous, the model assesses the impact of royalty changes enacted by these organizations on firm innovation while maintaining tractability. The remaining profits, $(1 - r)v(x, y)$, are allocated among implementers in proportion to their downstream innovations, $\frac{y_i}{y}$.

The revenue function for firm i is as follows:

$$b_i = (x + \beta y)\left[r\,\frac{\gamma_i x_i}{\gamma \cdot x} + (1 - r)\frac{y_i}{y}\right] \tag{1}$$

Where $\gamma_i \in [0, 1]$ represents the firm's technological proximity to the standard, capturing the technological knowledge developed by the firms, while $\gamma = \sum_{i=1}^{n} \gamma_i$. I assume that firms more closely aligned with the standard are likely to generate higher licensing revenues. Consequently, I weight the firm's revenues derived from royalty rates by γ_i, reflecting the notion that alignment with industry standards enhances the leverage of R&D investments in current standards development.

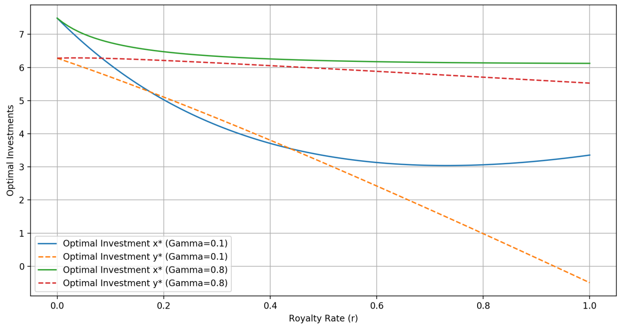
I consider the γ_i parameter to be exogenous. Although firms decide which technology classes to invest in, thereby making γ_i potentially endogenous, the technology proximity between a firm and a standard results from decisions made many years prior to the current period. This setup captures the effects of long-term strategic alignment on present revenues without making γ_i a dynamic decision variable. My purpose is to account for a broad range of observed technology proximities across firms ($\gamma_i = 1$, for instance, represents full technological alignment), enabling the analysis of innovation incentives across varying royalty rates r without introducing additional complexity into the profit function. Notably, I allow γ_i to serve as an intuitive measure of how past R&D affects current incentives without requiring a direct impact on the complexity of the profit function.

Considering both revenue streams, the objective function that firm i maximizes is defined as:

$$\max_{x_i, y_i} \pi_i = (1 - \epsilon) b_i + \epsilon \sum_{j=1}^{n} b_j - c_i(x_i + \frac{x_i^2}{2}) - m_i(y_i + \frac{y_i^2}{2}) \tag{2}$$

To develop upstream innovations, a firm incurs a cost $c_i(x_i + \frac{x_i^2}{2})$, where c_i is the unit cost. Similarly, downstream innovations y_i involve a cost $m_i(y_i + \frac{y_i^2}{2})$. In line with Baron et al. (2014), I weight the total industry revenue by ϵ to account for imperfect cooperation among firms, thus relaxing the assumption of joint profit maximization, which is common in the theoretical literature on R&D cooperation and standards development. By taking

Figure 1
'Optimal Investments vs. Royalty Rate (r) for Different Gamma Values



The figure plots the distribution of optimal innovations from the numerical simulations, comparing low-γ_i values with high-γ_i values of vertically integrated firms.

the FOCs of Equation 2, I obtain the following explicit equations defining the optimal standard-related innovations x_i and y_i in equilibrium[11]:

$$\begin{cases} x_i^* = \frac{x\left(\gamma x(\epsilon r-\epsilon-r+1)(\beta\epsilon ry-\beta ry+\beta y+\epsilon rx-\epsilon x-m_i y-rx+x)-(\epsilon rx-\epsilon x+m_i y^2-rx+x)(\beta\epsilon\gamma_i ry-\beta\gamma_i ry+c_i\gamma x-\epsilon\gamma x+\epsilon\gamma_i rx-\gamma_i rx)\right)}{\beta\gamma_i rxy(\epsilon-1)(\epsilon r-\epsilon-r+1)+(-\beta\epsilon\gamma_i ry+\beta\gamma_i ry+c_i\gamma x^2)(\epsilon rx-\epsilon x+m_i y^2-rx+x)} \\ y_i^* = \frac{y\left(\beta\gamma_i ry(\epsilon-1)(\beta\epsilon\gamma_i ry-\beta\gamma_i ry+c_i\gamma x-\epsilon\gamma x+\epsilon\gamma_i rx-\gamma_i rx)+\gamma(-\beta\epsilon\gamma_i ry+\beta\gamma_i ry+c_i\gamma x^2)(\beta\epsilon ry-\beta ry+\beta y+\epsilon rx-\epsilon x-m_i y-rx+x)\right)}{\gamma\left(\beta\gamma_i rxy(\epsilon-1)(\epsilon r-\epsilon-r+1)+(-\beta\epsilon\gamma_i ry+\beta\gamma_i ry+c_i\gamma x^2)(\epsilon rx-\epsilon x+m_i y^2-rx+x)\right)} \end{cases} . \quad (3)$$

A central question is how a change in the royalty rate r affects firms' innovative effort, especially in relation to their technological proximity to the standard. The cross-partial derivatives of optimal innovations with respect to R and γ would provide a deeper understanding of how firms adjust their strategies. would provide a deeper understanding of how firms adjust their strategies. To derive these cross-partial derivatives, I would need to find explicit equations for x and y and substitute them into the System of Equation 3. However, this approach would yield complex equations requiring advanced analysis, which is beyond the scope of this paper. Given the complexity of the System of Equation 3, I rely on numerical simulations to solve for the equilibrium innovations x_i and y_i aand to analyze how these equilibrium values vary with respect to changes in r across different values of γ_i.

Figure 1 shows the distribution of optimal innovations for low and high γ_i values across different royalty rates. As expected, low-γ_i firms exhibit a more pronounced reaction to variations in r that their high-γ_i counterparts. This observation supports the hypothesis

[11] See Appendix B for the full derivatives of these equations

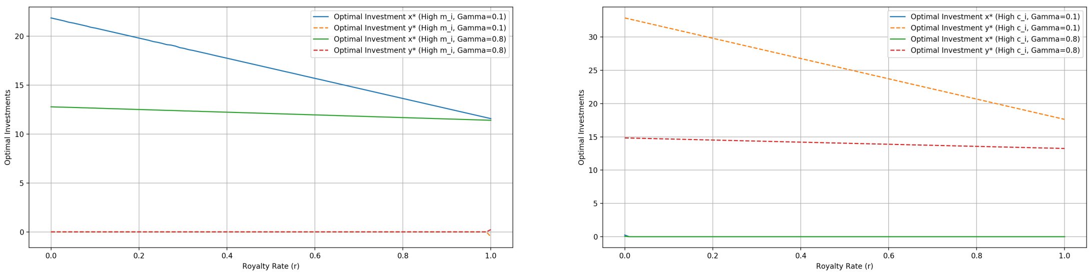
that firms less aligned with the standard are incentivized to adjust their investments more significantly in response to changes in the royalty rate, thereby emphasizing the implications of technology proximity in shaping innovation strategies. Intuitively, firms with lower γ_i re more sensitive to changes in royalty rates because they rely more heavily on external standard-essential patents (SEPs). Consequently, a decrease in r significantly lowers their licensing costs, providing stronger incentives to increase their innovations (x_i^*, y_i^*) in developing their own standard-related technologies, thereby reducing their reliance on royalties. In contrast, high γ_i firms offset the decline in licensing revenues due to a reduction in r by the increased y_i^* of low γ_i firms. This dynamic leads to a rise in their licensing revenues, resulting in stable optimal investments for these firms across varying values of r.

As the current model only considers firms that invest in both upstream and downstream innovations (vertically integrated firms), I expand my analysis to examine the impact of a decline in r on pure upstream and downstream innovators. I conduct a deeper analysis of the sensitivity of corner solutions for x_i^* and y_i^* at different γ_i. Figure 2a reports the distribution of optimal innovation for pure upstream firms, as they do not invest in downstream inventions due to high unit costs (m_i). Conversely, Figure 2b shows how the optimal innovation for pure downstream implementers varies with different $r$values, as these firms refrain from investing in upstream innovation given their high costs c_i. In both scenarios, innovations from low-γ_i firms are more sensitive to changes in the values of r compared to those from high-γ_i firms.

This model shows how SEPs royalty rates r and the proximity to the standard's space γ_i affect equilibrium outcomes. Using numerical simulations, I find that the effect of a decrease in the royalty rate R on investment depends on the firm's technological proximity γ_i. Firms with low proximity respond more strongly to a decrease in R. This aligns with the intuition that firms further from the standard's technology space have more room for improvement, while those closer have less incentive to invest further.

The empirical challenge lies in identifying whether a firm acts as vertically integrated, pure upstream innovator, or downstream implementer. Whereas I cannot directly test Equation 3, I can estimate the impact using a difference-in-differences approach by analyzing the effect of royalty rate changes across firms with varying degrees of technological

Figure 2
Optimal Investments vs. Royalty Rate (r) for Upstream and Downstream Innovators



(a) Corner Solution: High m_i (b) Corner Solution: High c_i

These figures plot the distribution of optimal innovations from the numerical simulations, comparing low-γ_i values with high-γ_i values. The first graph accounts for the optimal innovations in x_i^* when the unit cost for y_i^*, m_i is high such that firms don't have any incentive to invest in downstream innovation. The second graph accounts for the optimal innovations in y_i^* when the unit cost for x_i^*, c_i is high such that firms don't have any incentive to invest in upstream innovation.

proximity. This method allows for a comparison of firms' investment behavior before and after the IEEE policy revision, focusing on firms with differing levels of technological alignment with the standard.

4 Data

My main data source is the Searle Center Database (SCDB), a comprehensive and systematic database of technology standard documents and information about standard setting organizations.[12] The SCDB includes data on 629,438 standard documents issued by 598 SSOs from 1985 to 2018. For this study, I focus on standard documents related to the ICT sector, specifically those issued by the IEEE, while restricting the sample to the post-2000 period.[13] This yields 420 standard documents, each with publication dates, version histories, and identifiers.

In the SCDB, standard documents are identified by unique document identifiers, and declarations referring to the same standard project share a common identifier. However, the term technology standard can vary in meaning. It may refer to a single technical specification[14] or to complex systems described by multiple standard documents. More-

[12]See Baron and Spulber (2018) and Baron and Pohlmann (2018) for a detailed description of the database.

[13]As most SCDB standardization data is from the post-2000 period, given the rise during the beginning of the 21st century, I exclude observations before 2000, with minimal data loss.

[14]"A standard is a document that provides requirements, specifications, guidelines or characteristics

over, standards evolve over time, and the revision process varies across organizations.[15] I standardize the analysis by defining a technology standard as a set of documents linked by a shared version history and identifier aggregating information for 136 standards, referred to hereafter as standards.

This approach allows me to account for complementary and substitute documents that collectively define complex systems. By tracking the full standard history from its first release to final withdrawal, I can observe the standard-related patenting behavior of firms over time and study how policy revisions affect firms' future incentives to continue contributing to standard development.

The SCDB also contains data on declarations of standard-essential patents, including the declaring entities, declaration dates, patent numbers, and International Patent Classification (IPC) codes for each SEP. From this data, I collect two key information: the technology portfolio of each standard and the firms developing standard-essential technologies.

To define a standard's patent portfolio[16], I use the 4-digit IPC classification of essential patents declared in the pre-policy change period, starting from the first publication of the standard. This allows me to identify the technology space of a standard. If blanket disclosures are made, it becomes impossible to fully identify the standard's patent portfolio, leading to potential data gaps.[17] Nevertheless, if a standard has a large percentage of blanket declarations, accounting only for the observed IPC classes would not provide a realistic representation of the standard's technology space and potentially alter the results of the econometric analysis. To address this issue, I exclude standards where more than 25% of the IPC classes are missing, leaving 10 standards in the final sample.

To construct the sample of firms used in the econometric analysis, I start by collecting information regarding the declaring entities to standards issued by IEEE. The SCDB

that can be used consistently to ensure that materials, products, processes, and services are fit for their purpose." International Organization for Standardization (ISO), Standard Definition.

[15] Baron and Pohlmann (2018) found that many organizations issue different versions for their standards, each version replacing the former one. Standard organizations can also issue new standard documents amending existing ones, in which case the previous version remains active.

[16] See the Empirical measure subsection for a detailed explanation of how I construct the patent portfolio of a standard.

[17] This problem is part of a broader missing value issue. Missing values of the 4-digit IPC classes related to essential patents can be due to two different reasons: blanket disclosures and the lack of observation by the researcher.

includes 119 SEP holders for the 10 standards in the sample, of which 107 are firms. The remainder are universities, institutions, or governments. Since my analysis focuses on firm-level innovation, I limit the sample to these 107 firms. These firms represent upstream and vertically integrated innovators, contributing to standardization and developing technologies embedded in the standards.

For the purpose of my analysis, I add firm-level data from the Compustat database, focusing on R&D expenditure, sales, and employee numbers between 2010 and 2018.[18] These variables, known predictors of patenting and innovation, may influence the number of patents a firm files in standard-related 4-digit IPC classes (Hall et al., 2000; Hall and Ziedonis, 2001; Faber and Hesen, 2004). I further restrict the sample to firms with at least five consecutive years of data before and after the policy revision, resulting in 61 SEP-holding firms. From Compustat I also retrieve information about the industries and countries those firms are active in, which is the key information to select the full sample of firms affected by the policy revision.

To complete my sample and collect the set of potential standards downstream innovators, either vertically integrated firms that have not declared any patent as essential and implementers, I start by selecting firms active in the same industries and countries as the SEP holders, using 4-digit NAICS industry codes. Applying similar data availability criteria, I identify 1,862 firms for inclusion.

To track firms' innovation activity, I retrieve patent data from the European Patent Office's PATSTAT database, which includes more than 100 million patent documents. I collect information on patent application dates, filing entities, and IPC technology codes. Patents are counted by application year to better reflect R&D activity, and each patent is attributed to all associated technology classes.[19] From the whole sample of firms, I look for the ones who patented at least once in the period 2000-2017 in the set of technology classes related to the 10 IEEE technology standards and for which I have available data.

To merge patent data with firm data, I use the Harmonized Applicant Names (HAN) database developed by the OECD, which standardizes applicant names across datasets.[20]

[18] Because I collect firms' characteristics from compustat I focus specifically on public listed companies, representing the big players in the ICT sector.

[19] In my sample, on average, patents are linked to 1.68 technology classes.

[20] The OECD HAN database provides a grouping of patent applicants' names resulting from the cleaning and matching of names. Through the database, a common identification number is assigned to each group

Matching errors are common due to the volume of data, so I limit the analysis to firms for which I can confidently match names across Compustat, HAN, and PATSTAT. This yields patent application data for 36 SEP holders and 507 non-declaring firms, filing approximately 1.2 million patents.

After merging firm-level data with standard information, I construct an unbalanced panel dataset of 10 IEEE standards, 543 firms, and 5,053 firm-standard-year observations over the period 2010–2017. This dataset, covering firms across 28 4-digit NAICS sectors, provides a rich basis for analyzing the effects of standard-related policy changes on firm-level innovation, allowing for a detailed study of firms' responses to evolving SEP royalty policies.

4.1 Empirical Measures

Because some variables in the analysis are unobserved, I construct empirical proxies to capture relevant concepts. Below, I outline the key measures used in my analysis.

Standard-related Innovation: According to the theoretical model, changes in royalty rates for standard-essential patents directly affect firms' innovation in standard-related technologies. The IEEE's policy revision, which impacts licensing returns on SEPs, alters firms' expected profits from innovation, thereby investment decisions.[21] Ideally, firm-specific R&D investments in IEEE standards-related technologies would serve as the best measure of standard-related innovation. However, data on the amount of firms' investment in developing technologies for or implementing IEEE standards are unavailable.

To overcome this data limitation, I follow the methodology proposed by Baron et al. (2014), using the number of patents filed by a firm in technology classes related to a standard as a proxy for standard-related innovation.[22] This approach closely aligns with the theoretical model's emphasis on firms' investment in technologies linked to a standard, reflecting their technological proximity (γ) and responses to changes in royalty rates (R).

First, I identify the relevant 4-digit IPC classes associated with each standard based on

of names, and it is associated with a single company.

[21]The returns from a firm's innovation investment also depend on factors like bargaining power in cross-licensing negotiations, portfolio size, the importance of a given invention to the standard, and the standard's adoption rate in downstream markets.

[22]Bekkers et al. (2016) also find that patent applications in standard-related classes are strongly influenced by standardization activities.

the technology classes of SEPs declared essential to that standard. I then count the number of patents a firm files in these standard-related IPC classes as a measure of standard-related innovation.[23]

However, not all technology classes contribute equally to each standard. Some IPC classes may be associated with a larger share of patented inventions essential to a standard. Moreover, some IPC classes overlap between standards issued by different organizations, such as the IEEE and 3GPP (e.g., Wi-Fi standards vs. cellular standards like GSM and UMTS). Thus, at the 4-digit IPC level, patents related to IEEE standards may be confounded by patents related to other standards, introducing potential bias.

To mitigate this issue, I follow the weighting methodology proposed by Baron and Pohlmann (2013) and Baron and Pohlmann (2018). This method adjusts the patent count by assigning weights to each IPC class based on its relative importance to IEEE standards. Specifically, the weight (W_{jt}) assigned to each class is determined by the proportion of SEPs declared in that class relative to the total SEPs for standard s in year t. This ensures that technology classes with a larger share of essential patents receive greater weight in the measure, refining the estimate of standard-related innovation. Some SEPs are associated with IPC class zero, indicating a lack of specific classification. Including these in the weights could bias the measure by distorting the relative importance of other classes. Therefore, I exclude IPC class zero from the weighting scheme.[24]

The dependent variable of my analysis is defined as follows:

$$P_{ist} = \sum_{j \in J_s} W_{jt} * PatentFile_{ijt} \tag{4}$$

where J_s is the set of technology classes defining standard s, $PatentFile_{ijt}$ is the total number of patents filed by firm i in technology class j at time t, and W_{jt} is the weight associated to class j, measured as the share of SEPs declared in class j for standard s over the total SEPs for s in year t.

Because firms voluntarily declare SEPs to standard organizations, there might be some patents that are still relevant for a standard but that the firm decides not to declare as

[23]Several analyses, such as Baron et al. (2014), confirm the reliability of this measure in approximating standard-specific R&D investment.

[24]As a robustness check, I estimate the effect of the policy revision on standard-related patents by including IPC class zero in the weights. Results are provided in Table 6 of the Results Section.

so. Firms may, for strategic reasons, decide not to declare some patents as essential, even though those patents might be technologically superior. Additionally, some of the patents filed in standard-related technology classes may be commercially-essential - those critical for implementing a standard but not formally declared as essential (Bekkers et al., 2012). Both types of patented technologies, declared as essential and commercially-essential, are crucial in evaluating the innovative development of a standard. Moreover, IEEE allows blanket disclosures, which can bias the SEP count downward by not fully capturing a firm's innovation investment in a standard. Whereas the number of essential patents would be a poor measure of the firm's innovation investment in a standard, using the total number of patents filed in standard-related technology classes provides a more comprehensive view of a firm's innovative efforts around a standard.

Relying on the patenting behavior of firms as a window for standard-related innovation has several limitations. First, while patents reflect innovation outcomes, not all inventions are patented. Firms may choose to keep some innovations secret or refrain from patenting if commercial returns are uncertain (Archibugi, 1992; Archibugi and Planta, 1996). Furthermore, not all inventions are patentable, and patent-based measures may underestimate firms' total innovation efforts.

In addition, firms may over-patent strategically, particularly in standard-related areas, to enhance their bargaining position in cross-licensing negotiations or to increase their chances of holding SEPs. In such cases, the number of patents may overestimate the firm's true innovation effort. Over-declaration of SEPs can also inflate patent counts, introducing upward bias in innovation measurement by including some IPC classes in the standard's technology space that are not relevant. Industry experts and studies estimate that only 10-30% of declared patents are truly essential (Bekkers and Updegrove, 2013), further complicating the accuracy of patent-based innovation measures.

Another challenge is that policy changes may affect patenting behavior without altering innovation itself. Stricter intellectual property policies may shift firms' incentives to patent, even if their R&D efforts remain unchanged. Firms might also redirect R&D to standards under more favorable policies from other SSOs. However, evidence from Simcoe and Zhang (2021) suggests that such shifts in participation are unlikely, reducing concerns about this channel.

Despite these limitations, weighted patent counts in standard-related IPC classes serve as a practical and valuable proxy for firms' standard-related innovative efforts. This measure allows for empirical testing of the theoretical model's predictions regarding how firms adjust their innovative effort in response to policy changes, specifically in relation to variations in royalty rates at different levels of the firm-standard technology similarity. However, in contrast to the theoretical framework, my empirical analysis incorporates a comprehensive measure of standard-related inventions without differentiating between upstream and downstream innovation.

Technology Similarity: To measure the similarity between a firm's technological portfolio and the standards, I rely on patent data, drawing on prior methods used in the literature (Rosenkopf and Almeida, 2003; Gilsing et al., 2008; Baron and Pohlmann, 2013; Bar and Leiponen, 2014; Rosa, 2019). Using PATSTAT data, I construct a patent portfolio for each firm based on the IPC technology classes in which the firm has filed patents. Similarly, I follow Baron and Pohlmann (2013), who assess the position of standards in the technological space by identifying the IPC classes associated to patents declared essential to a standard, to define the patent portfolios of standards.

Following Baron and Pohlmann (2013) and Rosa (2019), I use the cosine similarity to assess the alignment between firms' and standards' technological portfolios. This method, which evaluates the similarity between vectors in multi-dimensional space, is well-suited for measuring technological proximity. This approach, proposed by Rosa (2019) to assess technological similarity among SEP holders, is adapted here to evaluate the alignment between the patent portfolios of firms and standards. Specifically, the cosine similarity between firm i and all standards $s \in IEEE$ is defined as:

$$TECH_{i,IEEE} = \frac{\vec{S}_s \cdot \vec{I}_i}{\|\vec{S}_s\|\|\vec{I}_i\|} = \frac{\sum\limits_{s \in IEEE} \sum\limits_{j=1}^{J} \sum\limits_{t<2015} \mathbb{1}\{IPC_{sjt} = j\} \, \mathbb{1}\{IPC_{ijt} = j\}}{\sqrt{\sum\limits_{s \in IEEE} \sum\limits_{j=1}^{J} \sum\limits_{t<2015} \mathbb{1}\{IPC_{sjt} = j\}} \sqrt{\sum\limits_{j=1}^{J} \sum\limits_{t<2015} \mathbb{1}\{IPC_{ijt} = j\}}} \tag{5}$$

where $\vec{I}_i$ and $\vec{S}_s$ are, respectively, the firms and IEEE patent portfolio, and J is the set of IPC classes in which firms patent and SEPs have been declared for IEEE standards. In this measure, the firm's vector $\vec{I_i} = (\mathbb{1}\{IPC_{i1} = 1\}, \ldots, \mathbb{1}\{IPC_{iJ} = J\})$ is defined based on the presence of patents in specific IPC classes, where $\mathbb{1}\{IPC_{ij} = j\} = 1$ if firm i has filed patents in IPC class j.

Similarly, the standard's vector $\vec{S_s} = (\mathbb{1}\{IPC_{s_1 1} = 1\}, \ldots, \mathbb{1}\{IPC_{s_S J} = J\})$ is defined based on the IPC classes associated with patents declared essential to standards issued by IEEE.

The cosine similarity metric takes values between 0 and 1, where 0 indicates no overlap between the firm's and IEEE's patent portfolios (orthogonal vectors), and 1 indicates perfect alignment (same direction). Unlike the Euclidean distance, the cosine similarity focuses on the direction of the vectors rather than their magnitude, making it particularly suited for this analysis where the number of patents filed in each class could distort the measure of technological proximity.

This distinction is important in the context of blanket declarations. By focusing on IPC classes rather than patent counts, the cosine similarity measure controls for potential distortions arising from blanket declarations. Firms may declare SEPs without revealing specific patent details, inflating the size of the standard's patent portfolio. However, because declared SEPs tend to cluster in specific technology classes, the inclusion of these classes in the patent portfolio is less likely to distort the overall technological alignment between firms and standards. I further mitigate concerns over blanket declarations by restricting the analysis to standards with fewer than 25% blanket declarations.

Despite the cosine similarity approach helps reduce bias from blanket declarations, over-declaration of SEPs can still lead to the inclusion of non-standard-related technology classes in the standard's portfolio, potentially inflating the measure of technological proximity. However, given the high degree of overlap in IPC classes across standards in the ICT sector, the number of technology classes that are unrelated to the standard but still included in the patent portfolio is likely low.

This empirical measure of technology similarity directly ties into the theoretical model's concept of technological proximity (γ), reflecting how closely a firm's innovation aligns with the technological space defined by standard-essential patents. This alignment is key to understanding how firms' innovative efforts respond to changes in standard-setting policies. As firms with a lower similarity (lower γ) are more exposed to the technological constraints

Table 1
Summary Characteristics of IEEE Standards Before and After Policy Revision

	Pre-period		Two-years Anticipation		Post-period	
	Mean	Std	Mean	Std	Mean	Std
Total number of standards	10		10		10	
Standards characteristics						
Number of SEP holders per standard	25.6	25.9	26.6	27.5	29.4	27.3
Number of disclosures made per standard	34.4	35.7	35.6	37.1	38.4	36.6
Number of essential patents declared per standard	112.7	128.5	112.9	132.8	120.4	129.7
Number of standard documents per standard	33.9	40.9	37.1	45.7	42.2	49.2
Number of technology classes per standard	76.8	134.6	68	137.6	68	136.4
Age of the standard at the time of declaration (mean)	8.9	7.3	11.40	7.4	13.9	7.3

Note: This table summarizes the characteristics of standards issued by IEEE, comparing cumulative numbers from 2012 and 2014 (pre-policy revision) to 2017 (post-policy revision). The ages of the standards are computed as the mean age before and after the policy change.

imposed by the revised licensing requirements, this measure allows for the identification of differential effects across firms, supporting the identification strategy used in the empirical analysis.

4.2 Descriptive Statistics

Table 1 provides summary statistics for the 10 standards in my sample, comparing their characteristics before and after the policy revision. For each standard, I compute cumulative values using data from the Searle Center Database, covering the period from the earliest available year to 2012 (Column 1), 2014 (Column 2), and 2017 (Column 3). This approach offers a comprehensive representation of each standard's characteristics over time, allowing for a comparison between the period before and after the policy change.

Of the 10 standards in the sample, 8 are classified under the information technology and 2 under telecommunications.[25] In addition to the well-known 802.11 standard (WiFi), other prominent IEEE networking protocols included in my sample are Ethernet (802.3), 1394 (FireWire), 802.6 (Distributed Queue Dual Bus), 802.16 (Working Group on Broadband Wireless Access), and 1666 (SystemC).

The standards report considerable heterogeneity in characteristics and importance, as shown by the high variance in the number of technology classes associated with each standard. This variation underscores the differing levels of importance and engagement

[25] To identify technology standards related to the ICT sector, I follow the International Classification for Standards (ICS) developed by the ISO organization. Standards with an ICS code of 33 fall under the Telecommunications category, while those with an ICS code of 35 pertain to information technologies. For a detailed explanation, see the ISO documentation at International Classification for Standards.

Table 2
Firms' Accounting Characteristics and Patent Portfolio Composition

	SEP Holders	NON-SEP Holders
Total number of firms	36	507
Firms characteristics		
Average R&D expenditures per year (millions)	4,178.7	125.2
Average number of employees per year (thousands)	107.6	7.6
Patent portfolio		
Average number of patents filed per firm per year	3,021.3	130.0
Average number of standard-related patents filed per firm per year	1,410.9	45.7
Total standard-related patents/total patents, average per firm (%)	47.2	42.2

Note: This table summarizes the characteristics of firms and their patent portfolios based on firm type (SEP holders vs. non-SEP holders) for the period 2010–2017.

by firms across standardization activities.

Table 2 outlines the characteristics and patent portfolio composition of firms in my sample, distinguishing between SEP holders (Column 1) and non-SEP holders (Column 2) during 2010-2017. The data indicate that SEP holders are typically large firms, with average annual R&D expenditures of $4,178.7 million and an average workforce of 107.6 thousand employees. In contrast, non-SEP holders are smaller, with average annual R&D expenditures of $125.2 million and an average workforce of 7.6 thousand employees.

Regarding patenting activity, SEP holders file an average of 3,021.3 patents per year, of which 1,410.9 are related to standards, representing 47.2% of their total filings. Non-SEP holders file significantly fewer patents, with an average of 130.0 per year, of which 45.7 are standard-related, accounting for 42.2% of their total. Although SEP holders focus more on standard-related technologies, the difference in the proportion of standard-related patents between SEP and non-SEP holders is relatively modest.

The characteristics of the firms suggest that SEP holders are predominantly large, established firms that invest heavily in R&D, though at a lower intensity relative to sales compared to non-SEP holders. Furthermore, the composition of SEP holders appears to be heterogeneous, likely reflecting variations in firm size, technological focus, and innovation incentives.[26] The predominance of large firms among SEP holders may introduce selection bias if their behavior alone is analyzed. Therefore, it is important to account for the broader population of firms, including non-SEP holders, to assess the full impact of the policy revision on innovation.

[26]This assumption is supported by the high standard deviations among upstream innovators. See Table 9, second column, in the Appendix.

Furthermore, the relatively small difference in the share of standard-related patents between SEP and non-SEP holders suggests that many non-SEP holders are still actively involved in innovation related to standardization, though they choose not to declare SEPs. This could be due to various strategic reasons, such as opting to keep innovations secret or avoiding the costs associated with participating in the standardization process. It is also possible that non-SEP holders face challenges in converting their R&D investments into patents, which results in lower patenting rates. These descriptive statistics provide valuable insights into the composition and innovation behavior of firms affected by the policy revision, laying the groundwork for further analysis of its impact on innovation incentives.[27]

5 Empirical Strategy and Identification

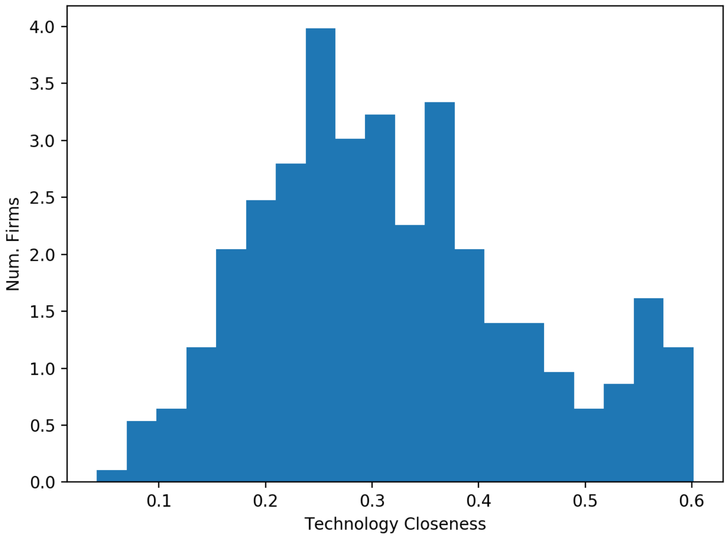
The 2015 IEEE patent policy had heterogeneous effects on upstream and downstream innovation, depending on firms' types in standards-related technologies. Due to observational limitations, I do not assess firm-specific effects but focus on broader trends among firms with similar types. Specifically, I examine the IEEE policy revision's impact on innovation in standards-related technologies by distinguishing between firms differentially affected by the policy change, based on the proximity of their technological portfolios to the IEEE technology space.

Figure 3 shows the distribution of firms' technological proximity to the IEEE technology space before 2015. There is significant variation in firms' proximity, largely explained by the different technological fields in which firms specialize. This variation allows me to classify firms into four groups based on their distance to the standards' technology space, with the inverse of $TECH_{i,IEEE}$ representing this distance. Firms in the first quartile are closest to the standards' space, while those in the fourth quartile are the furthest. I thus cluster firms into four quartiles: firms with a technological distance lower than 0.67 (with a minimum of 0.40) to the standards' technology space between 2000 and 2014; between 0.67 and 0.76; between 0.76 and 0.83; and above 0.83.[28]

[27] It should be noted that the data do not account for the relative importance of the patents to IEEE standards. Some patents may also contribute to other standards issued by different organizations, which could introduce confounding factors.

[28] Table 7 in the Appendix provides examples of real firms in the first and fourth quartiles, along with

Figure 3
Technology Closeness before Policy Revision



The figure plots the histogram of the technology closeness of firms' patent portfolios to IEEE technology space in the years before 2015. IEEE technology space is defined based on the IPC classes associated with the 10 standards in my sample. Each observation is at the firm level.

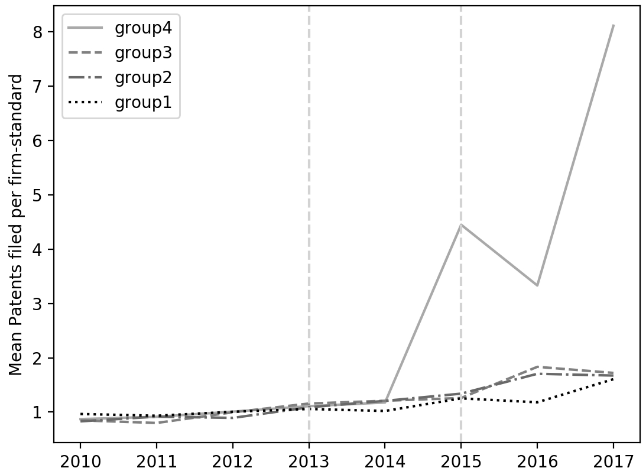
The theoretical model suggests that firms furthest from the standards' technology space should experience the greatest effects from the policy revision. The policy aimed to incentivize firms that were previously less involved in standards-related activities to participate, primarily by reducing SEP royalty rates. The post-2015 development of IEEE standards in software and internet technologies aligned with the rise of digital platforms and internet-based services, making the policy particularly attractive to implementers in emerging fields like computer software and web services.[29] As shown in Table 8 in the Appendix, 43% of firms in the fourth quartile (furthest from the standards) are involved in internet and software-related activities, compared to only 7% in the first quartile.

Several factors may explain why firms further from standards are less involved in standard-related activities. First, their technological focus may not align with pre-2015 IEEE standards. Second, firms in the higher quartiles, particularly those not declaring SEPs, may have lacked incentives to engage in the standardization process. Finally, high SEP royalty rates before 2015 may have discouraged these firms from adopting standards in downstream technologies. Many of these firms, typically not direct contributors to stan-

their respective distances to the IEEE.

[29]Notable post-2015 IEEE standards include IEEE 1906 (Nanoscale Communication), IEEE 1914 (Packet-based Fronthaul Transport Networks), and IEEE 2301 (Cloud Portability and Interoperability Profiles).

Figure 4
Class-Weighted Patents Filed per Firm-Standard Pair Before and After the IEEE Policy Revision



This figure shows the average number of patents filed per firm-standard pair over time across the four quartiles, normalized by the average number of patents filed by each firm before the policy revision. The dashed grey lines indicate the years 2013 and 2015, which mark the policy announcement and endorsement, respectively. The black line represents firms in the first quartile (control group), those that are technologically closest to the IEEE standards. The dark grey point-dashed line represents firms in the second quartile, the grey dashed line represents firms in the third quartile, and the light grey line represents firms in the fourth quartile.

dard setting organizations, may have viewed SEP licensing costs as a barrier to adopting these standards.

In contrast, firms in the same industries as SEP holders often face similar opportunities to declare standard-related technologies. Declaring a patent as essential is a strategic choice shaped by firm-specific characteristics and SSOs' policies. While some top R&D performers might limit involvement in standardization to prevent knowledge spillovers (Blind, 2006), others might have avoided SEP declarations due to the restrictive pre-2015 patent policies. Structural barriers also play a role. Standardization involves fixed costs, which can be prohibitive for small and medium-sized firms (SMEs). Despite these challenges, SMEs are often key users of standards, especially in downstream applications.

The policy revision was effective in increasing the standard-related innovative effort of firms further from the standards' space. Firms in the fourth quartile increased their patenting activity by around 100% on average compared to the pre-period, compared to a decline of almost 3% among firms in the first quartile. To exploit this variation, I use a continuous difference-in-differences approach (Acemoglu and Finkelstein, 2008; Farronato et al., 2020; Callaway et al., 2024), identifying the continuous treatment effect under a generalized parallel trends assumption (Callaway et al., 2024).

Figure 4 shows trends in class-weighted patent filings across quartiles, normalized by each firm's pre-period average.[30] I normalize by pre-period patenting behavior and adjust for firms' fixed effects to account for unobserved heterogeneity. Given the difference in pretreatment means across the quartiles, as shown in Table 9 in the Appendix, it may be unreasonable to expect that time-varying factors have equal level effects on the outcome. An alternative identifying assumption is to impose that, in the absence of the treatment, the average change in the mean outcome for treated groups would have been the same as the average percentage change in the mean outcome for the control group (See Wooldridge (2023)). However, given the similar trends followed by firms in the second and third quartiles and because interpreting differences in these parameters across different values of the treatment can be particularly challenging due to treatment effect heterogeneity (Callaway et al., 2024), I follow the methodology presented in Farronato et al. (2020). Specifically, I compare outcomes in the years before and after the policy revision across firms groups, using firms in the first quartile as the control group.[31]

For a given standard, firms that are technologically closer have strong differences from firms that are further away. Table 9 along with Figures 8-11 in the Appendix provide comparisons of some observable demographic characteristics of firms across quartiles and time. Given such strong differences, I might be concern that the parallel trends assumption does not hold for those groups. However, as noted by Farronato et al. (2020) and Wooldridge (2023), my difference-in-differences strategy does not require identical levels of the pre-treatment outcomes, but rather parallel trends, appropriately defined as reported in Figure 4 above.

[30] I normalize the number of standard patents filed by dividing by the average number of patents filed in the standard-related technology classes by each firm in the pre-period.

[31] As a robustness check, I performed the analysis using a multiple continuous difference-in-differences approach (Acemoglu and Finkelstein, 2008). The results are consistent with the main specification and presented in Appendix. My current approach does not lead to any loss in statistical power and efficiency compared to the standard model.

To quantify the policy's impact on patenting behavior, I estimate the following model:

$$\begin{aligned}\mathbb{E}\left[P_{ist}|X_{it}, X_{st}\right] =& exp(\delta_1(dPOST_{t>2014} * dGroup_{i,EEE}) + \lambda_1 SALE_{i,t-1} + \lambda_2 X'_{s,t-1} \\ &+ \tau_{age} + \varphi_i + \varphi_s)\end{aligned} \tag{6}$$

where P_{ist} is the weighted number of patents filed by firm i in the technology classes related to standard s in year t. The post-policy dummy $dPOST_{t>2014}$ captures the effect of the policy revision, while $dGroup_{i,EEE}$ identifies firms by their quartile. Specifically, a firm is included in the treatment group if it is in a quartile that is technologically further from the standard's space compared to firms in the first quartile. The coefficient of interest, δ_1 should be interpreted as changes in the outcome variable relative to the control group, and relative to the years before the policy revision was endorsed, as a percentage of the baseline mean.[32] Control variables include firm size ($SALE_{i,t-1}$), observed standard characteristics (X'_{st}), standard-age fixed effects (τ_{age}), and firm and standard fixed effects (φ_i and φ_s). To account for immediate feedback of the dependent variable to the covariates, I lag all time-varying controls by one year.

I account for economies of scale in patent generation and the influence of firm size on patent portfolios (Blind and Thumm, 2004; Blind and Mangelsdorf, 2008) by including $SALE_{i,t-1}$. Moreover, firms in certain industries are more likely to patent in specific technology classes due to the relative importance of these classes to their industry. Additionally, a firm's location may affect its patenting activity, driven by variations in patent systems or accessibility in different countries. However, industry and country effects are controlled for through φ_i and φ_s in the econometric specification.

To account for the influence of standards-specific characteristics on patenting activities, I include several variables. The importance of a standard to the ICT industry may drive a firm's innovation decisions. To capture this, I include the total number of documents referencing a common standard in the $X'_{s,t\text{-}1}$ vector. Additionally, I incorporate the total number of firms declaring essential patents as a measure of a standard's attractiveness. Prior theoretical work on standards and essential patents (Baron et al., 2014; Bekkers et al., 2017; Spulber, 2019) shows that the number of SEP holders affects the potential

[32] To avoid bias from log transformations, I use a Poisson regression, following Chen and Roth (2024).

licensing revenues a firm can earn from its patents. Lastly, I include fixed effects for standard age—defined by the number of years since the first publication of the standard document—to control for the natural decline in patent filings as a standard matures.[33]

Other regressors in Equation 6 address potential shocks and unobserved heterogeneity. I include firm- and standard-specific dummies to control for unobservable differences across standards and firms. For instance, pure innovators may focus their innovative efforts on select standards, while vertically integrated firms might contribute to a wider range of standards. Additionally, firms might allocate innovation resources strategically to standards in which they are key players in developing related technologies, conditional on firm-specific characteristics that are unobserved by the researcher. Lastly, because multiple technology classes can correspond to various standards, I control for unobserved factors affecting the firm's decision to invest in a particular standard versus others with similar technology domains. Unobserved and time-invariant effects across firms and standards are identified by firms' participation in multiple standards.

To account for firms potentially adjusting their behavior in anticipation of the policy change, I extend the model to estimate separate coefficients for the anticipation period (2014) and the post-policy periods (2015-2017). This specification allows me to isolate any pre-policy adjustments from the actual effects of the policy revision.[34]

An econometric challenge of all specifications is the overlap in technology classes across standards. Sharing a large share of technology classes implies that firm-standard pairs are not independently of each other. It is possible that firms forum-shopping between standards sharing common technology classes and that the policy revision may cause firms to substitute away from one standard to another, leading to an upward bias of the estimates. To solve this problem, I account for the overall distance between the firm and the standard setting organization, IEEE, clustering firms in the different groups based

[33]Figure 7 in the Appendix illustrates the distribution of patents filed before and after a standard's publication. As expected, patent filings decrease over time as a standard ages, justifying the inclusion of standard age in controlling for this decline.

[34]I estimate a more flexible version of the baseline specification of the form:

$$\begin{aligned}\mathbb{E}\left[P_{ist}|X_{it}, X_{st}\right] =& exp(\delta_{t_a}(dT_{t_a=2014} * dGroup_{i,EEE}) + \sum_{t_p=2015}^{2017} \delta_{t_p}(dT_{t_p} * dGroup_{i,EEE}) \\ &+ \lambda_1 SALE_{i,t-1} + \lambda_2 X'_{s,t-1} + \tau_{age} + \varphi_i + \varphi_s)\end{aligned} \tag{7}$$

Table 3
Effect of IEEE policy change on firm-standard patenting

		Standard-related Patents		Standard-related Patents		Standard-related Patents	
		(1)	(2)	(3)	(4)	(5)	(6)
Anticipation-Period							
	2nd Quartile		0.397***		0.398***		0.397***
			(0.042)		(0.041)		(0.042)
	3rd Quartile		0.313***		0.314***		0.313***
			(0.061)		(0.061)		(0.061)
	4th Quartile		0.378***		0.378***		0.378***
			(0.058)		(0.058)		(0.058)
Post-Period							
	2nd Quartile	0.168***	0.270***	0.168***	0.270***	0.169***	0.271***
		(0.055)	(0.062)	(0.055)	(0.061)	(0.055)	(0.062)
	3rd Quartile	0.169***	0.271***	0.168***	0.272***	0.170***	0.271***
		(0.064)	(0.078)	(0.064)	(0.078)	(0.064)	(0.078)
	4th Quartile	0.288***	0.417***	0.288***	0.417***	0.288***	0.417***
		(0.082)	(0.085)	(0.081)	(0.084)	(0.082)	(0.085)
Covariates		Yes	Yes	Yes	Yes	Yes	Yes
Standard Age FE		Yes	Yes	No	No	Yes	Yes
Year FE		No	No	Yes	Yes	No	No
Polynomial FE		No	No	No	No	Yes	Yes
Standard FE		Yes	Yes	Yes	Yes	No	No
Firm FE		Yes	Yes	Yes	Yes	Yes	Yes

Note: The coefficients reported for each quartile are estimated separately comparing the outcomes of the quartile of interest with the baseline group, represented by firms in the first quartile. The dependent variable is the weighted number of patents per firm-standard. The method of estimation is maximum likelihood for the Poisson model. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.For more granular difference-in-differences coefficients, see Appendix Tables 10, 11, and 12.

on this overall measure. Besides, I might be concern about an endogeneity problem that arises since firms decide in which technology classes to invest to. Because this decision was taken years before the sample of interest it is not of any concern.[35] Lastly, standard errors are clustered by firm-standard pair to address serial correlation.

6 Results

This section presents the empirical findings on how firms' standard-related patenting behavior responds to the IEEE's more restrictive licensing requirements. The results are validated through robustness checks. Based on the theoretical framework outlined in Section 3, I expect that firms in the fourth quartile—those furthest from the standards' technology space—will experience the largest impact, with the effect diminishing across the third and second quartiles.

Table 3 reports the econometric results, showing a statistically and economically sig-

[35] As a robustness check, I clustered firms based on their pre-2012 patent portfolios. The results, reported in Table 6, are consistent with the main specification.

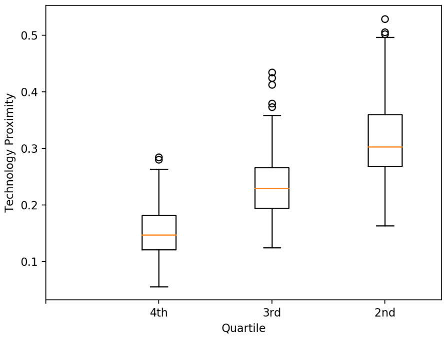
nificant increase in standard-related patenting following the IEEE policy revision. Each row corresponds to a different treatment group.

In Columns 1 the results are based on the model specified in Equation 6 , accounting for various fixed effects. The baseline period (2010-2014) precedes the 2015 policy revision, with the post-period beginning after this change. Consistent with theoretical expectations, standard-related patenting increased most significantly for firms technologically further. Firms in the fourth quartile increased patenting by 33.4%, followed by increases of 18.4% in the third quartile, and 18.2% in the second quartile. The coefficient estimates for δ_1 are consistent across all specifications.

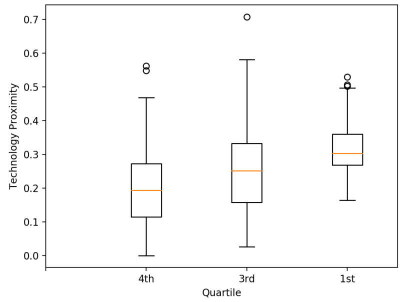
As Figure 4 shows, firms began to increase their standard-related patent filings two years before the policy change, with a sharp rise between 2014 and 2015. Columns 2 account for anticipation effects, confirming that the policy revision's impact became more pronounced post-2015.

Furthermore, the results indicate a non-monotonic pattern across the quartiles. While firms in the second quartile exhibit a smaller increase in patenting than those in the third quartile, this difference is not statistically significant. Figure 5 highlights technological proximity across firms in different quartiles, suggesting that second-quartile firms are, on average, closer in technological space to fourth-quartile firms than to third-quartile firms. This proximity likely explains the slightly smaller patenting response for the second quartile, as firms in both the second and fourth quartiles may have been filing patents in technology classes indirectly influenced by IEEE standards, even if not directly related to the standards.

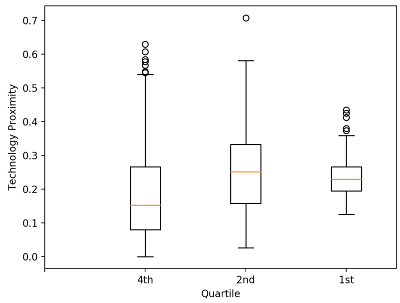
Figure 5
Technology Proximity across Quartiles



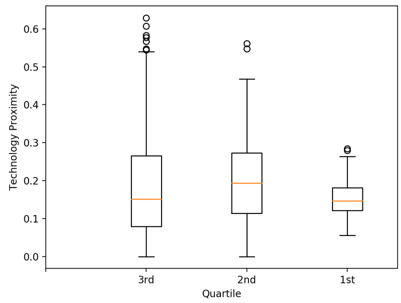
(a) 1st Quartile



(b) 2nd Quartile



(c) 3rd Quartile



(d) 4th Quartile

These figures show the box plots illustrating the technology closeness between firms in the first (top-left), second (top-right), third (bottom-left), and fourth (bottom-right) quartiles compared to firms in the other groups. The technology proximities are computed as the cosine similarities between a firm and all other firms in the remaining groups.

Table 4 further investigates this pattern by examining the effect of the policy change on non-standard-related patents. The results show positive and statistically significant effects for firms in the second and fourth quartiles, with no significant effect for third-quartile firms. This suggests potential spillover effects from standard-related to non-standard-related technologies, though the overlap in technology classes between different ICT standards might confound these results, potentially amplifying the observed effect of the IEEE policy change.

To expand my analysis, I examine the policy's impact on firms declaring standard-essential patents, as these firms are directly affected by the stricter licensing commitments. Because SEP holders represent a small subset of firms with unique characteristics that influence their ability to develop technologies essential to standards, I focus on two groups:

Table 4
Effect of IEEE policy change on Non-standard-related Patents

		Non-std Patents	
		(1)	(2)
Anticipation-Period			
	2nd Quartile		0.246***
			(0.039)
	3rd Quartile		0.084*
			(0.047)
	4th Quartile		0.335***
			(0.057)
Post-Period			
	2nd Quartile	0.078	0.139**
		(0.051)	(0.056)
	3rd Quartile	0.056	0.076
		(0.062)	(0.071)
	4th Quartile	0.409***	0.504***
		(0.065)	(0.074)
Covariates		Yes	Yes
Standard Age FE		Yes	Yes
Standard FE		Yes	Yes
Firm FE		Yes	Yes

Note: The dependent variable is the number of non-standard-related patents per firm-standard. The method of estimation is maximum likelihood for the Poisson model. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

first and second quartiles, both of which include SEP-declaring firms. The objective is to create a balanced sample of treatment firms (those declaring SEPs) and control firms (those that have never declared patents as essential to the IEEE but have comparable characteristics to SEP holders). This allows for a robust comparison in a difference-in-differences analysis in line with my identification strategy, where the control group consists of firms that are closest from the standards' technology space and have never declared any patent as essential.

Table 5 presents the results, which reveal a nuanced relationship between the policy revision and standard-related patenting. I find no statistically significant effect on SEP holders who are technologically closest to the standards (1st Quartile SEP holders), while those in the second quartile experience a significant negative effect post-policy revision. This suggests that firms further from the core technology of the standard are more negatively impacted by the policy revision, possibly due to their lower ability to leverage existing standard-related knowledge for innovation.

Table 5
Effect of IEEE policy change on SEPs holders

		Standard-related Patents	
		(1)	(2)
Anticipation-Period			
	1st Quartile - SEP Holders		-0.001
			(0.059)
	2nd Quartile - Non SEP Holders		0.391^{***}
			(0.067)
	2nd Quartile - SEP Holders		0.754^{***}
			(0.132)
Post-Period			
	1st Quartile - SEP Holders	0.073	0.073
		(0.073)	(0.082)
	2nd Quartile - Non SEP Holders	0.269^{***}	0.367^{***}
		(0.071)	(0.084)
	2nd Quartile - SEP Holders	-0.427^{**}	-0.210
		(0.178)	(0.194)

Note: The dependent variable is the weighted number of patents per firm-standard. The method of estimation is maximum likelihood for the Poisson model. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Conversely, non-SEP holders in the second quartile exhibit positive and significant effects in both the anticipation and post-policy periods. This suggests that these firms, despite not declaring SEPs previously, may view the policy change as an opportunity to innovate and eventually declare essential patents in future revisions of the standard. Firms that failed to develop essential technologies in earlier standard versions may now see the policy revision as a chance to capitalize on existing technologies. This is also true for the control group that could be potentially experience an increase in patenting in the post-period. Therefore, assuming that the control and the treatment group including SEP holders are affected by the policy revision in divergent directions, my estimates define the upper bound of the negative impact of the IEEE policy revision on firms' incentives to innovate in standard-related technologies.

Despite these findings, the econometric analysis has some limitations. The more restrictive patent policies may alter firms' patenting behavior in standard-related technology classes without necessarily reflecting increased innovation. Firms could be incentivized to focus on patenting more developed inventions rather than investing in entirely new technologies essential to a standard. Additionally, there is mixed evidence on how SEP royalties affect innovation. Some literature suggests that allowing SEP holders to capture more value from standardization encourages innovation (Sidak, 2013, 2016; Epstein and Noroozi, 2017), while others argue that stronger patent rights may reduce innovation, particularly in sequential and complementary innovation settings (Bessen and Maskin, 2009; Galasso and Schankerman, 2015).

Weaker interpretations of FRAND commitments may also lead to strategic over-patenting of marginal ideas (Kang and Bekkers, 2015; Righi and Simcoe, 2020), potentially reducing social welfare and diminishing the benefits of innovation (Shapiro, 2000; Geradin and Rato, 2007). Thus, while the increased patenting observed among treatment firms may reflect a response to the policy change, it could also represent strategic behavior rather than genuine innovation.

Nevertheless, the limitations to measure the standard-related invention through patenting and relying on IPC classes are likely to increase the variance of the error terms, leading to less efficient estimates of the coefficient of interest.

6.1 Robustness

Several other policy changes related to the licensing of standard-essential patents occurred around the same time as the IEEE's revision of its patent policy. These include the DOJ policy on SEP licensing[36], *InterDigital vs. Nokia* in the ICT Court [37], and the *Huawei vs. ZTE* in the Court of Justice of the European Union.[38] Given the timing of these developments, the effects of the IEEE's revised IPR policy could be confounded by these other changes.

Each of these rulings and policy shifts addressed the ability of SEP holders to seek injunctions, as well as the burden of proof in patent hold-up and reverse hold-up claims.

[36]In 2013, the USPTO and DOJ jointly issued a policy statement on remedies for the infringement of SEPs subject to voluntary FRAND commitments. The statement noted that while, in some cases, exclusionary remedies for infringement of SEPs may conflict with the public interest, such remedies may be appropriate when the potential licensee refuses to negotiate FRAND terms. See *Policy Statement on Remedies for Standards-Essential Patents Subject to Voluntary F/RAND Commitments 1–10 (Jan. 8, 2013)*, available at https://www.justice.gov/sites/default/files/atr/legacy/2014/09/18/290994.pdf.

[37]In 2015, the ICT court, in the case of *InterDigital vs. Nokia*, found no evidence of patent hold-up by InterDigital but identified reverse hold-up by Nokia. The court issued an exclusion order favoring the SEP holder and did not require the SEP holder to prove the standard implementer's unwillingness to negotiate FRAND licensing.

[38]In *Huawei vs. ZTE*, the European Court of Justice ruled that a SEP holder who committed to license patents on FRAND terms could violate competition rules (Article 102 TFEU) by seeking an injunction against a licensee under certain conditions. The ruling also outlined steps for negotiating SEP licensing agreements.

Table 6
Effect of IEEE policy change - Robustness checks I

		Bluetooth	Standard-related Patents (w0)	Tech Distance 2012
		(1)	(2)	(3)
Post-Period				
	2nd Quartile	0.130	0.167***	0.220***
		(0.119)	(0.053)	(0.055)
	3rd Quartile	-0.157	0.160***	0.226***
		(0.116)	(0.061)	(0.064)
	4th Quartile	-0.136	0.283***	0.346***
		(0.084)	(0.079)	(0.080)
Covariates		Yes	Yes	Yes
Standard Age FE		Yes	Yes	Yes
Standard FE		Yes	Yes	Yes
Firm FE		Yes	Yes	Yes

Note: The dependent variable is the weighted number of patents per firm-standard in the first and third columns. The first column reports the results for Bluetooth standards. In the second column, the dependent variable is weighted to account for zeros in the IPC classes related to the standard. In the third column, firms are clustered based on their patent portfolios from 2000 to 2012. The method of estimation is maximum likelihood for the Poisson model. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

As these changes targeted FRAND licensing for SEPs, they could potentially affect the interpretation of my results. For instance, the increase in standard-related patenting could partially be attributed to the *Huawei vs. ZTE* ruling, which was less favorable to SEP holders.

To assess whether other policy forces have influenced my findings, I conducted a difference-in-differences analysis using patents related to Bluetooth standards. Unlike other IEEE standards, Bluetooth working groups are subject to additional royalty-free licensing requirements. If other policies were driving the increase in standard-related patents, I would expect to observe similar effects for Bluetooth firms after the policy revision. However, if the IEEE's 2015 policy revision, establishing a FRAND royalty higher than a royalty-free commitment, was the main driver, there should be no significant effect on Bluetooth patents in the post-period. The results are presented in Column 1 of Table 6 and show that the coefficient for Bluetooth patents is not statistically significant, suggesting that other policy changes are unlikely to have influenced my findings.

Further robustness checks were conducted using two additional specifications of the baseline model. In Column 2 of Table 6, I present results for standard-related patents weighted by IPC classes, accounting for zeros in the standards' patent portfolios. In Column 3, I constructed the technology distance measure using firms' patent portfolios from before 2012 and re-clustered firms into quartiles based on this measure. Both specifications yield results consistent with the baseline, with no statistically significant differences. Additional robustness checks are provided in the Appendix.[39]

7 Conclusion

Standard setting organizations have revised their patent policies over the years to curb strategic behaviors by SEP holders and to focus more on the needs of users and implementers of standard technologies. Understanding how these stricter patent policies affect firms' innovation contributions in standards development is crucial. This paper adds to the existing literature by empirically examining the impact of the IEEE's 2015 patent policy revision on firms' upstream and downstream patenting activity in standard-related technologies.

In summary, the results of my analysis highlight the nuanced impact of the IEEE's 2015 policy revision on firms' standard-related innovation activities. The econometric analysis reveals a statistically significant increase in standard-related patenting across firms, with the largest effect observed among those initially positioned furthest from the standards' technological space (fourth quartile). This finding aligns with the theoretical expectation that the more restrictive licensing requirements would most impact firms that have greater distance from standard-related technologies. Importantly, the policy's effects do not follow a strictly linear pattern across technology quartiles, as firms in the second quartile—despite being closer to standards than third-quartile firms—also exhibit substantial patenting activity, likely due to their proximity to firms in other technology spaces. These findings are further supported by the examination of non-standard-related patents, which reveal potential spillover effects, particularly among firms in the second and fourth quartiles, suggesting that the policy may also influence patenting behaviors in adjacent technology classes.

The analysis of SEP-declaring firms further refines these findings. While firms with

[39]See Tables 13 and 14 in the Appendix for additional robustness checks. Table 13 presents the results of the multiple regression model following Acemoglu and Finkelstein (2008), while Table 14 provides the estimates from the event study analysis, with the baseline period set to 2010.

SEP holdings in closer technological proximity to standards (first quartile) show less responsiveness to the policy change, those positioned further away experience a negative impact on their innovation activities. In contrast, non-SEP holders—especially those in the second quartile—appear to benefit from the policy shift, suggesting that it opens up new opportunities for firms previously less involved in standards-related innovation.

In conclusion, the findings highlight how stricter licensing policies, such as the IEEE's 2015 revision, can significantly reshape the patenting landscape, creating both incentives and challenges for different types of firms. While some firms are encouraged to innovate and enter the standard-related technology space, those already involved may face diminishing returns on innovation. These results underscore the differentiated effects of policy changes in standard-setting environments across the technological spectrum

However, several areas remain for future research. First, other SSOs have also revised their licensing requirements, not just IEEE. To gain a broader understanding of the relationship between standard developers and patent policy changes, future work should examine multiple policy shifts over time. Additionally, firms' incentives to invest in standards vary based on their types, such as pure R&D innovators versus vertically integrated firms. Because multiple SSOs share overlapping technology classes, future research should explore how firms navigate these overlapping standards, providing deeper insights into their strategic behavior, investment decisions, and patenting strategies, while informing policies to promote competition within SSO patent frameworks.

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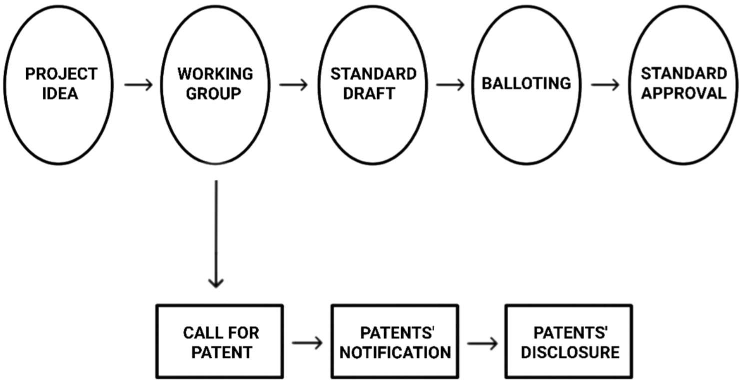
Figure 6
The IEEE Standardization Process



Source: *Standards Development at IEEE SA*, https://standards.ieee.org/beyond-standards/how-standards-are-made/

8 Appendix

A Additional Institutional Information

A.1 IEEE Standards development

The process of developing standards at IEEE SA can be described in five key steps, as illustrated in Figure 6.[40] Before the formal process begins, a technological need is identified, often driven by market demands. This need leads to the development of a new feature, typically resulting in the creation of a new standard. Once the need is recognized, it is transformed into a project proposal, and a formal request is submitted by a standards committee to the standard setting organization for approval. IEEE SA must then assess and approve the request, based on necessity and the availability of volunteers to support its development.[41] If approved, the committee forms a working group consisting of individuals and entities interested in the development of the standard.[42]

In the second step, firms, agencies, and individuals are invited to join the working group. The group's primary responsibility is to transform the project idea into a standard. The third step involves proposing technical solutions to the identified problem. Once

[40]This paragraph draws on *Standards Development at IEEE SA*, available at https://standards.ieee.org/beyond-standards/how-standards-are-made/.

[41]The IEEE Standards Board assesses whether the request is essential and if sufficient volunteers are willing to contribute to its development.

[42]While IEEE SA facilitates the standards development process, the standard committee is responsible for organizing the working group and related activities.

these solutions are compiled into a draft standard, the process moves to the fourth step, the balloting process. At this stage, the standard committee forms a balloting group of stakeholders who can vote on the proposed standard. While any interested entity can provide feedback, only votes from the balloting group count. A standard is approved if 75% of ballots are returned and if 75% of these cast a positive vote.[43] The final step is the approval process, where the working group submits the draft to the organization's Review Committee and subsequently to the IEEE Standards Board for final approval. Once accepted, the standard is published and made publicly available.

Regarding the declaration of standard-essential patents, there is no fixed timeline in relation to the standardization process. Firms can declare their SEPs at any point after the working group is established. During working group meetings, the chair issues a "call for patents," reminding participants that any technology suggested for inclusion in the standard must be disclosed if covered by patents. Firms holding essential patents are required to submit a Letter of Assurance, outlining their commitment to licensing the patents on fair, reasonable, and non-discriminatory (FRAND) terms. The letter must be submitted "as soon as reasonably feasible" and no later than the approval of the standard. Although IEEE publishes a list of accepted Letters of Assurance, it does not evaluate or validate the essentiality, infringement, or validity of the claimed patents.[44]

A.2 Procedure of IEEE policy revision

The process for revising the IEEE patent policy formally began on March 13, 2014, when the Patent Committee (PatCom) appointed an Ad-Hoc Committee to consider and recommend updates to the existing policy. The motivation behind the policy revision stemmed from growing disagreements between SEP owners and standards implementers, particularly concerning the interpretation of "reasonable rates" for SEP licenses. As noted, "the last several years have shown wide divergence between the owners of standards-essential patents (SEPs) and the implementers of standards, particularly over the meaning of 'rea-

[43] The balloting process typically takes 30 to 60 days.

[44] This paragraph draws on *STANDARDS BOARD BYLAWS – CLAUSE 6 – 8*, available at https://standards.ieee.org/about/policies/bylaws/sect6-7/, and *Understanding Patent Issues During IEEE Standards Development*, available at https://standards.ieee.org/wp-content/uploads/import/documents/other/patents.pdf.

sonable rates' for potential SEP licenses." [45]. This concern was echoed by key regulatory authorities, including the U.S. Department of Justice (DoJ), the Federal Trade Commission (FTC), and the European Commission, all of which emphasized the need for greater policy clarity.[46]

After a 15-month period of review, including the collection of over 600 public comments, the Ad-Hoc Committee approved a revised version of the fourth public draft in June 2014, which was subsequently forwarded to the Standards Board for consideration. In August 2014, the Standards Board voted to approve PatCom's proposed policy revision and recommended that the IEEE Board of Directors also approve the changes.

On February 2015, the U.S. DoJ issued a Business Review Letter endorsing the policy revision. The DoJ concluded that the revision had "the potential to benefit competition and consumers by facilitating licensing negotiations, mitigating hold-up and royalty stacking, and promoting competition among technologies for inclusion in standards." (Hesse, 2015). Shortly after, on February 8, 2015, the IEEE Board of Directors formally approved the policy revisions, with the new patent policy coming into effect in March 2015.

B Full First Order Conditions

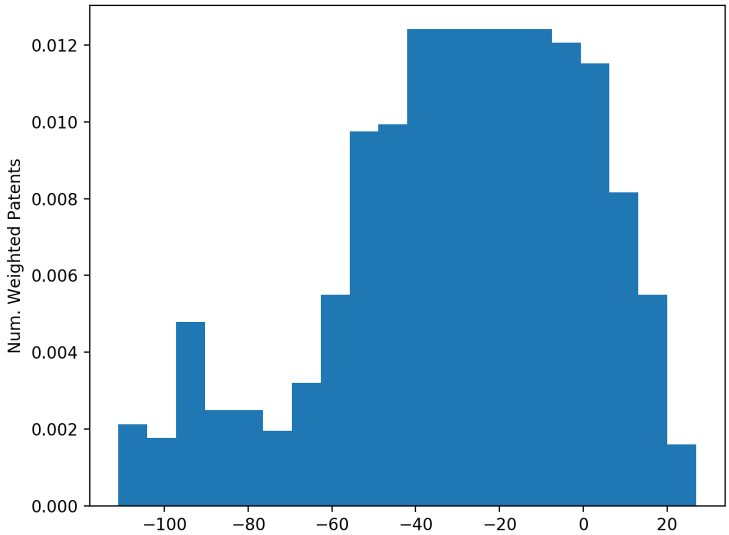
$$\begin{cases} \frac{\partial \pi_i}{\partial x_i} = (1-\epsilon)\left[r\frac{x_i*\gamma_i}{\gamma*x} + (1-r)\frac{y_i}{y}\right] + (1-\epsilon)\frac{r(x+\beta y)\gamma_i}{x*\gamma}(1-\frac{x_i}{x}) + \epsilon - c_i(1+x_i) \\ \frac{\partial \pi_i}{\partial y_i} = (1-\epsilon)\beta\left[r\frac{x_i*\gamma_i}{\gamma*x} + (1-r)\frac{y_i}{y}\right] + (1-\epsilon)\frac{(1-r)(x+\beta y)}{y}(1-\frac{y_i}{y}) + \epsilon*\beta - m_i(1+y_i) \end{cases} . \tag{8}$$

[45] *IEEE Request for Business Review Letter*, The United States Department of Justice, September 30, 2014, p. 4, available at .

[46] See Hesse (2012), available at , Ramirez (2014), available at , and Almunia (2012).

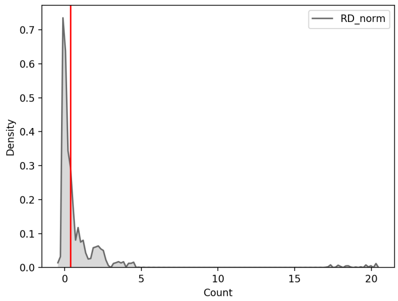
C Additional Figures and Tables

Figure 7
Weighted Number of Patents per Standard over the standard's lifetime

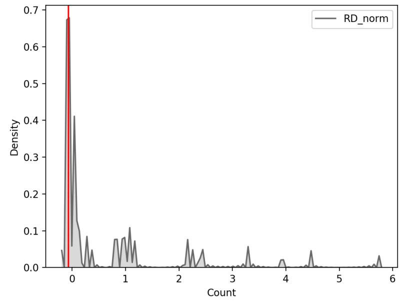


The figure shows the total number of weighted patents filed per standard in the years preceding and following the standard's publication.

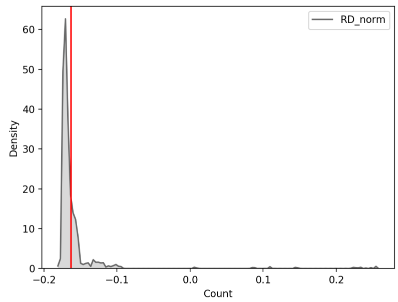
Figure 8
Heterogeneity Across Firms - R&D Expenditures



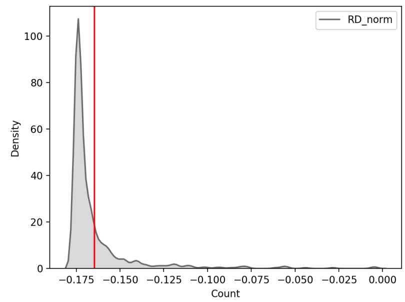
(a) 1st Quartile



(b) 2nd Quartile



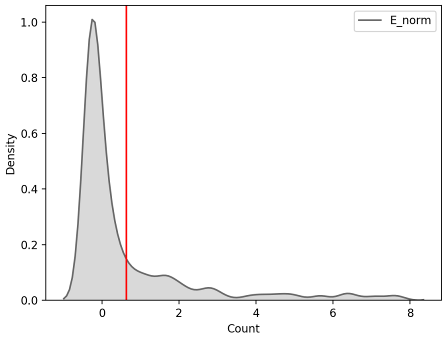
(c) 3rd Quartile



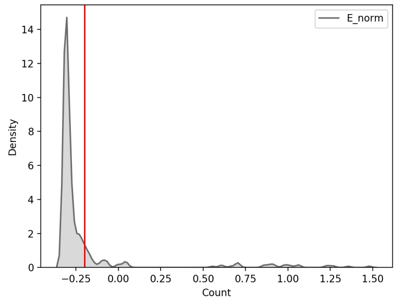
(d) 4th Quartile

These figures plot the distribution of R&D expenditures across firms within the four groups. Each observation represents a firm, and R&D costs are normalized across all firms in all quartiles. The red line denotes the average expenditure within each group.

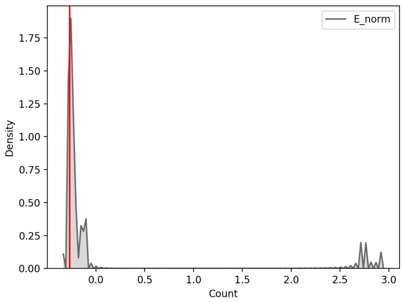
Figure 9
Heterogeneity Across Firms - Number of Employees



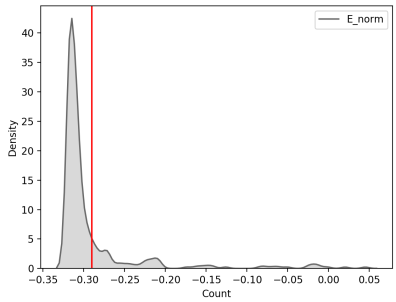
(a) 1st Quartile



(b) 2nd Quartile



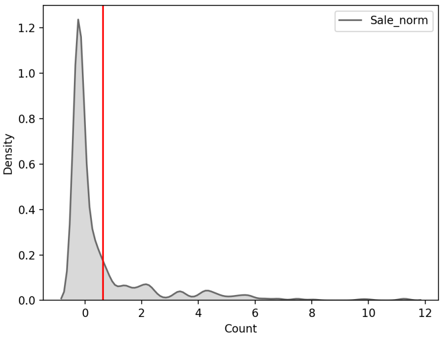
(c) 3rd Quartile



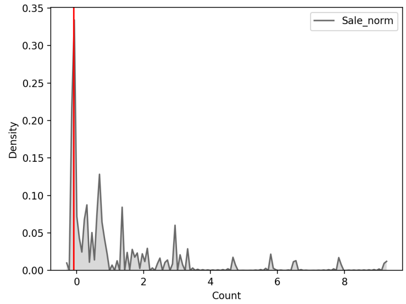
(d) 4th Quartile

These figures plot the distribution of the number of employees across firms in the four groups. Each observation represents a firm, and the number of employees is normalized across all firms in all quartiles. The red line denotes the average number of employees within each group.

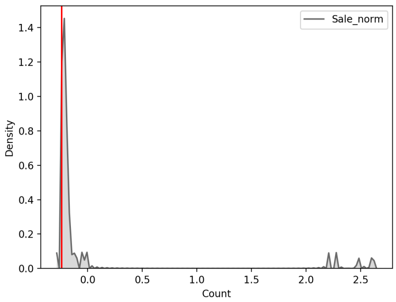
Figure 10
Heterogeneity Across Firms - Sales



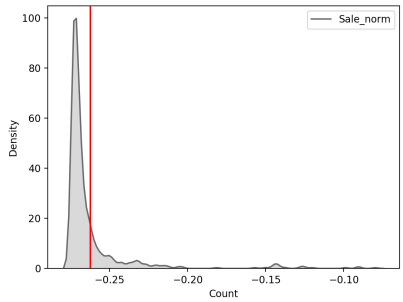
(a) 1st Quartile



(b) 2nd Quartile



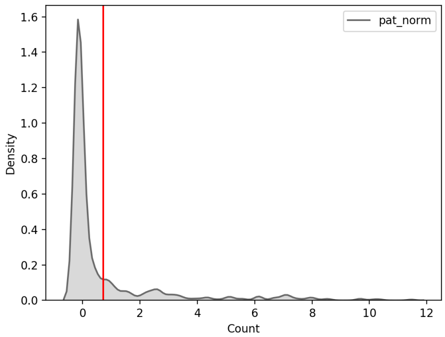
(c) 3rd Quartile



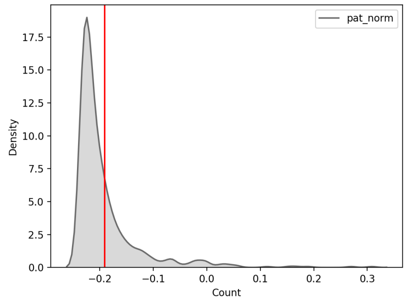
(d) 4th Quartile

These figures plot the distribution of sales across firms in the four groups. Each observation represents a firm, and sales are normalized across all firms in the quartiles. The red line denotes the average sales within each group.

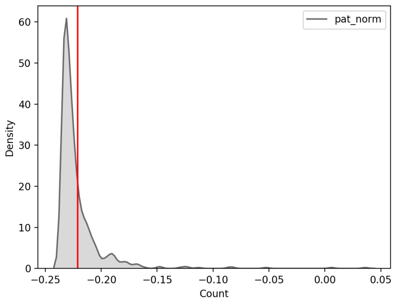
Figure 11
Heterogeneity Across Firms - Total Patenting



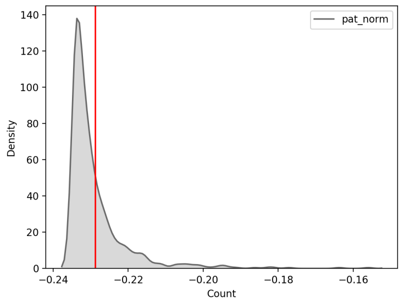
(a) 1st Quartile



(b) 2nd Quartile



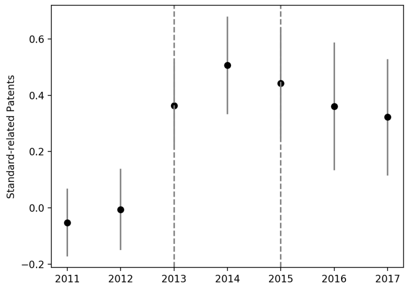
(c) 3rd Quartile



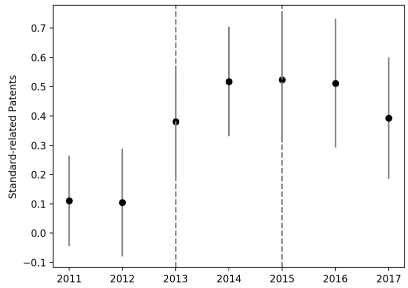
(d) 4th Quartile

These figures plot the distribution of patent counts across firms in the four groups. Each observation represents a firm, and patent counts are normalized across all firms in the quartiles. The red line denotes the average number of patents within each group.

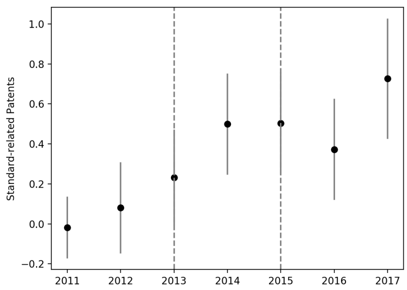
Figure 12
Estimates of the Effect of IEEE Policy Change



(a) 2nd Quartile



(b) 3rd Quartile



(c) 4th Quartile

The figures illustrate the results from regressions reported in Table 11 across three treatment groups: firms in the second, third, and fourth quartiles. Each observation corresponds to a firm-standard pair in a given year. The baseline period is set to 2010, with the control group comprising firms in the first quartile, which are technologically closer to the IEEE. The top-left figure shows the results for the second quartile, the top-right for the third quartile, and the bottom figure for the fourth quartile. The dashed light grey lines indicate the years 2013 and 2015, marking the announcement and endorsement of the policy revision by the organization, respectively. Vertical bars represent 95% confidence intervals.

Table 7
Top 10 Firms in First and Fourth Quartiles According to Their Technology Proximity

	Firm's Name	Technology Proximity
Top 10 Firms in the First Quartile		
	HANWANG TECH CO LTD	0.602
	PANASONIC CORPORATION	0.595
	SONY CORPORATION 7 0.591	
	TEXAS INSTRUMENTS INC	0.590
	LG ELECTRONICS	0.588
	SEIKO EPSON CORP	0.587
	NEC CORPORATION	0.586
	HON HAI PRECISION IND CO LTD	0.584
	IBM	0.583
	AT&T INC.	0.583
Top 10 Firms in the Fourth Quartile		
	ACEPLUX OPTOTECH INC	0.042
	INALWAYS CORP	0.072
	TIGERLOGIC CORP 4 0.072	
	CLEARFIELD INC	0.072
	TSEC CORP	0.072
	GRUBHUB INC	0.072
	MAXPOINT INTERACTIVE INC	0.072
	MINDBODY INC	0.072
	TAINERGY TECH CO LTD	0.083
	SHUTTERSTOCK INC	0.083

Note: This table presents the ten firms with the closest and furthest proximity to the standards' technological space.

Table 8
Distribution of Firms across Industries

	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
Machinery Manufacturing	5	2	4	1
Computer and Electronic Product Manufacturing	81	95	95	66
Electrical Equipment, Appliance, and Component Manufacturing	4	9	0	6
Transportation Equipment Manufacturing	2	2	0	0
Merchant Wholesalers, Durable Goods	1	1	0	0
Electronics and Appliance Stores	1	0	0	0
Publishing Industries (except Internet)	4	8	10	38
Telecommunications	10	5	9	2
Other Information Services	4	2	13	31
Lessors of Nonfinansial Intangible Assets (except Copyrighted Works)	2	1	1	2
Professional, Scientific, and Technical Services	6	4	4	13

Note: This table presents the distribution of firms across NAICS code industries and quartiles for the period 2010-2017.

Table 9
Firms' Accounting Characteristics and Patent Portfolio Composition per Quartile

	1st Quartile		2nd Quartile		3rd Quartile		4th Quartile	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Total number of firms	120		129		136		150	
Firms characteristics								
Average R&D expenditures per year (millions)	1,337.5	4,310.4	281.0	1,235.2	36.6	108.5	33.9	62.8
Average number of employees per year (thousands)	52.6	92.1	7.1	17.5	2.8	15.5	1.8	3.3
R&D/SALE (%)	1.06	18.5	0.19	0.82	0.19	0.82	0.18	0.27
Patent portfolio								
Average number of filed patents per firm per year	1,305.0	2,764.4	65.3	105.4	20.2	36.2	10.2	20.0
Average number of filed standard-related patents per firm per year	556.8	1,518.2	28.4	66.9	8.5	21.1	5.1	13.0
Total number of standard-related patents/total number of patents, average per firm (%)	0.37	0.29	0.40	0.33	0.43	0.35	0.53	0.38
IEEE Technology distance	0.46	0.08	0.29	0.03	0.22	0.02	0.14	0.03
Total number of firms holding SEPs	30		5		1		0	

Note: This table summarizes the characteristics of firms and their patent portfolios across quartiles for the period 2010-2017.

Table 10

Effect of IEEE policy change on firm-standard patenting - 2nd Quartile

	Standard-related Patents		Standard-related Patents		Standard-related Patents	
	(1)	(2)	(3)	(4)	(5)	(6)
Anticipation-Period		0.397^{***}		0.398^{***}		0.397^{***}
		(0.042)		(0.041)		(0.042)
$dPOST * dGroup_{i,EEE} = 2$	0.168^{***}	0.270^{***}	0.168^{***}	0.270^{***}	0.169^{***}	0.271^{***}
	(0.055)	(0.062)	(0.055)	(0.061)	(0.055)	(0.062)
Standard-firm technology distance	-1.323^{***}	-1.324^{***}	-1.323^{***}	-1.324^{***}	-1.323^{***}	-1.325^{***}
	(0.482)	(0.482)	(0.481)	(0.481)	(0.482)	(0.482)
Sales (log)	0.513^{***}	0.510^{***}	0.510^{***}	0.506^{***}	0.513^{***}	0.510^{***}
	(0.039)	(0.038)	(0.040)	(0.040)	(0.039)	(0.038)
N of SEP holders (log)	-0.028	-0.036	-0.045	-0.045	-0.028	-0.036
	(0.028)	(0.028)	(0.034)	(0.034)	(0.028)	(0.028)
Standard's documents (log)	0.100	0.045	0.144^{*}	0.145^{*}	0.100	0.045
	(0.098)	(0.105)	(0.081)	(0.081)	(0.100)	(0.105)
Standard Age FE	Yes	Yes	No	No	Yes	Yes
Year FE	No	No	Yes	Yes	No	No
Polynomial FE	No	No	No	No	Yes	Yes
Standard FE	Yes	Yes	Yes	Yes	No	No
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Num.Obs.	18,598	18,598	18,598	18,598	18,598	18,598
Wald chi2	427.90	531.86	316.31	423.29	1,595.48	1,837.44

Note: The dependent variable is the weighted number of patents per firm-standard. The method of estimation is maximum likelihood for the Poisson model. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 11

Effect of IEEE policy change on firm-standard patenting - 3nd Quartile

	Standard-related Patents		Standard-related Patents		Standard-related Patents	
	(1)	(2)	(3)	(4)	(5)	(6)
Anticipation-Period		0.313^{***}		0.314^{***}		0.313^{***}
		(0.061)		(0.061)		(0.061)
$dPOST * dGroup_{i,EEE} = 3$	0.169^{***}	0.271^{***}	0.168^{***}	0.272^{***}	0.170^{***}	0.271^{***}
	(0.064)	(0.078)	(0.064)	(0.078)	(0.064)	(0.078)
Standard-firm technology distance	-1.514^{**}	-1.515^{**}	-1.511^{**}	-1.511^{**}	-1.514^{**}	-1.515^{**}
	(0.600)	(0.590)	(0.589)	(0.589)	(0.590)	(0.600)
Sales (log)	0.522^{***}	0.521^{***}	0.519^{***}	0.518^{***}	0.522^{***}	0.521^{***}
	(0.040)	(0.040)	(0.041)	(0.041)	(0.040)	(0.040)
N of SEP holders (log)	-0.026	-0.036	-0.044	-0.044	-0.026	-0.036
	(0.029)	(0.029)	(0.035)	(0.035)	(0.029)	(0.029)
Standard's documents (log)	0.108	0.047	0.142^{*}	0.142^{*}	0.108	0.047
	(0.102)	(0.108)	(0.083)	(0.083)	(0.102)	(0.108)
Standard Age FE	Yes	Yes	No	No	Yes	Yes
Year FE	No	No	Yes	Yes	No	No
Polynomial FE	No	No	No	No	Yes	Yes
Standard FE	Yes	Yes	Yes	Yes	No	No
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Num.Obs.	18,436	18,436	18,436	18,436	18,436	18,436
Wald chi2	426.08	429.34	314.47	317.80	1,566.49	1,676.02

Note: The dependent variable is the weighted number of patents per firm-standard. The method of estimation is maximum likelihood for the Poisson model. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 12
Effect of IEEE policy change on firm-standard patenting - 4th Quartile

	Standard-related Patents		Standard-related Patents		Standard-related Patents	
	(1)	(2)	(3)	(4)	(5)	(6)
Anticipation-Period		0.378^{***}		0.378^{***}		0.378^{***}
		(0.058)		(0.058)		(0.058)
$dPOST * dGroup_{i,EEE} = 4$	0.288^{***}	0.417^{***}	0.288^{***}	0.417^{***}	0.288^{***}	0.417^{***}
	(0.082)	(0.085)	(0.081)	(0.084)	(0.082)	(0.085)
Standard-firm technology distance	-1.582^{***}	-1.583^{***}	-1.574^{***}	-1.574^{***}	-1.582^{***}	-1.583^{***}
	(0.574)	(0.574)	(0.573)	(0.573)	(0.574)	(0.574)
Sales (log)	0.523^{***}	0.522^{***}	0.520^{***}	0.519^{***}	0.523^{***}	0.523^{***}
	(0.040)	(0.040)	(0.041)	(0.041)	(0.040)	(0.040)
N of SEP holders (log)	-0.026	-0.035	-0.044	-0.044	-0.026	-0.035
	(0.029)	(0.029)	(0.036)	(0.036)	(0.029)	(0.029)
Standard's documents (log)	0.107	0.046	0.140^{*}	0.140^{*}	0.107	0.046
	(0.103)	(0.109)	(0.083)	(0.083)	(0.103)	()0.109
Standard Age FE	Yes	Yes	No	No	Yes	Yes
Year FE	No	No	Yes	Yes	No	No
Polynomial FE	No	No	No	No	Yes	Yes
Standard FE	Yes	Yes	Yes	Yes	No	No
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Num.Obs.	18,522	18,522	18,522	18,522	18,522	18,522
Wald chi2	443.40	517.23	342.60	413.50	1,589.85	1,770.87

Note: The dependent variable is the weighted number of patents per firm-standard. The method of estimation is maximum likelihood for the Poisson model. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 13
Effect of IEEE policy change - Robustness checks II

		Standard-related Patents	
		(1)	(2)
Anticipation-Period			
	2nd Quartile		0.396^{***}
			(0.042)
	3rd Quartile		0.315^{***}
			(0.061)
	4th Quartile		0.380^{***}
			(0.058)
Post-Period			
	2nd Quartile	0.167^{***}	0.269^{***}
		(0.055)	(0.062)
	3rd Quartile	0.172^{**}	0.273^{***}
		(0.064)	(0.078)
	4th Quartile	0.292^{***}	0.421^{***}
		(0.082)	(0.084)
Covariates		Yes	Yes
Standard Age FE		Yes	Yes
Standard FE		Yes	Yes
Firm FE		Yes	Yes

Note: The dependent variable is the weighted number of patents per firm-standard. The method of estimation is maximum likelihood for the Poisson model in the multiple regression, accounting for all groups in a single specification. The control group is the first quartile, and the baseline period is 2010-2014. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 14
Effect of IEEE policy change on firm-standard patenting - Event Study

		2nd Quartile	3rd Quartile	4th Quartile
Pre-Period				
	2011	-0.053	0.110	-0.018
		(0.060)	(0.078)	(0.077)
	2012	-0.006	0.104	0.080
		(0.073)	(0.093)	(0.115)
	2013	0.363***	0.381***	0.232*
		(0.077)	(0.096)	(0.120)
Anticipation-Period				
	2014	0.506***	0.517***	0.499***
		(0.087)	(0.094)	(0.127)
Post-Period				
	2015	0.442***	0.524***	0.503***
		(0.099)	(0.109)	(0.128)
	2016	0.361***	0.512***	0.372***
		(0.114)	(0.111)	(0.127)
	2017	0.322***	0.393***	0.726***
		(0.104)	(0.105)	(0.151)
Covariates		Yes	Yes	Yes
Standard Age FE		Yes	Yes	Yes
Standard FE		Yes	Yes	Yes
Firm FE		Yes	Yes	Yes

Note: The dependent variable is the weighted number of patents per firm-standard. The baseline period is 2010. Standard errors are presented in parentheses and allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.