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

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Abstract

In this paper, I empirically study the effect of IEEE's IPR policy change in 2015 on standard-related innovation. I construct a novel dataset of companies that have declared at least one patent as essential for an IEEE standard (the treatment group). I then collect a sample of firms active in the same industries and having similar characteristics but which have not declared a patent as essential to IEEE (the control group). Using an inverse probability weighting difference-in-differences approach, I provide causal evidence that the IEEE IPR policy change led to a 40.4% reduction in standard-related patenting among the firms affected by the change.

JEL Classification: O31, L15, O34, L44

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1 Introduction

Technology standards play a central role in the Information and Communication Technology (ICT) sector, where independently designed innovations are highly interconnected. Such a complex technological system requires that firms work together in order to guarantee the interoperability of technologies, products, and services. Standard Development Organizations (SDOs) have played an important role in this context, allowing the development of standards through the collaboration of different stakeholders. Since the standard-setting process often involves diverse interests, a critical role of SDOs is to regulate the licensing of standard essential patents (SEPs), i.e. intellectual property rights on the technologies necessary for the implementation of the standard (Bekkers et al., 2014). To achieve an efficient process of the licensing of essential patents, SDOs need to ensure a balance between promoting the adoption of the standard in the downstream market and incentivizing the developers of key technologies to join and contribute to standards development.

SDO licensing requirements have been a controversial topic that has attracted much discussion among academic scholars and legal practitioners. This paper follows a difference-in differences strategy to estimate how the SDO Intellectual Property Rights policy affects the innovative effort of firms in standards development. I exploit a large policy change that occurred in 2015 at the Institute of Electrical and Electronics Engineers Standards Association (IEEE SA), which arguably put pressure on the royalties that the holders of standard essential patents could charge, to assess the impact of a more restrictive (for SEP holders) IPR policy on standard-related innovation. This research contributes to the longstanding debate among policymakers, specialists, and SDOs on how technology standards and standard essential patents should be regulated.

The licensing rules for patents declared essential have been central to cooperative standards development. Most SDOs require their members to commit to license SEPs under fair, reasonable and non-discriminatory (FRAND) terms. The objective of a FRAND commitment is to balance the incentives of diverse firms involved in standards development and facilitate a wide diffusion of the standards. Specifically, a FRAND commitment seeks to ensure that technology contributors can earn an appropriate return on their innovation. On the other hand, it allows firms to access standards for a reasonable cost. FRAND clauses are designed to prevent the exploitation of locked-in positions and market power (Shapiro, 2000; Lemley and Shapiro, 2006; Farrell et al., 2007; Lerner and Tirole, 2015), which firms may gain from the inclusion of their technologies in technology standards, and avoid potential underinvestment of standards' implementers due to this uncertainty on SEP licensing costs (Swanson and Baumol, 2005).[1]

Starting in the early 2000s, policymakers and standard specialists began to raise the concern that the FRAND commitment was intended but was not enough to prevent patent hold-ups. In an attempt to mitigate the perceived risk, the IEEE SA announced an update of its Intellectual Property Rights (IPR) policy in February

[1] Repeated interaction in standard setting can alleviate the hold-up problem, as shown in Larouche and Schuett (2019). For a detailed discussion of patent hold-up problem in standardization, see also Lemley and Shapiro (2006).

2015. Two main changes lie at the center of the policy revision. First, firms declaring to hold essential patents are recommended to base their royalties on the Smallest Salable Patent Practicing (SSPP) unit and not on the value of the end product. It has been argued that a consequence of this recommendation is to cut down the maximum royalty a firm can ask for its essential patents (Layne-Farrar et al., 2014; Llobet and Padilla, 2016).[2] Second, SEP holders must agree to forgo their right to seek injunctions against licensees, except under limited circumstances. If the right for injunctions is absent for SEP holders, implementers face an incentive to infringe essential patents, as they know that at most, they would eventually have to pay a reasonable fee (Contreras and Gilbert, 2015). Therefore, the policy update harms the innovation incentive of firms that rely on the SEP royalties to monetize their standard-related innovation. Following the revised patent policy endorsed by IEEE, several firms started refusing to commit to licensing their SEPs under the new licensing rules (Gupta and Effraimidis, 2018).

To empirically estimate the effect of the policy change on firms' standard-related innovation, using data from the Searle Center Database, PATSTAT, and Compustat, I construct a novel dataset of companies that have declared at least one patent as essential for an IEEE standard (the treatment group), before the policy revision. I then collect a sample of firms active in the same industries with similar characteristics as treatment firms but without declaring any essential patents to IEEE (the control group). The treatment and the pool control group are unbalanced in their characteristics, such that some firm-specific and unique features can drive the selection into the treatment group. To control for the substantial heterogeneity across treatment and control firms, I rely on a two-stage estimation procedure. In the first stage, I estimate a logit-based propensity score equation, which assesses the probability of a firm declaring a patent as essential for a standard. Using the estimated probabilities for each firm-standard pair, I can compute the inverse probability weights to assign to each pooled control unit. I, therefore, construct a weighted sample of treatment and control firms. Using a difference-in-differences approach, I then estimate the effect of the policy change on the class-weighted patenting intensity of firms in the standard-related technology classes.

The results of the econometric analysis provide causal evidence that the IEEE IPR policy change led to a reduction in standard-related patenting among the firms affected by the change. Notably, due to a more restrictive patent policy, essential patent holders file 40.4% patents less in the standard-related technology classes. As it can be assumed that members and stakeholders learned about the aim of the board to change the IPR policy before the policy update was publicly released, I test for an anticipation effect of firms holding essential patents. Excluding the two years before the policy change amplifies the effect by decreasing the firms' innovation by 49.2% (21.9 patents).

[2] Furthermore, even though using SSPPU as a baseline in defining the royalty rate is only a recommendation, the fact that other alternative methods are not recommended in the updated policy increases the likelihood that SSPPU would be the only methodology followed in the negotiation of essential patent licensing fees. See Sidak (2014); Gautier and Petit (2019) for more details on the Smallest Salable Patent Practicing Unit.

There are several mechanisms that could explain the decline in standard-related patenting among SEP holders. Notably, firms could have reduced their R&D spending, or they could have started patenting less. To investigate how the patent policy change drove the decrease in standard-related patents, I rely on two other specifications of the baseline model, using the total R&D costs and the overall number of filed patents as the dependent variables, respectively. My results show a non-statistically significant effect of the policy revision on R&D expenditure and on the number of patents filed by treatment firms, suggesting that those two factors did not drive the decline in standard-related patents. In addition, firms declare patents as essential to multiple standards issued by several organizations, and technology standards in the ICT sector share multiple technology classes. Since the share of standard-related patents with respect to the total number of patents filed stays constant after 2014 and I observe no effect of the policy change on total patenting, my results suggest that firms are substituting away to other standards issued by other organizations.

Since firms with divergent interests join standardization, I further investigate the heterogeneity of the effect across firms. The extent to which more restrictive patent policies affect the firms' standard-related innovation depends on how the IPR policy affects the monetary incentive firms face when they decide on the amount of innovation to invest in a standard, which in turn may depend on firm size. For instance, vertically integrated firms, typically large companies, can benefit from their participation in standardization through downstream sales, taking the standard as inputs. On the other hand, pure innovators, usually small and medium size firms, rely on the licensing of the patents protecting the technologies included in the standard to benefit from their involvement. To account for the effects of the IEEE policy update on firms facing different incentives, I follow the changes-in-changes methodology proposed by Athey and Imbens (2006) and test the impact of a more restrictive patent policy on firms depending on their size. Vertically integrated firms typically have large patent portfolios, while firms with small and medium-sized patent portfolios are likely to represent pure R&D innovators. To corroborate my assumption, I develop a novel methodology, relying on the list of licensors and licensees of a subset of patent pools, which allows me to identify vertically integrated firms. I find a negative effect of the policy change for firms up to the 75th percentile, with a stronger effect for the mean ranks of the distribution. Conversely, I observe a positive effect for firms with a large patent portfolio (90th percentile). My analysis are consistent with the idea that the policy change positively affects large firms that benefit from the implementation of the standard. At the same time, it harms pure R&D firms, which are more reliant on intellectual property rights to appropriate a return on innovation.

As robustness checks, I run alternative specifications of the baseline model. First, since other policy changes occurred at the same time as IEEE revised its patent policy, which could confound the estimated impact, I use the firms declaring essential patents to standards developed by the Bluetooth working group as my treatment group in the baseline model. Second, I test for an effect on outcomes known not to be affected by the policy change, focusing on a time frame characterized by no policy change. I do not find a significant effect of the policy change with either specification.[3]

Several papers have studied the IEEE policy revision. However, empirical research provided mixed support for the effect of the policy change on standard-related innovation. IPlytics (2017, 2018)[4] undertook several empirical analyses of the IEEE policy revision and published a series of reports. Focusing on essential patents declared, declarations made, and new standards documents approved and published, they provide empirical evidence for a positive effect of the new patent policy on standards development. Their findings suggest that standardization activities have increased in all mentioned dimensions since the updated patent policy.[5] Gupta and Effraimidis (2018) study how the policy revision has affected several aspects of standards development focusing on the standards issued by the IEEE 802 LAN/MAN Working Groups. They first analyze the submission pattern of Letters of Assurance, documents through which SEP holders outline the declarations of essential patents and agree to comply with the licensing rules of the organization, and they emphasize how the new patent policy led to the submission of negative disclosure letters. They also find a delay in the approval of 802 standards, studying the changes in the comment resolution process following the policy revision.[6] Simcoe and Zhang (2021) find little evidence of a decline in SSO participation and standard-related innovation by SEP holders caused by the policy change. They corroborate their results on different measures of participation and innovation and on a variety of treatment and control groups. While they rely on the unweighted count of patents as an alternative measure of standard-related innovation, they test their econometric specification at the Cooperative Patent Classification main group-year level, associated with each patent declared essential to the IEEE 802.11 Committee. This paper contributes to this stream of literature by providing causal evidence of the new IEEE patent policy effect on standard-related innovation at the firm level. In contrast to the previous literature, I rely on the class-weighted patents count, which allows me to account for the relative importance of each technology class for the standard as a proxy for standard-related innovation.

The paper proceeds as follows. Section 2 describes the standard-setting process with a focus on IEEE and its patent policy revision. In Section 3, I develop the estimation procedure and the identification strategy. Section 4 presents the data. Section 5 presents the sample design and some descriptive statistics, comparing the treatment, the pool control, and the weighted group. The results of the empirical analysis and robustness checks are discussed in Section 6. Section 7 concludes.

[3] Other robustness checks are described briefly in the Results section and presented in detail in the Appendix.

[4] IPlytics is a german company developing IP tools to support the analysis of the technology context and market competition. In so doing, they provide access to several patents, SEPs, and standards databases.

[5] *Empirical study on patenting and standardization activities at IEEE* (2017), *IEEE's Empirical Record of Success and Innovation Following Patent Policy Updates* (2018).

[6] However their results are not supported by a proper test for statistical inference.

2 Standard setting and IPR policy

Formal technology standards are developed in standard development organizations (SDOs). An SDO is an institution actively involved in the development of technology standards by facilitating the coordination and collaboration of diverse participants. Because standards typically draw together technologies developed by multiple firms, the role played by such organizations in coordinating the innovation effort of different agents is critical. They achieve their purpose by defining the standards development procedure and setting the rules members must comply with to participate in the standardization process. These rules usually refer to the process, the majority required for standard approval, and how the licensing of standard essential patents is governed. SDOs differ in the procedures followed for developing and reviewing technology standards. Due to the adoption of different rules and processes by different organizations, the influence exerted by these organizations in the development, timing, and likelihood of the adoption of a standard varies widely (Lemley, 2002; Simcoe, 2003; Chiao et al., 2007; Farrell and Simcoe, 2012; Bekkers and Updegrove, 2013).

In standard development organizations, firms compete to have their technologies included in the standard while coordinating their innovation activities in developing the standard (Leiponen, 2008). Through their involvement in standard-setting, firms can gain substantial economic benefits from coordinating innovation efforts (Irwin and Klenow, 1996; Baron et al., 2014). Apart from avoiding duplication of investments, firms can benefit from their inclusion in the social network created by cooperation in the standard (Bar and Leiponen, 2014) and knowledge exchange (Delcamp and Leiponen, 2014). However, the standard-setting process can become intensely competitive since standards are usually formed at an early stage of a technology life cycle, and there is a variety of alternatives among which a standard development organization must choose. Several studies have documented strategic behavior by firms contributing to standards development (Lehr, 1996; Bekkers, 2001; DeLacey et al., 2006). Notably, since the selection of a standard has significant implications for the firms participating in standardization, firms might seek to promote their own agenda (DeLacey et al., 2006) or to delay or block the development of specific standards (Lehr, 1996) by manipulating the process defined by the standard development organizations.

Furthermore, the inclusion of specific proprietary technologies developed by a firm in a standard has important economic implications. From the firm's perspective, owning a technology to be included in a standard can assure a steady stream of future licensing revenues from essential patents. At the same time, users of the standards can increase their bargaining power in cross-licensing negotiations by holding standard essential patents (Bekkers et al., 2002, 2011). Focusing on the determinants of the declaration of essential patents, Bekkers et al. (2011) found that both the intrinsic value of the patented technologies and the involvement of SEP holders in the standard-setting process play an important role when firms decide on declaring standard essential patents. However, involvement in the process represents a stronger determinant. The increase in market power by firms owning standard essential patents, through eliminating substitute technologies and making inventing around the selected technology impractical, has been a source of concern for policymakers and specialists. The perceived risk of patent hold-up (Shapiro, 2000; Lemley and Shapiro, 2006; Farrell et al., 2007), that is an increase in ex-post royalty fees compared to the value of ex-ante royalties negotiated before the inclusion of the technology in a standard, has forced standard organizations to impose licensing commitments on the holders of essential patents. In addition, the last decades have been characterized by legislative reforms and antitrust intervention in standard-setting activities (Baron and Pohlmann, 2018).

2.1 IEEE Standard development organization

The Institute for Electrical and Electronics Engineers Standards Association (IEEE SA) is a globally recognized standard development organization of IEEE, not formally authorized by any government. While it was founded in the United States in 1890, it became global in its members and influence. IEEE SA focuses on developing technologies in electric, electronics, and telecommunication areas. Its most influential ICT standards are Ethernet, 802.11 wireless networking standard, and Firewire. Participation in standards development is subject to a fee. IEEE SA members enjoy added benefits, including but not limited to the ability to hold working group positions, vote on standards, assume leadership positions in standards working groups and activities, and participate in elections for IEEE SA governing bodies. In any case, being a member does not require any obligation to contribute to the standard development; in fact, most of the members at IEEE SA do not bring any contribution to such development.[7]

To prevent opportunistic behavior by SEP holders, IEEE SA has developed two licensing rules to add to its governing bylaw: SEP holders must declare the ownership of patents that may be infringed by implementing a standard, and they commit to accepting as compensation for their patents a fair, reasonable, and non-discriminatory royalty (FRAND commitment). FRAND is meant to ensure that implementers of the technology have access to the technology for a reasonable cost and that patent holders receive adequate compensation for their innovation. IEEE SA also allows blanket declarations, a generic statement through which a contributor declares to hold essential patents for a standard without specifying the patent numbers.[8]

Developing standards at IEEE SA can be explained in five steps. I describe here the standards development process at IEEE SA, as presented in Figure 1.[9] Before the actual standards development process starts, the initial step is the identification of a technological need, that arises from the consumers in a market.

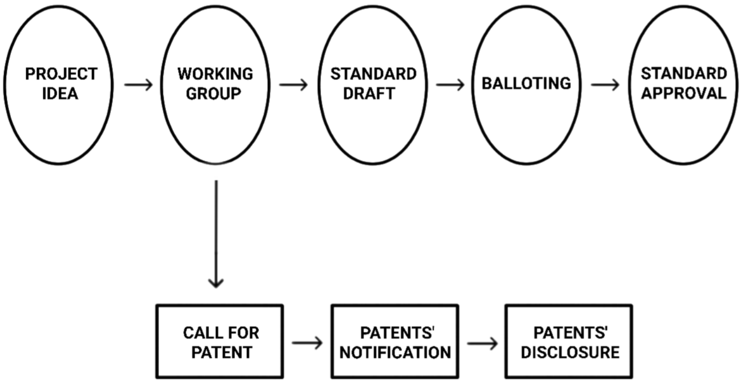
The technological need requires a new feature that must be developed to respond to the need and usually gives rise to a new standard. The identified need is turned into a project idea, and a formal request from a standard

[7]See IEEE SA Standard Association for more details on IEEE SA.

[8]For a detailed description of the SDO patent policy see Bekkers et al. (2017) and Baron and Spulber (2018).

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

Figure 1
The IEEE Standardization Process



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

committee is submitted to the standard development organization. Once presented, IEEE SA has to approve the request.[10] If approved, the standard committee can create a working group of individuals and entities.[11] All interested firms, agencies, and individuals can join the working group. The role of the working group is to transform the idea into a concrete standard. When the working group has been established, the involved entities start providing possible technical solutions to the problem in the third step. This process results in a draft standard, which in the fourth step goes into a balloting process. The standard committee forms a balloting group containing individuals or entities interested in the standard. While any interested entity can comment on the standard draft, only votes by the balloting group members count toward approval. A standard is approved if 75% of all ballots from the group are returned and if 75% of these express a positive vote.[12] The last step involves the approval of the standard. Therefore, the working group submits the standard to the organization's Review Committee, followed by the Standard Board for final approval. After review and acceptance, the approved standard is made publicly available.

Concerning the declaration of standard essential patents, there is no specific timing compared to standardization. When the working group is set, at any time, firms can declare to hold patents that are essential for the implementation of the standard. At each working group meeting, the chair of the working group issues a call for patents, informing the participants that if they are informed about any technologies suggested to be included in the standard covered by patents, they must disclose this information. As the holder of the essential patent, the firm informs the involved parties of its position by submitting a Letter of Assurance. Assurance is to be provided "as soon as reasonably feasible in the standards development process, and no later than the approval of the standard." While IEEE publishes the list of accepted Letters of Assurance, it is not responsible for identifying, validating, and assessing the infringement or the essentiality of the claimed patents.[13]

[10]Specifically, the IEEE Standard Board, in assessing the request, determines if it is needed and if enough volunteers are willing to develop it.

[11]It should be noted that while IEEE SA helps in facilitating the standards development, the standard committee is responsible for organizing the development team and all related activities

[12]The balloting process can take 30 to 60 days.

[13]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 De-*

2.2 IEEE patent policy update

In 2015, IEEE SA adopted some controversial changes to its patent policy, following concerns of the policy community regarding any potential strategic use of SEPs by their holders. Even though the policy amendments became effective after February 2015, they were the result of a process that started two years before the update took place.[14] The organization did not publish the revision process until 2015, but it can be assumed that members and stakeholders learned about the aim of the board to change the patent policy before the policy update was publicly released.[15] There has been a legal debate on whether the revisions of the patent policy refer to changes, and so they apply only to licensing commitments received after the new policy became effective, or clarifications of the ambiguity around the weak definition of RAND royalties in prior commitments.

The revision includes 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.[16] In so doing, the updated patent policy provides greater clarity on four critical aspects around the definition of FRAND royalties:[17]

- Clarity of *Reasonable Rate*: the revised patent policy provides for the SEPs for which IEEE as an accepted letter of assurance "appropriate compensation to the patent holder for the practice of an Essential Patent Claim excluding the value, if any, resulting from the inclusion of that Essential Patent Claim's technology in the IEEE Standard."

- Definition of *Compliant Implementation*: in an attempt to provide clarifications on the word Non-Discriminatory the policy revision introduces a definition of Compliant Implementation as "any product (e.g., component, sub-assembly, or end-product) or service that conforms to any mandatory or optional portion of a normative clause of an IEEE Standard and providing that the requested licensing assurance shall extend to any Compliant Implementation that practices the Essential Patent Claims for use in conforming with the IEEE Standard." In addition, the policy provides three factors that should be considered in determining a reasonable rate: "(1) the value the patented functionality contributes to the smallest saleable Compliant Implementation; (2) the value contributed by all Essential Patent Claims for the same IEEE Standard practiced in that Compliant Implementation; (3) existing licenses covering use of the Essential Patent Claim, conditional on that such licenses were not obtained under the explicit or implicit threat of a Prohibitive Order (e.g., injunction or exclusion order), and are otherwise sufficiently

velopment, available https://standards.ieee.org/wp-content/uploads/import/documents/other/patents.pdf.

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

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

[16] For an exhaustive explanation of the IEEE SA policy update, and its revisioning process see Zingales and Kanevskaia (2016).

[17] The four aspects quoted below are taken from *Draft IEEE Standards Board Bylaws: Draft 39 versus Current Policy,*, IEEE, and *IEEE Request for Business Review Letter*, The United States Department of Justice, September 30, 2014, available at https://www.justice.gov/sites/default/files/atr/legacy/2015/02/17/311483.pdf.

comparable to the proposed license."

- Availability of *Prohibitive Orders*: the updated policy provides that "the submitter (or its successor) of a Letter of Assurance is not permitted to seek a Prohibitive Order unless the implementer fails to participate in, or to comply with the outcome of, an adjudication, including an affirming first-level appellate review, if sought by any party within applicable deadlines, in that jurisdiction by one or more courts that have the authority to determine Reasonable Rates and other reasonable terms and conditions; adjudicate patent validity, enforceability, essentiality, and infringement; award monetary damages; and resolve any defenses and counterclaims."

- Permissible demands for *Reciprocal License*: concerning cross-licensing negotiations, the revised policy clarifies that "where a Submitter's Accepted Letter of Assurance has indicated reciprocity, a potential licensee cannot both receive the benefit of the Submitter's Letter of Assurance and refuse to license to that Submitter the licensee's own Essential Patent Claims on the same standard."

The policy update has been highly controversial: the amendments and the process that led to their adoption have been severely criticized. First, following the policy update, several contributors to the technology standards at IEEE-SA refused to submit their Letter of Assurance, through which they commit to license their essential patents under the new licensing policy. Most of those firms are big players in the ICT industry, such as Qualcomm, Alcatel-Lucent, Ericsson, General Electric, and InterDigital. Their motivations were based on the idea that the policy update would have changed the balance of power between the innovators and users of ICT technologies (Teece, 2015).[18] By contrast, a number of participants in IEEE-related standard setting welcomed the policy update, including Apple, Broadcom, Dell, Hewlett Packard, Intel, and Samsung.

Second, the revised policy was not drafted by all interested stakeholders. The process was dominated by major standard implementers, who defended their own interests that found a counterpart in certain policy changes (Hoffinger et al., 2015; Zingales and Kanevskaia, 2016). Standard-related technology developers, who should have been represented in the committee as a counterweight to equipment manufacturers and vendors, were involved in the process only at its final stages (Zingales and Kanevskaia, 2016). The unbalance of the process followed for revising the patent policy was also perceived by some participants in standards development at IEEE. For example, after the revisions were approved, Qualcomm stated that " more than 15 major technology companies whose engineers contribute to the IEEE standards objected to the policy changes, but they were refused a voice in the development of the new rules." and "...Through every step of this process, IEEE members were denied an open debate of the merits, potential consequences and even basic explanations of these policy changes and why they were developed in the first place." [19] InterDigital submitted a similar statement in an

[18]See *Qualcomm Responds to Updated IEEE Standards-Related Patent Policy*, Qualcomm ,February 2015, available at https://www.electronicdesign.com/technologies/communications/article/21205060/qualcomm-responds-to-updated-ieee-standardsrelated-patent-policy, and *Re: Licensing Assurances and IEEE's 2015 Patent Policy,*, InterDigital, March 2015, available at http://wpuploads.interdigital.com.s3.amazonaws.com/uploads/2015/03/Letter-to-IEEE-SA-PatCom.pdf.

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

open letter to IEEE[20] and in an article published in EE Times.[21]

The Antitrust division published another Business Letter in 2020, which reversed its position with respect to the IEEE policy change, taken in the Business Letter published in February 2015. Even though in the 2015 letter, the US DoJ stated its support for the policy change at IEEE, underlining the fact that clarity and certainty in the licensing negotiation of essential patents would have yielded a net benefit for society, in assuring this it focused only on the potential risk of patent hold-up by SEP holders without accounting for the potential damage to standard participation and future innovation.[22]

3 Methodology

To assess the implication of more restrictive patent policies on firms' standard-related innovation, I follow a difference-in-differences strategy(Rosenbaum and Rubin, 1984; Hirano et al., 2003; Heckman and Vytlacil, 2005; Abadie and Imbens, 2006; Athey and Imbens, 2021; Ryan et al., 2019), exploiting the changes in the IEEE patent policy in 2015. In so doing, I define the treatment group as the set of firms that have declared at least one patent as essential for any standard issued by IEEE. Relying on industries where treatment firms are active, I construct a control sample of firms with similar characteristics to my treatment sample but that has never declared any patent as essential to an IEEE standard. In order to identify the effect of the policy's restrictiveness on the patenting behavior of firms in standards development, I model a patent production function (Hall and Ziedonis, 2001) per firm in each standard. I then compare the change in the patenting intensity of treatment firms in the standard-related technology classes with a comparable set of firms after the policy revision. An interaction term identifies whether a firm is affected by the policy change. This indicator is constructed based on the firm's ownership of an essential patent and the years after the policy change.

Since firms can decide first whether to declare a patent as essential and second which patents specifically declare, there might be some patents that are still relevant for a standard but that the firm decides not to declare as essential or that it does not mention in the declaration document. Therefore the number of SEPs declared does not approximate the full standard-related effort exerted by a firm. To solve this source of bias, I measure the standard-related innovation at the firm level as the number of patents filed in the standard-related technology classes.[23]

Even though I control for the bias due to the decision of which patents are declared as essential within a firm's

[20] *Re: Licensing Assurances and IEEE's 2015 Patent Policy,*, InterDigital, March 2015.

[21] See *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/.

[22] *UPDATED RESPONSE TO ELECTRICAL AND ELECTRONICS ENGINEERS, INCORPORATED'S 2015 REQUEST FOR A BUSINESS REVIEW LETTER*, The United States Department of Justice, September 10, 2020, available at https://www.justice.gov/atr/page/file/1315291/download.

[23] See the Empirical measures subsection for a detailed definition of the innovation contribution of firms in standards.

patent portfolio, accounting for the total number of standard-related patents, I need to account for differences between the treatment and the control group. Covariates between the treated and the controlled units are unbalanced, suggesting that firms included in the control sample are highly heterogenous and differ from firms declaring SEPs. Notably, since firms can decide whether to declare a patent as essential for a standard, this decision is not random, and it is likely to be affected by observed and unobserved standards and firms' specific characteristics. On the one hand, firms declaring to own an essential patent are not necessarily successful innovators: the developers of the most valuable technologies might decide to refrain from participating in the standard development to avoid unintended spillovers. Blind (2006) finds an inverted-U shape relationship between R&D expenditures and the firm's participation decision in standardization, suggesting that top R&D performers may limit their involvement in the standardization process to avoid unintended knowledge spillovers. On the other hand, firms contributing to standards development might succeed in developing essential technologies and obtain a patent protecting them, conditional on some specific firms' characteristics. Besides strategic reasons, there is a structural explanation. The cost of participating in standardization activities is a fixed cost, and small and medium firms can face several barriers before benefiting from standards.

However, as my control group is composed of firms active in the same industries and countries as SEP holders, they face the same opportunities to develop an essential technology for a standard as the firms in the treatment group. Therefore they might have voluntarily decided not to declare a patent as essential to the standard organization. By contrast, since the treatment group is composed of firms owning standard essential patents, they may face incentives to intensively patenting in standard-related classes. While unobservable strategic factors can lead to a downward bias problem in my econometric specification, the propensity to patent in standard-related technologies by treatment firms compared to control firms can bias the estimates of the effect upwards. Therefore the direction of the bias is a priori ambiguous.

To reduce the selection biases that can affect my empirical results, I implement a two-stage estimation procedure where in the first stage, I compute the average treatment on the treated (ATT) weights, using the propensity scores estimated through a logistic regression model (Rosenbaum and Rubin, 1983, 1984, 1985; Imbens, 2004; Abadie and Imbens, 2006). The propensity score weighting allows me to control for the selection into the treatment group based on observable characteristics by defining a weighted control sample of competing firms that do not declare any patent as essential to an IEEE standard but that have similar characteristics as SEP holders in the pre-period. In the second stage, I assign the weights computed from the propensity scores estimated in the first stage to the control sample in implementing the difference-in-differences (DID) methodology. The DID approach allows me to deal with the selection of unobservables, conditional on covariates, and to estimate the causal effect of the policy change on the treatment group.

3.1 Propensity scores and Inverse probability weights

To provide causal evidence of the effect of the more restrictive IEEE patent policy, I have to account for the differences between treatment and control firms. Thus, in the first stage of my methodological approach, I define the weights to assign to each treatment and control unit in the second stage of the empirical estimation. To compute the inverse probability weights, I start by defining a binary outcome per type of firm (treated and control), in which dT_{is} takes the value of 1 if firm i declares to own an essential patent to standard s before the policy revision, and zero otherwise. I then estimate a logit-based propensity score equation using pre-period information. The probability of firm i declaring an essential patent in standard s is defined as follows:

$$Pr(dT_{is} = 1|TECH, X, S) = \frac{\exp(\alpha_0 + \alpha_1 TECH_{is} + X_i'\alpha_2 + S_s'\alpha_3 + \upsilon_c + \upsilon_m + \upsilon_s)}{1 + \exp(\alpha_0 + \alpha_1 TECH_{is} + X_i'\alpha_2 + S_s'\alpha_3 + \upsilon_c + \upsilon_m + \upsilon_s)} \quad (1)$$

where α_0 is a constant, $TECH_{is}$ is the technology similarity between the firm and the standard patent portfolio the year prior to the first declaration of essential patents by firm i to standard s, X_i' and S_s' are firms and standards characteristics observed at the time of declaration, υ_c and υ_m are respectively country and industry fixed effects, υ_s captures standard unobserved specific determinants of the firms' participation decision.

The decision of a firm to contribute to standards development depends on observable and unobservable factors. To partially control for the endogenous allocation of the innovation contribution of firms across standards, I use a measure of the technology similarity between a firm's and a standard's patent portfolios $TECH_{is}$, as defined in the Data section. Since the technology classes overlap across standards, a patent can potentially be essential for multiple standards. Thus, a firm can decide which standards it wants to declare the patent to. Given two standards with similar portfolios as the firm, there might be intrinsic determinants that affect the firm's decision to declare a patent as essential to one standard and not to the other, holding the patent portfolio of the firm constant. Accounting for the technology similarity of firm-standard pairs allows me to measure firm-standard specific factors that are unobserved to the econometrician but are important drivers of the self-selection of the firm in the treatment or control group.

To control for the observed heterogeneity across standards, I include in the vector S_s' the overall number of standard-related documents composing a standard in the years before a firm declares a patent as essential and the number of companies declaring essential patents. Besides, I control for unobserved heterogeneity in standards by absorbing a set of fixed effects at a standard level. Notably, specific standards might be more attractive for a larger share of firms, given their importance for a specific sector.

Following the literature on standard participation (Blind and Thumm, 2004; Blind, 2006; Blind and Mangelsdorf, 2008; Baron et al., 2018) and the literature studying the determinants of essential patents declarations (Farrell et al., 1992; Bekkers, 2001; DeLacey et al., 2006; Bekkers et al., 2011, 2012, 2017), the vector X_i' includes R&D expenditures, sales, and the total number of patents filed[24] before the first declaration of firm i to standard s. Several studies suggest that a certain level of knowledge is required to benefit from contribution to standardization.[25] However, high R&D performers are less likely to declare the ownership of essential patents to prevent disclosure of important knowledge.[26] To control for the heterogeneity in the level of investments and technological knowledge across firms, I include R&D and $R\&D^2$ in my specification. Besides, as mentioned above, firms might face some barriers to entry in standards development due to high fixed costs. I, therefore, include sales to account for the size of the firm, controlling for the heterogeneity in profits across firms and their size.[27]

To control for the unobserved firms' determinants that can affect the firms' participation decision in the development of a standard, I use a set of country υ_c and industry, υ_m, fixed effects, defined by the country and the 4-digit NAICS code associated to each firm. For instance, firms in some industries are more likely to participate in specific standards because of the degree of importance of the standard-defined methods for the industry. Besides, the firm's location may affect its participation decision in developing a specific standard because of the geographical proximity of the working group.

Using the estimates from Equation (1), I can compute the propensity scores for each firm-standard pair in my sample, defined as the estimated conditional probabilities to be in the treatment group and the ATT weights. Specifically, the weights for treated firms equal 1, while the weights for control firms are computed as follows:

$$weight_{att,is,dT=0} = \frac{p_{score,is,dT=0}}{1 - p_{score,is,dT=0}} \tag{2}$$

where p_{score} is the propensity score assigned to each firm in the control group. The propensity scores and the derived inverse probability weights allow me to design and analyze a nonrandomized study since it mimics some of the particular characteristics of a randomized controlled trial, reducing concerns for selection bias (Austin, 2011).

3.2 Patent equation

Since my interest is to understand how the SDO's patent policy affects the standard-related patenting of firms contributing to a standard, in the second stage of my estimation procedure, I estimate a patent production function that relates the number of patents filed by a firm in the set of technology classes related to a standard with the patent policy regime in place in the years before and after the policy revision (Hall and Ziedonis, 2001;

[24] Blind and Thumm (2004) discuss the influence of a small sample of European firms characteristics on the likelihood of joining formal standardization activities. They find that the more intense the patent activity of firms is, the lower the likelihood to join the standardization process.

[25] Baron et al. (2018) investigate the roles of R&D expenditures, patent behavior, and downstream market position in a firms decision to participate in standard activities and find that R&D expenditures are positively correlated with the firms' involvement in standards development.

[26] By contrast, Blind (2006) finds an inverted-U shape relationship between R&D expenditures and the firms participation decision in standardization.

[27] Blind and Mangelsdorf (2008) focus on service companies in Germany and confirm that company size, export activities, and R&D expenditures are all important drivers of participation in standardization activities.

Hausman et al., 1984). The equation I estimate is of the form:

$$ln(P_{ist}) = \delta_3 dT_{is} * Post_{t>2014} + \beta_1 Size_{i,t-1} + \beta_2 S'_{s,t-1} + \gamma_i + \gamma_s + \tau_{age} + \epsilon_{ist} \quad (3)$$

where $ln(P_{ist})$ is the outcome, measured by the logarithm of the weighted number of patents filed by firm i in the technology classes related to standard s in year t, dT_{is} is a dummy variable which captures possible differences between the treatment and the control group, $Post_{t>2014}$ is a dummy variable which equals one for years after the policy change, $Size_{i,t\text{-}1}$ is the size of the firm, standard characteristics are included in the vector $S'_{s,t\text{-}1}$, τ_{age} is a set of standard-age fixed effects, γ are a set of time-invariant firm and standard unobserved fixed effects, and ϵ_{ist} is the idiosyncratic term. To account for immediate feedback of the dependent variable to the covariates, I lag all time-varying controls by one year.

The coefficient of interest, δ_3, multiplies on the interaction term $dT_{is} * Post_{t>2014}$ that equals 1 for the observations in the years after the policy was changed, $Post_{t>2014}$, and the occurrence of the declaration of a firm for a standard, dT_{is}. Notice that the dT_{is} variable defines whether a firm is in the treatment or control group. Specifically, a firm is included in the treatment group if it declares to own an essential patent for a standard issued by IEEE.

Several studies have documented economies of scale in generating patents, and others have highlighted a relationship between the size of the firm and its patent portfolio composition (Blind and Thumm, 2004; Blind and Mangelsdorf, 2008). Since the size of the firm is likely to affect the number of patents filed in the standard-related technology classes, I include in my specification $Size_{i,t\text{-}1}$, which measures the number of employees. Besides, I control for industry and country effects, including a set of dummies for the 4-digit NAICS sector and the country where the firm is located. Firms in some industries are more likely to patent in specific technology classes because of the degree of importance of those classes for the industry compared to others. Furthermore, the location of a specific firm may affect its propensity to patent because of the patent system in force or the accessibility to patents in a given country. However, it should be noticed that the industry and the country effects are controlled for by γ_i and γ_s in the econometric specification unless they change over time.

In addition to accounting for the firms' characteristics in the patent regression, it is necessary to deal with the standards-specific characteristics that may affect the patenting activities of firms in the standard-related technology classes. Notably, the importance of a given standard for the ICT industry can affect the amount of related innovation the firm decides to develop. To measure the importance of a standard, I include the total number of documents referring to a common standard, and the total number of standard essential patents declared in the $S'_{s,t\text{-}1}$ vector. I further include the total number of firms declaring to own an essential patent as a measure of the attractiveness of the standard. As theoretical works on standards and essential patents have shown (Baron et al., 2014; Bekkers et al., 2017; Spulber, 2019), the number of SEP holders affects the licensing revenues a firm can earn from its essential patents. Lastly, I include standard-age fixed effects, defined by the number of years that elapsed since the publication of the first standard document, to control for a natural decline of the technology standard due to its life cycles.[28]

The other regressors in Equation (3) are included to control for shocks and unobserved heterogeneity. I use a set of firm and standard-specific dummies, which allow me to control for unobservable heterogeneity across standards and firms. For instance, pure innovators are more likely to contribute more innovative effort to some standards rather than others compared to vertically integrated firms that might be willing to contribute to several standards. At the same time, firms may have decided to invest a certain amount of innovation in standardization as they are the only successors in developing some standard-related technologies, conditional to unobserved (to the researcher) firm's specific characteristics. In addition, as multiple technology classes are related to multiple standards, I need to control for unobservable determinants of the amount of innovation contribution a firm decides to invest in a standard compared to a standard with a similar technology space.

4 Data

4.1 Data sources

My main data source is the Searle Center Database (SCDB), a comprehensive and systematic database of technology standard documents and information about standard developing organizations.[29] The database contains information regarding the characteristics of more than 629,438 standard documents issued by 598 SDOs from 1985 to 2018. For my analysis, I focus on the set of standard documents related to the ICT sector issued by IEEE.[30] During this period, I observe 420 standard documents, their publication date, the version history, and the identifier associated to each document.

The SCDB collects information at the standard document level and associates the same identifier to all declarations referring to the same standard document. It is important to understand that there is not a common definition of the term technology standard: the word standard can refer to a technical specification, i.e. standard document[31], or it can refer to complex technology systems described by multiple standard documents (standard project). Moreover, standards change over time: the process of revising a standard to keep up with technology

[28] Figure 10 in the Appendix shows the distribution of patents filed before and after the publication of a standard. As can be expected, the number of patents filed decreases as the standard becomes older; this information is consistent with the assumption of using the age of the standard in order to control for a natural decline in the number of patents filed in the standard-related technology classes. See the Methodology section for a detailed explanation.

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

[30] Since standardization rose during the beginning of the 21st century and most of the information regarding standards in the SCDB are collected in the years after 2000, I drop those observations before 2000 from my sample. Keeping only the observations after 2000 leads to minimal loss of data.

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

change can take different forms according to the standard organization.[32] For my analysis, I define technology standards as the set of standard documents referring to a common standard project. Relying on the *standard document identifier* and *documentid*, I group all standard documents and the related declarations that refer to the same standard project. I obtain aggregate information for 182 technology standards. Since I am interested in standard projects, I refer to standard projects as standards for this project.

Since I focus on the full set of standard documents published over the years, starting from the standard document where I observe firms submitting their first declaration, I can track the patenting behavior of firms in standardization over time. I, therefore, account for the technological changes of a standard. Focusing on the standard project level allows me to study how the policy change affects the future incentive of firms to continue contributing to the development of the standard.

Besides standards information, the SCDB provides data about the declarations made by who holds the IP right over the technologies included in each standard (SEP holders): these data include the name of the companies making the declaration, the year of the declaration, the patent numbers declared in the letter of assurance, and the International patent classification (IPC) classes associated to each essential patent. I use these data to retrieve two types of information useful for my analysis: the standards patent portfolio and the set of firms contributing to the development of a standard.

Concerning the first type of information, I rely on a relatively aggregate level of technology. I use the 4-digit IPC classification of the set of essential patents declared to a standard in the entire period of observation in order to define the technology space (patent portfolio) of the standard.[33] Companies are allowed to make blanket disclosures at IEEE. In those cases, I cannot observe the list of essential patents, and so the associated IPC classes. If a technology standard receives only blanket disclosures, I am not able to infer the patent portfolio of that standard.[34] For the purpose of the analysis, I restrict the sample to technology standards with 4-digit IPC class information. I observe information on 27 technology standards issued by the organization.

I then define any firm declaring before the policy change to own an essential patent for a standard issued by IEEE as a contributor to the standard development. Firms declaring essential patents to IEEE are subject to the SDOs policy change, so they are the subjects of interest. The SCDB contains information on the declarations made by 147 essential patent holders for the 27 standards in my sample: of these, 128 are firms, and the remaining part is composed of universities, national and international institutions, and governments. Since I am interested in standard-related innovation at the firm level, I focus only on the 128 firms.

[32] 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.

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

[34] 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.

For the purpose of my analysis, I also add information about bibliographic data of patents filed by treatment firms from the European Patent Offices PATSTAT database. PATSTAT contains data relating to more than 100 million patent documents, starting from the beginning of the twentieth century. I collect a set of patent statistical information regarding the patent's application date, the number of forwarding citations the patent receives, and the 4-digit IPC technology codes assigned to the patent. Due to the delay between application and issuance dates, I count patents using the year of application. In this way, I follow more closely firms' R&D investments over time. Moreover, given that each patent can be classified into more than one technology class, I count each patent related to a class as a separate patent. In other words, a patent is double-counted if it has been assigned to two different technology classes.[35]

I complete my analysis with data on firms' characteristics from the Compustat database. Specifically, I use the information on R&D spending, total revenue, and the number of employees for the companies in my sample between 2000 and 2018. All variables are known determinants of firms patenting activity and thus may affect the number of patents filed by a firm in the set of standard-related 4-digit IPC classes (Hall et al., 2000; Hall and Ziedonis, 2001; Faber and Hesen, 2004). Several studies also show how these variables are likely to affect the decision of firms to declare a patent as essential and thus to be involved in standards development (Blind and Thumm, 2004; Gandal et al., 2004; Blind, 2006; Baron et al., 2018), as explained in the Methodology section.

Accounting for the information concerning the number of employees, I classify firms in the treatment group into four categories according to their size: small firms have less than 315 employees during the entire period[36]; medium-size firms have more than 315 but less than 1,200 employees; large firms have more than 1,200 employees but less than 6,000; and very large firms have more than 6,000 employees. I also collect data about the 4-digit NAICS code and the country code of each firm, which is useful to define the control group for my analysis, as explained in the following subsection. I restrict the analysis to firms that have data on Compustat for at least five consecutive years.

To merge the datasets, I rely on firm names and algorithms to match string variables.[37] Furthermore, I link the firm-level data to the specific standard information based on the firm's declaration in the 15 years before the policy change. Finally, because the effect I focus on occurred in 2015, I keep only the observations between 2011 to 2018. Thereby I limit the treated group to a sample of 27 standards issued by IEEE and 61 firms declaring at least one essential patent for this set of standards.

[35] In my sample, on average, patents are linked to 1.38 technology classes.

[36] The maximum number of employees per firm is lower than 315 (first quartile of the distribution) during the period 2000-2018.

[37] Specifically, I use the Harmonized Applicant Names (HAN) database developed by the OECD to retrieve the patent applications of each firm in the Worldwide Patent Statistical Database (PATSTAT). 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 of names, and it is associated with a single company. First, I determine the set of identifiers associated with my sample of 128 SEP holders from the HAN database, and then I merge this information with the patent database to collect data on the firms' patent portfolios. As the HAN database includes more than 6 million identifiers and I rely on algorithms to match firms' names, I succeed in matching the application identifiers for 110 firms out of the 128 declaring to own an essential patent.

4.2 Control group

To construct a sample of firms comparable to the 61 firms holding at least one essential patent, I start by collecting data from Compustat of the firms active in the same 4-digit NAICS industries and countries as the 61 firms in the treatment group. I assume that firms active in the same industries as essential patent holders face the same opportunities to develop, and thus to declare, an essential technology for a standard as the treated companies. I then select only firms for which I have available accounting information for at least five consecutive years in the period of interest.

From these firms, I look for the ones who patented at least once in the period 2000-2018 in the set of technology classes related to the 27 IEEE technology standards and for which I have available data, following the same process as described in the Data sources subsection.[38] As highlighted in the subsection, the HAN dictionary covers more than 6 million names, and matching errors may be met due to a large amount of data processed within the database. For this reason, also taking into account the size of the sample I obtain from the collection process of accounting data, I am not able to check all the names in the control group. Thus I keep only firms for which I identify a match in name grouping from Compustat to the HAN database. Therefore I gather a sample of 1,862 firms filing around 1,200,000 patents.

After matching the firm's characteristics with the patent portfolio data, it leaves a pooled sample of 878 control firms prior to the propensity score weighting. I drop two firms as they are extremely large and they are not comparable with the treatment firms. I then connect the accounting and patent data for the control firms with standard information, taking into account the set of technology classes related to each standard. Notably, the firm is counted in the control group for a standard if it files at least a patent in one of the IPC classes related to the standard.

Lastly, for the purpose of applying the propensity score methodology, I omit from my sample the observations related to declarations occurring in the years before 2001.[39] After merging firms' data with the standard information for both treated and control companies, I build up an unbalanced panel dataset of 27 technology standards issued by IEEE, 848 companies active in 23 4-digit NAICS sectors, 12,937 company-standard pairs observed over a period of 8 years (2011-2018). For each company-standard pair, I observe the number of filed patents by the specific company in the set of technology classes related to a standard per year, and I include a dummy variable indicating whether the company declares to own an essential patent for the standard.

[38] See footnote 29.

[39] For a detailed explanation, see subsection 5.1

4.3 Empirical measures

Since some of the variables I use in my analysis are not observed and have to be created, I need to construct empirical indicators. Specifically, I define the following measures:

Standard Contributors: I consider any firm declaring a patent as essential before the policy change for a standard issued by IEEE as a contributor to the standard development. Because I focus on the innovation contribution of firms in a standard project over the years, my unit of observation is at the firm-standard level.

Standard-related Innovation: Since the patent policy endorsed by the organization directly or indirectly affects the return on innovation a firm can earn from licensing its essential patents[40], the policy revision has a direct effect on the firms' amount of innovation investment allocated to develop standard-related technologies. Therefore R&D contributions would be the natural outcome to test for the effect of more restrictive IPR policies on firms' standard-related innovation. However, there is no available information about the amount of investment a firm makes in developing each standard to which it contributes. Since I cannot disentangle the share of R&D cost allocated to each standard, I follow the methodology proposed by Baron et al. (2014), and I use the number of patents filed by a company in the set of technology classes related to a standard as an alternative outcome measure of standard-related innovation.[41] Specifically, in the first step, I identify the set of 4-digit IPC classes that are technologically relevant for each standard, relying on the IPC classification associated with each patent declared as essential. Second, I count the number of all patents filed by a firm in the standard-related technology classes as a measure of standard-specific innovation.[42]

Moreover, for each standard, not all technology classes are equally important. Some IPC classes may be associated with a larger share of patented inventions that are included and necessary for a standard. In addition, IEEE standards overlap in many classes with 3GPP standards. Therefore, for a relatively aggregated level (4-digit) of technology classes, WiFi patents will likely be dominated by cellular-related patents (GSM, UMTS, CDMA, CDMA2000). Given that some classes might be more important to IEEE standards relative to other standards issued by other organizations, by accounting only for the number of patents filed in classes with declared SEPs, regardless of the importance that each class has for the IEEE-related standard, my measure would be affected by the patents declared to 3GPP, whose relative number would, in turn, be affected by the policy endorsed by a different organization. To avoid confounding my measure by those patents, I follow the methodology proposed by Baron and Pohlmann (2013), and in Baron and Pohlmann (2018), and I account for the relative importance of each technology class to standards issued by IEEE. Specifically, I weigh the number

[40] It should be noticed that the return a firm can earn from its innovation investment also depends on other factors such as its bargaining power in cross-licensing negotiations, which in turn is affected by the portfolio size of a firm and its market power in the relevant market, by the importance of a given invention for the standard, as well as the share of adoption of the standard in downstream markets.

[41] citetbekkers2016causal use the technology classes associated to SEPs and find that patent applications in standard-related classes are more likely to be affected by standardization activities.

[42] It has been shown that this measure represents a good approximation of standard-specific R&D investment. Several analyses have been conducted to corroborate the reliability of their novel measure. The results can be found in Baron et al. (2014).

of patents filed in each 4-digit technology class so that the weights assigned to the different classes associated with a standard in counting the related patents match the weights in the IPC groups of declared patents. Notably, suppose a technology class represents a high percentage of the total number of standard essential patents declared. In that case, I assign high importance to the class and thus to the patents filed, regardless of the number of patents filed by the firm in the class.[43] The dependent variable of my analysis can therefore be 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 in time t, and W_{jt} is the weight associted to class j, measured as the share of essential patents declared to standard s associated to class j over the total number of SEPs for s in year t.

As highlighted by Baron et al. (2014), an alternative approach to track the R&D contribution of firms in standards development would be to count the number of essential patents declared by a firm. Even though essential patents represent the inventions at the firm level directly associated with a standard, they are a small share of patenting around standards (Bekkers et al., 2012). As firms decide voluntarily to declare to own an essential patent to the standard organization, there might be some patents that are still relevant for a standard but that the firm decides not to declare as essential. Accounting only for essential patents as a measure of the innovation contribution of firms in standards can lead to biased estimates in my analysis: firms, for strategic reasons, might have declared some patents as essential and have decided not to declare others, even though those patents might be technologically superior.

Furthermore, some of the patents filed by firms in the technology classes related to a standard might be commercially essential, i.e. patents not declared as essential but that cover method of implementation that produce cost reductions or quality improvements for products using the standard as an input (Bekkers et al., 2012). In economic terms, a commercially essential patent has at least one substitutive technology, while an essential patent has no substitute. Both types of patented technologies, declared as essential and commercially essential, are relevant in evaluating the innovative development of a standard. It is also important to recognize that the date of the formal declaration is not necessarily linked with the standard development process (Spulber, 2019) and it can be highly strategic, likely to occur before the publication of a technical standard (Ganglmair and Tarantino, 2012; Bekkers et al., 2012). So, while the number of essential patents would be a poor measure of the firm's innovation investment in a standard, the total number of patents filed in the standard-related technology classes provides a better description of the innovative process of a firm around a standard over time.

[43] To also account for the quality of the firm's innovation contribution in standards development, I also test the effect of the policy revision on the number of citation-weighted patents. Therefore, I construct an alternative measure by weighting the number of patents filed in the set of technology classes related to a standard by the number of forward citations each patent receives. The number of times subsequent patents cite a patent is commonly used in economic research as a proxy of the quality of a patent in terms of importance (forward citations) (Harhoff et al., 1997; Hall et al., 2000; Hall and Ziedonis, 2001; Sampat and Ziedonis, 2004).

The interplay between standards and patents is another important aspect to account for when measuring the technology innovation around standardization. On the one hand, patents and standards are inherently different. Patents describe and protect a new invention from competitors by using innovations to create new products or processes that can be introduced and commercialized in the market. In contrast, standards describe a particular method or technology, usually composed of different patented inventions. On the other hand, patents and standards are highly interrelated. Firms invest in R&D activities and invent and patent a variety of new methods while competing for the inclusion of the patented technologies in the standard. Besides, many patented inventions are developed in the process of standard development by addressing needs and objects defined by standard organizations, which in turn may or may not be included in the standard. Indeed, many firms make contributions to standards under development. At the same time, standard organizations build on new technological developments to create new standards. And the development of new technology standards may lead to new patentable inventions in the methods for standard implementation.

Relying on the patenting behavior of firms as a window for standard-related innovation has several limitations. First, while patents are a direct outcome of the inventive process, not all inventions are patented since firms may face an incentive to keep some novel methods secret. Besides, firms are more likely to patent inventions expected to have a commercial impact (Archibugi, 1992; Archibugi and Planta, 1996). On the other hand, not all inventions are technically patentable. Therefore measuring the standard-related innovation of firms as the number of patents filed is likely to underestimate firms' investment in the research and development of new technologies and, thus, the real outcome of the innovation process. Second, accounting for the interplay between standards and patents, firms may face different incentives for over-patenting in standard-related technologies. Notably, holding the level of innovation constant, firms may file an excessive number of patents in order to increase their bargaining power in cross-licensing negotiations. In addition, firms may over-patent inventions to increase their likelihood of holding standard essential patents, thus assuring a larger share of standard-related licensing revenues. In these cases, the number of standard-related patents would be biased upward since it would over-estimate the innovation effort exerted by firms in standardization.

Lastly, since I focus on patenting, I cannot disentangle the effect of the policy change on the firm's standard-related innovation from the effect that a more restrictive policy would have on the willingness to patent inventions. For instance, more restrictive patent policies may affect the firms' incentive to patent some inventions while keeping the incentives to innovate unchanged. If this is the case, firms may keep innovating but be incentivized not to patent their inventions. Another channel through which a more restrictive patent policy can affect SEP holders' patenting behavior is incentivizing firms to switch patenting towards more favorable SSOs. However, the policy revision would affect the incentive to patent through a reallocation of R&D activities to standards issued by other organizations, and therefore it would affect the innovation contribution of firms in IEEE standards.

Technology Similarity: I rely on patented technologies to measure the technology similarity between firms and standards (Rosenkopf and Almeida, 2003; Gilsing et al., 2008; Baron and Pohlmann, 2013; Bar and Leiponen, 2014; Rosa, 2019). Using PATSTAT data on filed patents, I construct a patent portfolio for each firm in my sample by accounting for the technological classes a firm file patents in, as defined by the International Patent Classification. In the same line, I follow Baron and Pohlmann (2013), who measure the standards position in the technology space by accounting for the IPC classes associated to any patent declared essential to a standard to define the standards patent portfolios. I, therefore, use the SCDB data on essential patents to identify the set of technology classes related to a standard. Following the approach proposed by Baron and Pohlmann (2013) and Rosa (2019), I then rely on the cosine similarity[44] as a measure of the technology similarity between firm i and standard s, defined as follows:

$$TECH_{i,s} = \frac{\vec{S}_s \cdot \vec{I}_i}{\|\vec{S}_s\| \|\vec{I}_i\|} = \frac{\sum_{j=1}^{J} \sum_{t<2015} \mathbb{1}\{IPC_{sjt} = j\} \mathbb{1}\{IPC_{ijt} = j\}}{\sqrt{\sum_{j=1}^{J} \sum_{t<2015} \mathbb{1}\{IPC_{sjt} = j\}} \sqrt{\sum_{j=1}^{J} \sum_{t<2015} \mathbb{1}\{IPC_{ijt} = j\}}} \quad (5)$$

where $\vec{I}_i$ and $\vec{S}_s$ are, respectively, the firms and the standards patent portfolio, and J is the set of IPC classes in which firms patent and in which standards have essential patents. In order to construct the firms and the standards patent portfolio respectively, I consider the IPC classes a firm has filed patents in and a standard has patents declared as essential, and not how many patents are in each class. Specifically, using PATSTAT data on filed patents, I construct a patent portfolio for each firm by accounting for the specific IPC classes a firm files patents, according to the 4-digit International Patent Classification. I, therefore, define the vector of IPC classes associated with firm i as $\vec{I}_i = (\mathbb{1}\{IPC_{i1} = 1\}, \ldots, \mathbb{1}\{IPC_{iJ} = J\})$, where $\mathbb{1}\{IPC_{ij} = j\}$ equals 1 if the technology class j is a technology class where firm i had filed patents to in the years before the policy was changed. Consequently, using the SCDB data on essential patents, I also construct the patent portfolio of a standard, taking into account the technology classes associated to each patent declared as essential to the standard. I thereby define the standard patent portfolio as a vector associated with standard s as $\vec{S}_s = (\mathbb{1}\{IPC_{s1} = 1\}, \ldots, \mathbb{1}\{IPC_{sJ} = J\})$, where $\mathbb{1}\{IPC_{sj} = j\}$ equals 1 if the technology class j is associated to the SEPs declared to standard s in the years before the policy was changed, and 0 otherwise. In the last step, I compute the cosine of the angle of the two defined vectors to retrieve the degree of technological similarity between firm i and standard s. Since there can only be a non-negative number of 4-digit IPC classes in each vector, the cosine similarity can take values between 0 (vectors are orthogonal) and 1 (vectors have the same direction).

As also recognized by Rosa (2019), the advantage of the cosine similarity over the euclidean distance is that it does not depend on the size of the vectors but on their directions. Notably, by measuring the cosine angle as

[44] In order to construct the technology similarity between the firms patent portfolios and the standards ones I start from the measure defined by Rosa (2019). Compared to my measure, in her paper, she defines the cosine similarity to assess the technological similarity of SEP holders.

defined in Equation (5), I account for the IPC classes which compose the patent portfolio without accounting for the number of patents filed in each class. Mathematically, it measures the cosine of the angle of two vectors in a multi-dimensional space. This measure helps me to partially control the problem of blanket declarations. Since firms are allowed to declare to own essential patents without revealing any specific information about those patents, the size of the standards patent portfolio, in terms of the number of essential patents per technology class, can be distorted. Because patents declared essential to a common standard share several technology classes, it is less likely that a technology class is not included in the composition of the patent portfolio of a standard, even if I observe blanket declarations. Therefore by using the cosine similarity instead of the euclidean distance to compute the technology similarity between a firm and a standard patent portfolio, the direction of the patent portfolio is unlikely to be affected by blanket disclosures.

5 Sample design, evaluation and descriptive statistics

In this section, I first present the weighted sample of treatment and control firms as a result of the propensity score estimation. I also evaluate the weighted control group in providing estimates of the causal effect of the policy revision on treatment firms. I then present some descriptive statistics of firms, comparing the treatment, pool control and weighted control samples, and standards.

5.1 Sample design and evaluation

To construct a balanced sample of treatment and control firms that have never declared any patent as essential to IEEE but with comparable characteristics as firms declaring to hold SEPs, I first estimate the probability of the firm declaring standard essential patents to IEEE standards as a function of observed and unobserved characteristics. To construct the sample of weighted control firms, I rely on firms' characteristics and patent portfolios in the years before the declaration by the treatment group. Since I have accounting information from 2000, I delete from my sample the firm-standard pairs for which I observe a declaration in the years before 2001. I, therefore, collect declaration data about 61 treatment firms, 787 control firms, and 27 standards in the 15 years before the policy was revised and estimate a logit regression. The predicted conditional (on a vector of observed covariates) probabilities from the logit regression define the propensity scores for each firm in the control group.

Table (1) shows the results of the logistic regression. The dependent variable is a binary outcome dT_{is} (Treat), which takes the value of 1 if firm i declares to hold an essential patent in standard s during the period 2001-2014. Results based on the baseline specification (1 year lagged values) are presented in Column 3.[45] In accordance

[45] Column 1 of Table (1) includes only firms' characteristics as control variables. Instead, Column 2 presents the results of the baseline specification using 1-year lagged values without including industry, country, and standards fixed effects.

Table 1
Firms decision to declare essential technologies

	Logit 1 Year Lag	Logit 1 Year Lag	Logit 1 Year Lag
Dependent Variable dT_{is}			
Technology similarity	1.003	1.363***	1.585**
	(0.652)	(0.299)	(0.713)
R&D (log)	11.414***	6.779***	10.721***
	(1.375)	(0.622)	(1.546)
$R\&D^2$ (log)	−5.242***	−3.168***	−4.894***
	(0.670)	(0.301)	(0.752)
Sales (log)	7.365	8.001	1.546*
	(0.923)	(1.411)	(0.356)
Total Patents filed (log)	0.253***	0.135***	0.291***
	(0.036)	(0.015)	(0.038)
SEP holders per standard (log)		−0.114*	1.833***
		(0.059)	(0.482)
Total documents per standard (log)		−0.118***	−3.327***
		(0.045)	(0.536)
Industry FE	Yes	No	Yes
Country FE	Yes	No	Yes
Standard FE	Yes	No	Yes
Number of observations	22,157	30,071	22,157
Log Likelihood	-336.81	-758.59	-283.92

Note: The dependent variable is a binary outcome in which dT_{is} takes the value of 1 if firm i declares at least an essential patent for standard s during the period 2005-2014. The parameters are estimated by maximum likelihood. Standard errors are robust to arbitrary heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

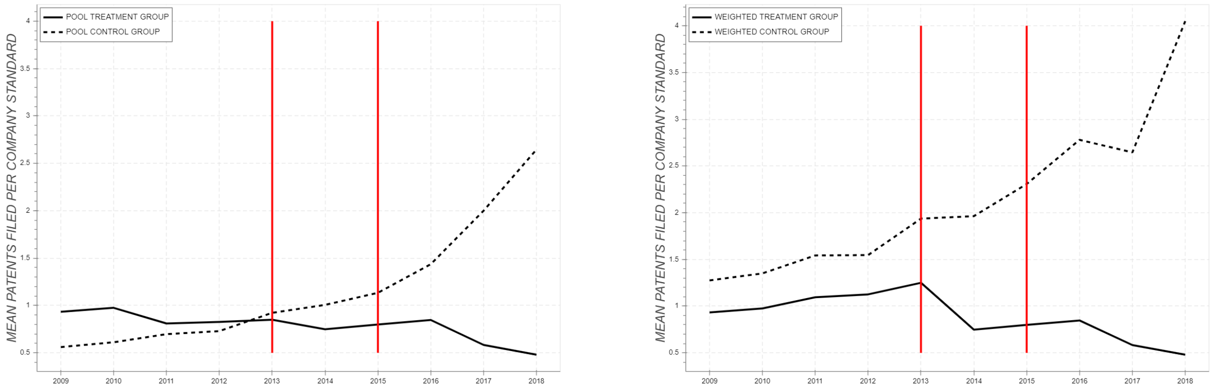
with my hypothesis, one of the variables capable of predicting firms' decisions to contribute to standards development is the technology similarity between the firms and standards patent portfolios. The more similar in terms of technology classes, the greater the likelihood that a firm will declare a patent as essential for a standard. Furthermore, in line with the findings of previous studies on participation in standards development, my results show that the size of the firm's patent portfolio and R&D expenses are significant determinants of the choice of firms to contribute to standardization. Notably, there is an inverted-U shape relationship between the R&D expenses and the likelihood of declaring an essential patent for a standard. This result supports the idea that, on the one hand, high R&D performers are less likely to contribute to the development of a standard as they are more prone to keep their innovation out of standardization to avoid unintended spillovers. On the other hand, the result shows that a minimum level of knowledge is required to be involved in standards development. By contrast, the size of the firm measured by its revenue does not have a statistically significant effect on the participation decision of firms. Aside from firms' characteristics, standards characteristics seem to have a strong impact on the likelihood of firms to declare essential patents.

Relying on the estimated propensity scores from Table (1), I can then compute the weights to assign to each control firm-standard pair used in the difference-in-differences estimation. In other words, I select a weighted sample of control firms by weighting the observed characteristics of the pool controls. Since I cannot estimate the propensity scores for all control firm-standard pairs from the pooled sample, I restrict the analysis to a sample of 61 treatment firms, 509 weighted control firms, and 27 standards.

Table 2
Summary Statistics: pool vs weighted sample

	Treated	Pool Control	Weighted Control	T-test Pool	T-test Weighted
R&D Expenses (log)	6.598	3.069	5.349	25.95*	6.36*
Size (log)	3.091	0.295	3.289	21.96*	-0.96
Sales (log)	3.156	0.285	2.736	26.2*	1.2
Total Patents filed (log)	8.849	5.030	7.286	21.82*	6.57*

Note: This table summarizes the mean in variables, comparing the treated and the untreated samples in the pre-period 2001-2014. Total patents filed measure the aggregate number of patents filed before the declaration to the SDO.



(a) Patents filed per firm-standard pairs before and after IEEE policy change

(b) Patents filed per firm-standard pairs before and after IEEE policy change

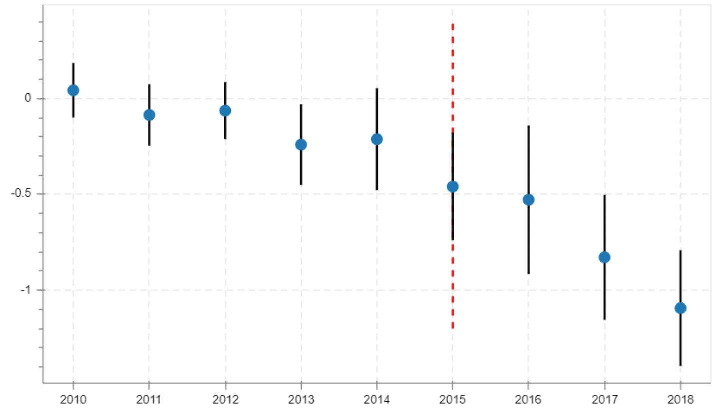
Figure 2
These figures show the average number of standard-related patents filed per firm-standard pair over time, comparing the distributions of treatment and control firms in the pooled sample (left) and in the weighted sample (right).

Table (2) reports the results of the weighted sample based on the estimates from the logit regression. Specifically, it compares the moments of the treatment, the pool control, and the weighted control samples. Overall, the weighted sample of comparable firms presents similar characteristics as firms declaring essential patents. The balance of firms' characteristics is important in order to partly deal with the issue of heterogeneity across firms. Several factors can explain this high heterogeneity. First, SEP holders are a small subset of firms in the population with specific confounding characteristics that affect the likelihood of succeeding in developing standard-specific technologies and declaring those technologies as essential. Moreover, how I construct the control sample affects the heterogeneity between the treatment and control group: specifically, a firm is included in the control group of a standard if it files at least a patent in one of the technology classes related to the standard. Since standards can share multiple technology classes[46], a firm not declaring any patent as essential can be included in multiple control groups for several standards. This leads to an imbalance between the treatment and the pool control group.

To establish the validity of the methodology I employ, below I show that the parallelization of trends assumption holds for the weighted sample, which is in favor of my inverse probability weighting technique and therefore supports my causal claims from the econometric results. Figure 2 compares the average class weighted number of patents filed per firm-standard pairs by treated and pool control firms (left graph) and the treatment and weighted control firms (right graph), both normalized by the average patents filed in the pre-period.[47] In other

[46]This can be explained by the fact that all the standards in my sample are related to the ICT sector.
[47]I normalize the number of standard patents filed by dividing by the average number of patents filed in the standard-related

Figure 3
Estimates of δ over time



words, normalizing by the pre-period patenting behavior of firms, I adjust the means for both unweighted and weighted samples by firms fixed effects, such that I account for the firms' unobserved heterogeneity. Focusing on the weighted sample, the treatment and the weighted control groups follow a parallel path before the policy change, and they diverge after 2013. SEP holders start decreasing the average number of patents filed in the standard-related technology classes two years before the policy changed, suggesting an anticipation effect of the policy revision by essential patent holders.[48] The similarity in the pre-trends between treated and control firms assesses the parallel trends assumption, which is crucial for the validity of the difference-in-differences estimates.

For the validity of my parallel trends assumption, I also perform a pre-treatment parallel trends test by including a time trend variable and an interaction term of the treatment and post-variables with a time variable.[49] The defined specification reports no statistically significant coefficients in the pre-period and start being significant two years before the policy was changed.[50] The time effect on the treatment group is reported in Figure 3. Since zero is in the confidence intervals between 2010 and 2013, the test results support the assumption that the linear trends in the outcomes are parallel prior to treatment.[51]

5.2 Descriptive statistics

Table (3) summarizes the firms' characteristics and portfolio composition of the treatment, the pool control, and the weighted control groups from 2009 to 2018. For instance, SEP holders, on average, have more than 87

technology classes by each firm in the pre-period.

[48] IEEE Website, News Releases Section, 2015, Patent Policy Update. I also test for an anticipation effect of firms. The regression output is presented in the subsequent section.

[49] The patent equation I estimate is of the form:

$$ln(P_{ist}) = \sum_{n=2009}^{2014} \delta_n (dT_{is} * Pre_n) + \sum_{n=2009}^{2014} \delta_n (dT_{is} * Post_n) + X'_{i,t-1}\beta_1 + S'_{s,t-1}\beta_2 + \gamma_i + \gamma_s + \tau_{age} + \epsilon_{ist}$$

Where Pre_n and $Post_n$ are dummy variables equal to 1 for the years of interest.

[50] The results of the econometric analysis are presented in Table (15) in the Appendix.

[51] However, Roth (2022) shows that pre-trend tests are often underpowered, and failure to reject parallel trends could mask important bias from non-parallel trends. He finds that the magnitude of violations of parallel trends against which there is a 50% and 80% power can be sizeable and often comparable in size to the estimated treatment effect.

Table 3
Firms Accounting Characteristics and Patent Portfolio Composition

	Treat	Pool Control	Weighted Control
Total number of firms	61	787	509
Firms characteristics			
Average R&D expenditures per year (millions)	2,403.9	132.1	1,711.4
Average number of employees per year (thousands)	87.2	6.5	72.33
R&D/SALE (%)	12.0	37.6	45.1
Patent portfolio			
Average number of filed patents per firm per year	1,949.8	64.0	1,440.6
Average number of filed standard-related patents per firm per year	172.2	2.5	48.6
Total number of standard-related patents/total number of patents, average per firm (%)	37.8	33.9	36.5

Note: This table summarizes the characteristics of firms and their patent portfolio per type of firm in 2011- 2018.

thousand employees and invest around 2,400 USD million on R&D per year. The R&D investment represents 12% of the total amount of revenue. In contrast, pool control firms are smaller in size, with 6.5 thousand employees, and they invest less in R&D.[52] However, they invest more than 37.6% of the total revenue in R&D. This data suggests that firms declaring patents as essential are unique big firms who invest a small share of their sales, compared to a set of pool firms active in the same industries as essential patent holders. At the same time, they are likely to be heterogenous in their composition. [53]. Indeed, the firms in the treatment group represent a special sample of SEP holders, such that the treatment group consists of some of the world's highest spending firms in terms of R&D investment.[54]

Concerning their patenting behavior, SEP holders patent more than 1,949 patents per year than pool control firms that patent 64 patents on average. Furthermore, the share of the patenting around standardization is around 38% of the total number of patents filed over the entire period of interest for the treatment group. This data suggests that SEP holders' inventions are mainly focused on standard-related technologies, compared to the set of pool control firms (33.9%). There are two likely explanations for these differences. On the one hand, firms that do not declare to hold any essential patent may be the ones that fail to transform their investments into innovation or patent their invention. Thus they result in patenting less compared to SEP holders. On the other hand, it might be that control firms invest a greater contribution in innovation development but decide to keep their inventions secret and benefit from staying outside of the standardization process.

The data suggest that strong differences exist between the treatment and the pool control groups regarding firms' characteristics and patenting behavior.[55] To control for the high heterogeneity across firms and define a comparable control sample, I use the propensity score method to assign weights to control units, as explained in the Methodology section. The statistics regarding the weighted control sample are reported in Column 3 of Table (3). The weighted control group of firms is more similar to those in the treated sample compared to the pool control. However, they still differ in some dimensions with respect to treatment firms. For instance, weighted control firms invest less in R&D activities and file fewer patents in standard-related technology

[52] The average R&D expenditures are around 132 USD million.
[53] This assumption is suggested by the high standard deviations reported in Table (8)
[54] I have included firms providing information regarding their balance sheets on Compustat or Orbis when available. I have included a complete list of all treatment firms in Table (9) in the Appendix.
[55] Detailed summary statistics of the full sample are shown in Table (8) in the Appendix.

classes.[56] Nevertheless, they are similar to SEP holders in terms of size and total patents. The descriptive results suggest that my treatment sample comprises firms characterized by unique features likely to affect firms' standard-related activities.

Table 4
Summary Statistics of IEEE Standards

	2012	2014	2016	2018
Total number of standards	27	27	27	27
Standards characteristics				
Number of SEP holders per standard	148.0	184.2	220.2	236.1
Number of disclosure made per standard	194.1	241.1	285.4	308.8
Number of standard-related patents filed per standard	25,619.9	50,402.4	22,867.5	42,162.9
Number of essential patents declared per standard	3,587.5	4,414.4	5,264.7	5,695.4
Number of standard documents per standard	305.8	368.6	444.0	478.8
Age of the standard at the time of declaration (mean)	7.3	9.8	11.8	13.8

Note: This table summarizes the characteristics of standards issued by IEEE, comparing the cumulative numbers in 2012 and 2014, before the policy revision, to the cumulative numbers in 2016 and 2018. The data regarding the number of standard-related patents are calculated by accounting only for the treatment firms in my sample. Standards ages compute the mean age of standards before and after the policy change.

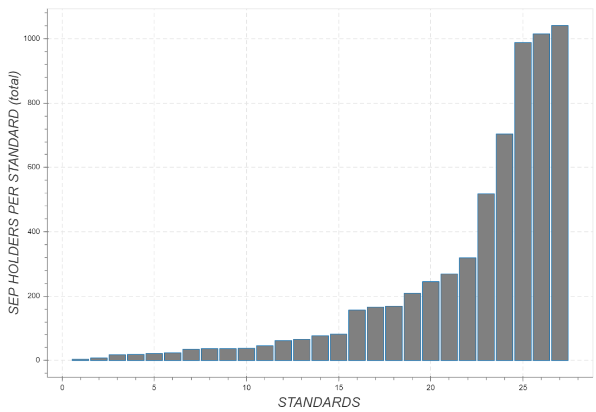
Concerning technology standards, over the 27 standards in the sample, 24 technology standards are classified in the information technology field while 3 standards are in telecommunications.[57] These standards include the 802.1 (LAN/MAN working group), 802.2 (LLC working group), 802.3 (Ethernet working group), 802.11 (WLAN working group), 802.15 (Working Group for Wireless Specialty Networks), 802.16 (Working Group on Broadband Wireless Access), 802.17 (RPR working group), 802.21 (Handover Services working group), 802.22 (WRAN working group), 1394 (PWG working group), 1588 (Precise Networked Clock Synchronization (PNCS) working group), and 1619 (SIS-WG - Security in Storage Working Group). The standards in my sample are heterogenous in their characteristics and importance, as reported by the high variance in the number of 4-digit technology classes associated to each standard.[58] While the most famous standard issued by IEEE is 802.11, also known as WiFi wireless networking standard, other significant IEEE networking protocols included in my sample are Ethernet (802.3), Zigbee (802.15.4), and 1394 (FireWire). The importance of the studied standards is also reflected in the overall number of firms involved in standardization activities and the total patenting around standardization. As shown in Table (4), in 2018, the average number of firms declaring essential patents to the standards in my sample is 236, and the average number of patents filed in standard-related technology classes is more than 42,000 per standard. This data suggests that the interaction and interplay between firms competing for the inclusion of technologies in standards and the innovation exerted in standards development are different parts of a common but complex game played by several agents.

Table (4) reports the summary statistics of the 27 standards, comparing the characteristics of the standards

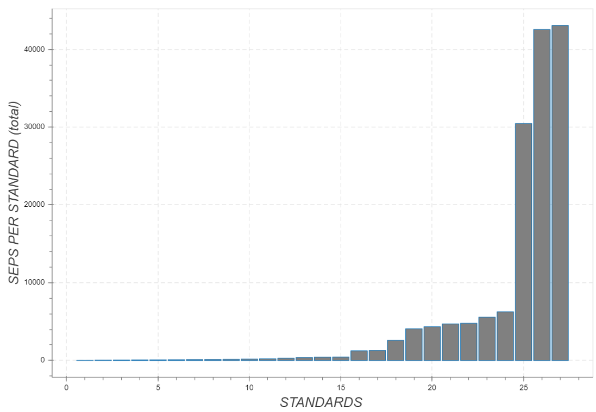
[56] Whether these two dimensions are correlated is an open empirical question.

[57] In order to select the technology standards related to the ICT sector, I follow the International Classification for Standards (ICS) developed by the ISO organization. Specifically, standards with an ICS code of 33 are classified in the Telecommunications field, while standards with an ICS code of 35 are deployed for developing information technologies. See the ISO documentation for a detailed explanation at International Classification for Standards.

[58] Table (10) in the Appendix provides the primary 4-digit technology classes identified as relevant to each of the standards in the sample.



(a) Distribution of SEP Holders per Standards



(b) Distribution of Standard Essential Patents per Standards

Figure 4

These figures show the cumulative number of all SEP holders (left) and standard-related patents (right) filed by SEP holders across the 27 standards in 2018. Data Source: Searle Center Database.

before and after the policy revision. All the variables reported in the table, except for the number of standard-related patents and the age of the standard, are computed, accounting for the whole standard history available in the Searle Center Database. Specifically, I calculate the cumulative values of the characteristics of the standards from the first available year in the database to 2012 in Column 1 and 2014 in Column 2, while Columns 3 and 4 report the cumulative values until 2016 and 2018, respectively. This allows me to provide representational information concerning each standard in the years before and after the policy change. However, since I cannot collect full information regarding the patenting behavior for the population of SEP holders, the number of standard-related patents accounts only for the patents filed by the firms declaring SEPs in my sample in 2011-2018.

While the number of firms declaring standard essential patents increased by 28.2% after the policy change, the number of patents filed in the standard-related technology classes decreased by 16.3% on average. It is unclear whether this decline reflects the impact of the policy revision or a natural decline concerning the life cycles of technology. However, standards in my sample keep growing and evolving: the number of documents composing a standard increased by 29.9% on average after 2014. The new standard documents issued in the years after the policy update can explain the increase in the number of SEP holders and declarations in the same period.[59] However, as reported in Baron and Pohlmann (2018), a large share of declarations made to IEEE are blanket declarations. Therefore my sample accounts for very few specific disclosures related to the complete set of standards issued by IEEE.

Focusing on the distribution of firms among standards, standards in the first quartile have, on average, no more than 35.5 firms declaring essential patents. In contrast, standards in the fourth quartile have 1,041 SEP holders, with an average number of around 236 firms per standard.[60] Furthermore, the distribution of firms among standards is unbalanced towards a subset of big standards projects, as shown in the left graph of Figure

[59]See Table (11) in the Appendix for a comprehensive description of each standard.
[60]The data are computed on the cumulative numbers reported for each standard in 2018.

4. The number of essential patents declared across standards also underlines the presence of a few big projects, as reported in the right graph of Figure 4.[61] The distributions of the patents filed in the standard-related technology classes and essential patents across standards are highly skewed, with few standards holding most of the patents. Indeed, standards in the third and fourth quartiles of the distribution have, on average, 178,858 and 374,329 patents filed in the standard-related technology classes and 4,616 and 43,057 essential patents, respectively. While standards in the first and second quartiles of the distribution have, on average, 23,331 and 49,234 standard-related patents and 126.5 and 438 SEPs declared, respectively. Accounting also for the number of technology classes per standard as a measure of the broadness of a standard project, it is straightforward that the sample is composed of a few broad standards and many minor projects.

6 Results

The following empirical analysis includes four subsections. In Section 6.1, I analyze how firms' standard-related patenting varies, given a change to more restrictive licensing requirements in the IEEE patent policy. In Section 6.2, I investigate whether the decline in standard-related patenting is affected by the policy revision through total patenting or by affecting R&D investments. Section 6.3 widens my analysis by testing for heterogeneity of the effect according to the business model of treatment firms. Lastly, Section 6.4 reports some robustness checks.

6.1 Difference-in-differences results

To test the empirical implication of a more restrictive SDO patent policy on the innovation contributions of firms in a standard, firstly, I analyze the effect of IEEE policy change on firms patenting activity in technology classes related to a set of 27 standards. The dataset is a panel, and the unit of analysis is the firm-standard pair per year.

The results of the estimations of the patent production function are shown in Table (5). Column 1 reports the results of the model based on the unweighted sample. The coefficient of the policy change is negative and highly significant. However, the unweighted sample is prone to a self-selection bias since firms self-select into the treatment and control group due to factors likely to be correlated with the firm's choice of declaring essential patents. The issue of self-selection is particularly important in this specification since the pool control group consists of firms that could declare a patent as essential but have chosen not to.

In Column 2, I report the results of the same model reported in Equation (3) but using a different estimator than the estimates in Column 1. Specifically, I try to address the self-selection problem by running the analysis on the weighted sample of firms.[62] The propensity score methodology considerably reduces unobserved hetero-

[61] The three major standards holding the larger share of SEPs are IEEE 802.16, IEEE 1394, and IEEE 802.11.
[62] See Table (12) in the Appendix for different specifications of the baseline model.

Table 5
Effect of IEEE policy change on firm-standard patenting

	OLS Unweighted	OLS Weighted	OLS Weighted - Anticipation Effect
Dependent Variable			
Standard-related Patents (log)			
Independent Variables			
Post	-0.003	0.330***	0.679***
	(0.007)	(0.067)	(0.123)
dT*Post	−0.632***	−0.518***	−0.678***
	(0.058)	(0.080)	(0.128)
Size (Employees)	0.011***	0.125***	0.129***
	(0.003)	(0.036)	(0.036)
SEP holders per standard (Total)	−0.606***	-0.940	−1.034**
	(0.166)	(1.695)	(0.397)
Standard documents (Total)	0.341*	-0.158	0.377
	(0.177)	(0.923)	(0.315)
Standard-essential patents (Total)	0.415***	1.268	0.977**
	(0.088)	(1.301)	(0.352)
Standard Age FE	Yes	Yes	Yes
Standard FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Number of observations	59,240	59,229	58,310
adj. R^2	0.81	0.92	0.91

Note: All variables are in log form, except for *Post* and $dT * Post$. The dependent variable is the logarithm of the number of patents per firm-standard. The method of estimation is the fixed effect model. Standard errors are in parentheses, and they allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

geneity and strongly improves the fit of the model. Controlling for observed and unobserved factors affecting the decision of a firm to contribute to standards development decreases the magnitude of the effect of a change in the IEEE policy on standard-related innovation. For changes in the IEEE policy, firms that declare the ownership of standard essential patents file on average 14.20 patents less in the standard-related technology classes, which corresponds to 40.4% less compared to the average patents filed by treatment firms in the post-period in the absence of a policy change.[63]

As shown in Figure 2, SEP holders started decreasing the number of patents filed in the standard-related technology classes two years before the policy changed, with a significant decline between 2013 and 2014. To test for an anticipation effect of the policy revision by firms holding essential patents, I compare the patenting activities of treatment and control firms in standard-related technology classes in 2009-2012, excluding observations in the years 2013 and 2014, and the four years after 2014.[64] Column 3 shows the results, taking into account the anticipation effect. As compared to the results in Column 2, the effect of the policy revision on the firms' innovation contribution in standard technologies classes increases in magnitude. Excluding the two years before the policy change leads to a decrease in the innovation contribution of firms by 49.2% (21.9 patents).

The IEEE's more restrictive patent policy has a significant negative effect on firms' standard-related patenting

[63] The effect of the policy change on SEP holders is computed by comparing the estimates of the expected log of standard-related patents in each combination of the dT and *Post* variables. Moreover, since the values are in the log form, I transform the differences between expected values to percentages using the formula $100(e^x - 1)$ where x is the difference between $[log(Patents_{treated,post}) - log(Patents_{treated,pre})]$ and $[log(Patents_{control,post}) - log(Patents_{control,pre})]$.

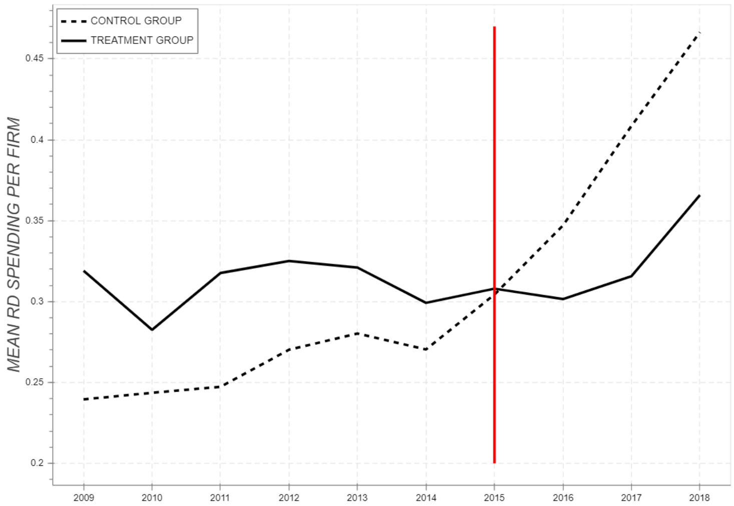
[64] In this specification of the model, the period of interest is 2009-2012/2015-2018.

across all reported specifications. Firms that invest in the development of technologies included in the first version of a standard have the incentive to keep investing in the technological development of future revisions of the standard, as they can benefit from knowledge spillovers generated by the contribution in the previous releases of the standard. In contrast, more restrictive policies can decrease the firms' incentives to declare essential patents and thus reduce the standard-specific innovation in the future development of the standard by affecting the return on standard-related innovation. However, non-declaring firms may also have the incentive to declare SEPs and invest in developing future generations of a standard. Notably, while they failed in developing technologies essential for the first generation, this does not exclude their ability to build on the existing technologies to create new inventions that could be included in future versions of the same standard and so become the owners of essential patents. Therefore, in the same vein, the policy revision is likely to negatively affect the incentives for control firms to declare SEPs and, in turn, their standard-related innovation. Conditional on the impact of more restrictive patent policies affecting the control and the treatment group in the same direction, the estimates of my analysis define the lower bound of the effect of the IEEE policy revision on the incentive for firms in standard-related innovation.

Nevertheless, since I rely on the class-weighted patents filed in the standard-related technology classes to measure the innovation contribution of firms in a standard, the econometric analysis presents some limitations. More restrictive patent policies could simply affect the patenting behavior of firms in standard-related technology classes. For instance, firms might be incentivized to patent fewer developed inventions while keeping investing in creating new technologies essential for a standard. In addition, the literature has provided mixed support for two alternative hypotheses with respect to the relationship between SEPs royalties and innovation. On the one hand, it has been advocated that allowing SEP holders to capture a greater share of the created value from standardization would provide stronger incentives to innovate (Sidak, 2013, 2016; Epstein and Noroozi, 2017). Notably, Layne-Farrar et al. (2014) and Ganglmair et al. (2012) show that a more lenient interpretation of the FRAND commitment can promote innovation and standard participation. On the other hand, while the economic theory suggests that stronger patents can lead to more innovation, that is not always the case (Heller and Eisenberg, 1998). In fact, in a setting where innovation is sequential and complementary, stronger patents can reduce aggregate innovation (Bessen and Maskin, 2009; Galasso and Schankerman, 2015).

Moreover, a weak definition of FRAND-royalty can incentivize firms to over-patent marginal ideas with a little ex-ante value but can still be used to claim a share of the ex-post value from standardization (Kang and Bekkers, 2015; Righi and Simcoe, 2020). Firms may over-patent for a given level of innovation since they can use the technologies protected by patent rights as a bargaining chip in standard-related activities. Therefore the estimated decline in patenting by treatment firms may not be detrimental from a social point of view. More restrictive patent policies might reduce the incentive for excessive patenting by SEP holders, which in turn increases social welfare (Shapiro, 2000; Geradin and Rato, 2007).

Figure 5
Normalized Average R&D Spending per firm and year



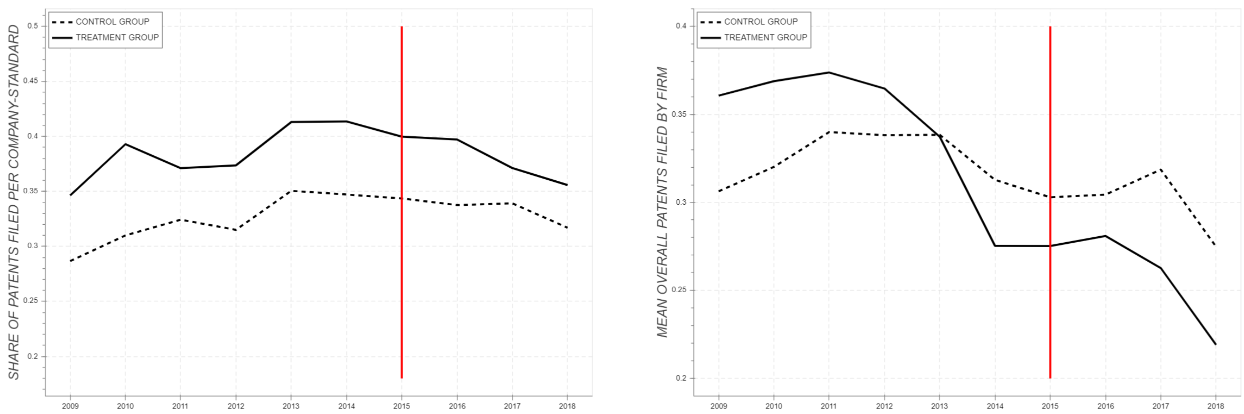
Data Source: Compustat

Lastly, since I observe Chinese firms entering standard-related technology classes and starting patenting intensively in the years before the IEEE policy revision, they are likely to be included in the control group and, as discussed above, affected by the policy change. This would result in biasing the policy change's effect on firms' patenting behavior. However, since I construct a balanced sample of weighted control firms and control for observed firms' specific features in the pre-period, I argue that including this type of firms is unlikely to affect the estimated result.

6.2 Total patents and R&D expenditures

Several mechanisms can explain the decrease in patenting by SEP holders. Specifically, a decline in R&D spending or the overall number of patents filed might explain how the policy change drives the decline in standard-related innovation. As an initial exploitation of the mechanisms behind the policy revision that could potentially affect the decline in standard-related patenting, I plot in Figure 5 the trend of R&D costs for the treatment and the weighted control groups. Since firms in the treatment and control groups are highly heterogeneous in their innovation expenditures, and to avoid comparing averages with a different number of observations, the data are normalized by the value of R&D expenditure in 2005. A firm decline in R&D spending could have driven the observed decrease in the standard-related patents after changing the policy. However, the Figure suggests that both treated and control firms did not decrease their R&D spending after the policy change occurred. Therefore, descriptive evidence supports the hypothesis that a decrease in standard-related innovation is not associated with a decline in the firms' innovation investment.

In Figure 6, I compare the distribution of total patents filed by treated and control firms over time with the share of patents filed in standard-related technology classes over the overall number of patents. While the number of standard-related patents decreases after IEEE changes its patent policy, the share of patents filed in



(a) Share of standard-related patents over total patents (b) Normalized total patents

Figure 6

These figures show the share of standard-related patents over total patents (left) and the total number of patents (right) filed by treated and control firms before and after the IEEE policy change.

the standard-related technology classes stays constant throughout the period of interest, as shown in the left graph of Figure 6. Since ICT standards issued by different organizations are likely to share multiple technology classes, it might be that firms holding essential patents at IEEE moved to other organizations with more favorable policies after the IEEE policy revision. On the other hand, firms might have decreased the total number of filed and standard-related patents, which would explain a constant share over time. As shown in the right graph of Figure 6, SEP holders started filing fewer patents after 2013 on average. Even if the number of patents declined for firms in the control group after this year, it increased after the policy change, with a relative pick in 2017. In order to test whether a decline in the standard-related innovation at IEEE is driven by a decrease in the overall amount of filed patents rather than by a substitution effect to other standard technologies, I test for the effect of the policy update on the total number of patents.

To empirically investigate the mechanisms behind the policy revision that drove the decreasing number of standard-related patents filed after 2015, I run two other specifications of my model, with R&D costs and total patents as dependent variables. The results are presented in Table (6). Since the patent policy endorsed by the organization can affect the firm's decision on the amount of the innovation investment to allocate for the development of standard-related technologies by affecting their return on innovation, I estimate the effect of the policy change on the overall R&D investments at the firm level (Columns 1 and 2). The coefficient of the variable of interest is not statistically significant, suggesting that the policy revision did not affect the R&D investment of firms. This outcome, combined with an increase in the normalized average R&D spending by treated firms after 2015, as shown in Figure 5, suggests that the decrease in the number of standard-related patents is unlikely to be explained by a decline in the innovation investment of firms.

Furthermore, the decrease in the number of standard-related patents can be driven by a decline in the total number of patents filed in the years after the policy revision. Even if I do not observe a decrease in measures that can affect the number of filed patents, such as R&D expenditures and sales, I observe a decline in the

Table 6
Effect of IEEE policy change on outcomes

	OLS Weighted	OLS Weighted - Anticipation Effect	OLS Weighted	OLS Weighted - Anticipation Effect
Dependent Variable	R&D expenditure	R&D expenditure	Total patents	Total patents
Post	-0.160^{***}	-0.072	0.433^{**}	0.745^{***}
	(0.050)	(0.060)	(0.068)	(0.147)
dT*Post	0.063	0.091	-0.390^{**}	-0.494^{**}
	(0.054)	(0.059)	(0.060)	(0.103)
Size (Employees)	0.482^{**}	0.511^{***}	-0.064	0.012
	(0.076)	(0.079)	(0.062)	(0.056)
SEP holders per standard (Total)	-0.685^{*}	-0.381	-0.736	-0.767^{*}
	(0.404)	(0.399)	(1.587)	(0.457)
Standard documents per standard (Total)	0.367^{*}	0.350^{**}	-0.124	0.175
	(0.254)	(0.151)	(0.865)	(0.304)
Standard-essential patents (Total)	0.448	0.204	0.878	0.765^{*}
	(0.364)	(0.326)	(1.304)	(0.411)
Standard Age FE	Yes	Yes	Yes	Yes
Standard FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Number of observations	53,164	51,952	53,167	51,956
adj. R^2	0.98	0.97	0.93	0.92

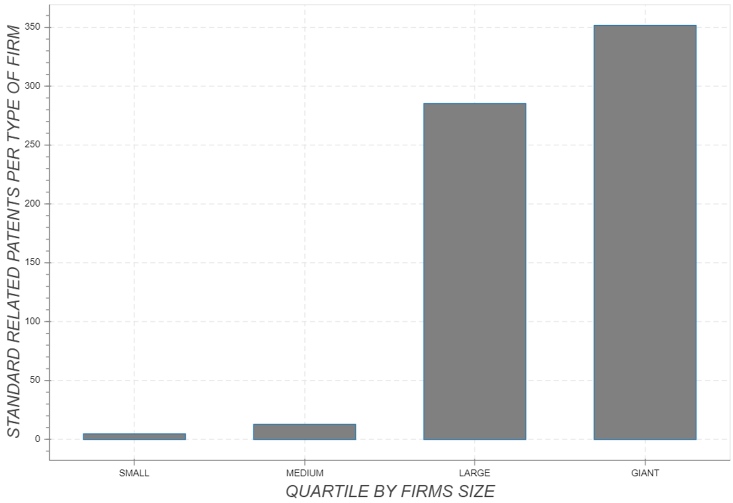
Note: All variables are in log form, except for $Post$ and $dT * Post$. The dependent variable in the first two columns is the R&D expenditure per firm-year. The dependent variable in the last two columns is the logarithm of the number of total patents per firm-year. The method of estimation is the fixed effect model. Standard errors are in parentheses, and they allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

overall number of patents filed by firms in the post-period. Columns 3 and 4 in Table (6) report the results of the baseline model, using the total number of filed patents as the dependent variable. The policy revision has a statistically significant effect for both the weighted sample and when accounting for an anticipation effect. Moreover, the effect is lower in magnitude compared to the same effect on standard-related patents. Since standard-related patents are included in the count of the overall number of patents, the dependent variable is still affected by the policy change. This explains why I observe a statistically significant but weaker effect on total patents. These results suggest that the policy revision has a weak effect on the total number of filed patents by SEP holders, and thus it is unlikely that the decrease in standard-related innovation at IEEE is correlated to a decline in the absolute number of patents.

6.3 Heterogenous IPR policy effect

Even though the fixed effects and the set of standard-specific control variables should deal with the issue of heterogeneity within treatment firms, some unobserved firm-specific features are likely to be correlated to the firms' innovation in standards development that the model does not capture. For instance, pure R&D innovators are more likely to be negatively affected by patent policy changes concerning licensing requirements compared to vertically integrated firms since they are more reliant on intellectual property rights to earn the return on the developed inventions. Vertically integrated firms can instead face an incentive to increase their innovation contribution in a standard due to a change to more restrictive rules (Bekkers et al., 2017; Spulber, 2019). A decrease in the price of the standard technologies can increase the demand for the patented technologies and, thus, the final good by lowering its production costs. So, given the heterogeneity of the contributors involved in standards development, the decisions made by the SDO can have a significant and divergent effect on the

Figure 7
Distribution of standard-related patents by size of firms



Note: The reported numbers of total patents are divided by 1000.

willingness to contribute by firms with different business models.

To show evidence documenting the relationship between the size of a firm, its business model, and its patent portfolio, I start by plotting the distribution of standard-related patents over firms according to their size. Figure 7 suggests that most of the patents are held by a set of few very large firms (fourth quartile of the distribution). In contrast, small and medium-size firms hold a few shares of standard-related technologies protected by intellectual property rights.

To better understand whether firms in the third and fourth quartile of the distribution are also vertically integrated, I classify each firm in my treatment sample according to its business model. I rely on the list of licensors and licensees of a set of patent pools to identify the business model of the 61 firms in my sample. Starting from the idea that if a firm is both a licensor and licensee in a given patent pool is likely to both develop the technologies that are necessary for the implementation of the standard, and so it is the owner of standard essential patents and to use the standard for the production of downstream goods, I classify a firm as vertically integrated when it is present in both lists. From my data collection, I am able to retrieve information on 49 firms out of 61. Moreover, of those firms I have information on, 32 are coded as vertically integrated, while 17 as either licensor or licensee.[65]

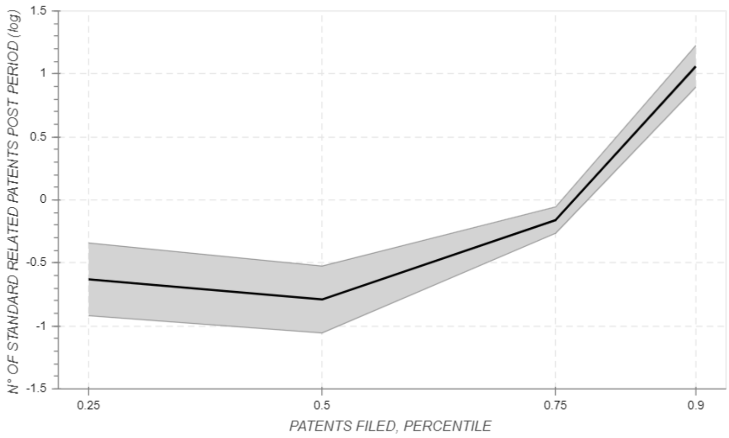
Figure 8 plots the 61 treated firms by their size, in terms of the number of employees, and patent portfolio, according to their business model. Specifically, I classify firms into two types according to their business model:

[65] Since it is hard to determine firms' business model, especially regarding firms that develop technologies for standards that can be implemented in a wide range of products, I follow this novel patent pool strategy to classify firms as vertically integrated with respect to standard projects. Nevertheless, this methodology presents several limitations. First, I cannot observe the complete set of licensors and licensees for all patent pools worldwide. However, I can collect information on a subset of patent pools for which I have available data. Therefore, some firms classified only as licensors or licensees in my sample might be vertically integrated into other patent pools outside my sample. Besides, regarding the 20 firms for which I do not observe any information, it could be that those firms are vertically integrated but have decided to refrain from joining any patent pool to gain more bargaining power in cross-licensing negotiations.

Figure 8
Vertically Integrated Firms and Patent Portfolios

Note: The reported numbers of total patents are divided by 1000.

Figure 9
Treatment Effect on the Treated



vertically integrated and not vertically integrated. I also assume that the companies that I have no information for are not vertically integrated. The Figure shows that vertically integrated firms are the ones bigger in size and with larger patent portfolios. Besides, comparing this Figure with Figure 6 and taking into account the specific firms included in each quartile, the data suggest that vertically integrated firms are also the ones holding the larger share of declared essential patents for standards.

I extend my analysis of the heterogeneity in the policy revision by empirically investigating the effect of a more restrictive patent policy on the innovation contribution of firms in a standard, according to their sizes. For this purpose, I rely on the changes-in-changes methodology (Athey and Imbens, 2006). Athey and Imbens (2006) and develop a non-linear difference-in-differences model which allows for heterogeneous changes over time and across groups in the effect of interest. Given the high degree of heterogeneity in the incentives firms face to contribute to the development of a standard, it is likely that the policy change affects firms differently at different points in the distribution. The results are shown in Figure 9.[66] The effect is strong and negative for the

[66]The estimates of the econometric analysis are reported in Table (16) in the Appendix

mean ranks of the distribution (25th to 75th percentiles), but the coefficient of interest turns positive for the 90th percentile. Since vertically integrated firms usually build large patent portfolios, while R&D innovators are small firms that concentrate their innovation around few but valuable patents, the results of the analysis may hint at a negative effect of the policy change on those firms that depend on the monetization of innovations, while it affects positively firms that usually use the technology standard as input and benefit from the selling of the end products. Notably, vertically integrated firms can benefit from their involvement in standard setting through the sales of downstream standard-related products. However, since they require the implementation of the standard, they are likely to be involved in cross-licensing negotiations with all the owners of standard-essential patents. Therefore, giant firms, which are shown to be vertically integrated as suggested in Figure 8, might face an incentive to increase the number of standard-related patents (1) to increase their bargaining power in cross-licensing negotiations and (2) to assure a larger share of the ex-post surplus from standardization.

6.4 Robustness

Table 7
Effect of IEEE policy change on outcomes - Robustness check

	OLS Bluetooth	OLS Placebo	OLS Placebo
Dependent Variable			
Standard-related Patents (log)			
Independent Variables			
Post	-0.064	0.035	-0.088
	(0.183)	(0.094)	(0.052)
dT*Post	-0.092	-0.119	-0.076
	(0.199)	(0.080)	(0.055)
Size (Employees)	0.058***	0.051**	-0.011
	(0.012)	(0.018)	(0.009)
SEP holders per standard (Total)	-0.915	-0.300	-0.352
	(1.881)	(0.267)	(0.587)
Standard documents per standard (Total)	-0.187	0.318**	0.187
	(1.075)	(0.139)	(0.478)
Standard-essential patents per standard (Total)	1.293	0.063	0.068
	(1.384)	(0.178)	(0.246))
Standard Age FE	Yes	Yes	Yes
Standard FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Number of observations	1,652	18,818	18,737
adj. R^2	0.91	0.88	0.88

Note: The dependent variable is the number of standard-related patents in all specifications. The first column tests for the effect of firms contributing to the Bluetooth working group as the treatment group and weighted control firms as the control group. The baseline weighted sample is used in Columns 2 and 3. The period of interest in the second Column is 2008-2011. In contrast, the period of interest in the third Column is 2007-2010. The method of estimation is the fixed effect model. Standard errors are in parentheses, and they allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Several other policy changes involving the licensing of standard essential patents occurred at the time that IEEE revised its patent policy (the DOJ policy on SEP licensing[67], *InterDigital vs. Nokia* in the ICT Court [68], and *Huawei vs. ZTE* in the Court of Justice of the European Union[69]). Therefore the impact of the revised IEEE IPR policy can be confounded with other changes that took place over the same period. The court decisions, and the rules that derived, involved the threat of injunctions that SEP holders can exert by excluding licensees from the licensing negotiations of essential patents and the burden of proof for evidence of patent hold-up by the licensor and reverse hold-up by implementers. Since the subject of the disputes concerned FRAND licensing for standard-essential patents, all the related policies could potentially blur the causal interpretation of my results. Notably, the decline in standard-related patenting by SEP holders could have been the result of the less favorable (for SEP holders) decision in *Huawei vs. ZTE.*

To test for other policy forces affecting the results of my analysis, I run a difference-in-differences model where the treatment group is defined by the firms declaring essential patents to standards issued by the Bluetooth working group, and the control group is defined by a set of weighted firms that have not declared any patents as essential to Bluetooth standard. Bluetooth working group within IEEE is subject to additional royalty-free requirements. Therefore, if other policies drive the decline in standard-related patents by SEP holders, I expect to observe an effect on Bluetooth firms after the policy revision. Nevertheless, if only the more restrictive IEEE patent policy in 2015 caused a change in the patent behavior of firms, and since the policy revision led to the definition of a FRAND royalty higher than a royalty-free commitment, I should not observe any statistically significant effect on the patents filed in Bluetooth standard-related technology classes in the post period. The results are presented in Column 1 of Table (7). The coefficient is not statistically significant for the weighted Bluetooth sample, which tends to speak against the presence of other factors affecting my results.[70]

Besides, as additional robustness checks and to test for an effect on outcomes that are known to be unaffected by the policy change, I run two other specifications of the baseline model, taking into account the time frame 2008-2011, assuming that the policy change occurred in 2010 (Column 2 of Table (7)) and I have tested for a policy effect on standard-related patents in 2007-2010 and a hypothetical policy change in 2009 (Column 3 of Table (7)). I find no statistically significant effect of either assumed policy revision. Other robustness checks are presented in the Appendix.[71] Specifically, I use two-year lagged covariates to check for possible bias in the

[67]In 2013, the USPTO and the DOJ jointly issued a policy statement related to remedies for infringement of standards-essential patents subject to voluntary F/RAND commitments. That statement noted that "while in some circumstances, an exclusionary remedy for infringement of a standards-essential patent subject to a F/RAND commitment may be inconsistent with the public interest for those patents, an exclusionary remedy may be appropriate in other circumstances, such as when the potential licensee constructively refuses to engage in a negotiation to determine F/RAND terms." *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..

[68]In 2015, in the case of *InterDigital vs. Nokia* the ICT determined no evidence of patent-hold up by InterDigital, but it found evidence of reverse hold-up by Nokia issuing an exclusion order in favor of the SEP holder. In reaching this conclusion, the ICT did not require the SEP holder to prove that the standard implementer was unwilling to be involved in negotiations involving a FRAND licensing.

[69]In *Huawei vs. ZTE* the Court of Justice of the European Union ruled that the holder of a standard essential patent that has committed to license SEPs on FRAND terms may be found in breach of the competition rules (Article 102 TFEU) by seeking an injunction against a potential licensee in certain circumstances. In doing so, the ECJ defined several steps that should be followed in SEP patent licensing negotiations.

[70]It should be noticed that this is a simplification of the baseline and that it presents several shortcomings.

[71]I have also tested for an effect of the policy change, using the citation-weighted patents as the dependent variable of my specification. See Table (13) in the Appendix for the results on citation-weighted patents.

timing between when the innovation costs occur and the application of the patents. All specifications controlling for two-year lagged variables lead to similar results as in the baseline model[72].

7 Conclusion

SDOs have changed their patent policies over the years to prevent strategic behaviors by SEP holders. As the patent policies regarding SEPs became more restrictive for owners of standard essential patents, they focused more on users and implementers of the standard technologies. Since it is also important to understand how strengthened patent policies affect the innovation contribution of innovators in standards development, this paper contributes to the literature by empirically analyzing the effect of IEEE patent policy revision on the standard-specific patenting behavior of firms holding essential patents.

My results show a negative relationship between the number of class-weighted patents filed by SEP holders in the standard-related technology classes and the degree of restrictiveness of IEEE patent policy. SEP holders reduce, on average, their innovation contribution to standards by 40.4% after the policy revision. To investigate how the policy change drives the decline in standard-related patents, I test for the effect of the policy change on other factors that might be correlated with the innovation contribution of firms in standardization. Specifically, the decrease in the overall number of filed patents or R&D expenses at the firm level can explain the lower number of patents filed in standard technology classes. After testing for other factors, my results suggest that the decrease in the absolute number of patents and R&D costs are unlikely to be drivers of the decline of the innovation contribution of SEP holders in technology standards.

This research sheds some new light on how SDOs patent policies affect the firms' incentive to innovate in standards development, by studying the effect of a more restrictive (for SEP holders) patent policy on the class-weighted patents filed in the 4-digit technology classes at the firm level. Several issues are left for future research. First, not only has IEEE changed its policy, but other SDOs have also updated their licensing requirements. In order to better understand the relationship between standard developers and patent policy requirements, further research should focus on extending the model to several policy changes at different points in time.

Besides, firms declare essential patents to multiple standards issued by several organizations, and technology standards in the ICT sector share multiple technology classes. The decrease in the number of patents filed by SEP holders in the technology classes related to standards issued by IEEE might have been balanced by a reallocation of the firms' investments in standards issued by other organizations, implying a consequent increase in standards-related innovation. Even if I observe a decrease in the total number of patents filed by firms after

[72] The results of the econometric analysis are presented in Table (14) in the Appendix.

the policy change, the share of patents filed in the standard-related technology classes over total patenting remains constant over the entire period of interest. This evidence suggests that firms might substitute away to other technology standards issued by other standard development organizations.

Lastly, firms face different incentives to invest in standards according to their type of business (pure R&D innovators and vertically integrated firms), and they declare multiple patents to multiple standards in other SDOs. Modeling the movement of firms among technology standards can shed more light on the strategic behavior of firms, their incentive to invest and patent inventions in technology standards, and how to promote competition via SDOs patent policies.

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8 Appendix

8.1 Procedure of IEEE policy revision

The process of the IEEE policy revision started on March 13, 2014, when the Patent Committee (PatCom) appointed an Ad-Hoc Committee to consider and recommend updates to the IEEE patent policy. The reasoning behind the decision of the organization to revise its policy was that "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 "reasonable rates" for potential SEP licenses. " [73]. This view was reinforced by the DoJ, the FTC, and the European Commission, which expressed the need for policy clarifications.[74] Following a 15-month long process and the reception of more than 600 comments, the Ad-Hoc Committee approved a revised version of the fourth public draft in June 2014 and forwarded it to the Standards Board for consideration. On August 2014, the Standards Board voted to approve the proposed policy revision from PatCom and to recommend that the Board of Directors approve the policy.

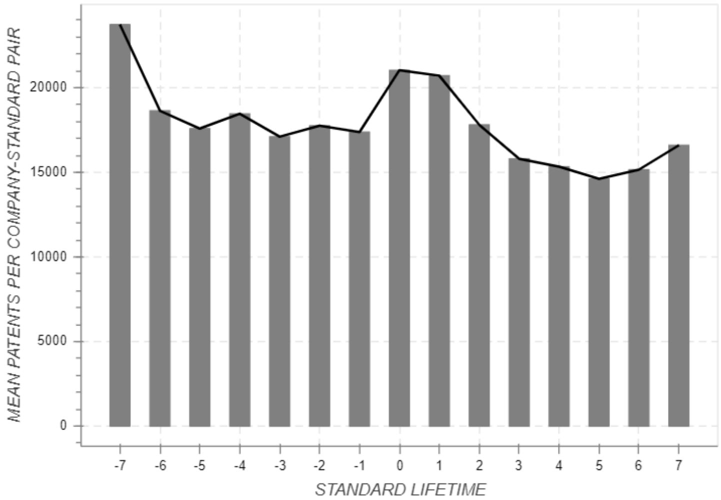
On February 2015, the US DoJ issued a Business Letter supporting the policy revision, stating that "the policy revision has the potential to benefit competition and consumers by facilitating licensing negotiations, mitigating hold up and royalty stacking, and promoting competition among technologies for inclusion in standards." (**?**). Finally, the Board of Directors approved the revisions on February 8, 2015, and the new patent policy became effective in March 2015.

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

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

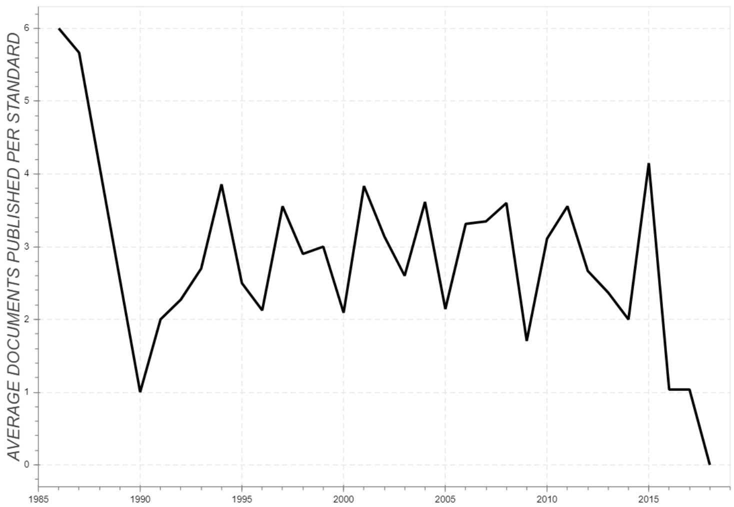
8.2 Graphs and Tables

Figure 10
The average number of patents filed in years before and after the standard publication



Data Sources: Searle Center Database, PATSTAT

Figure 11
The average number of standard documents published per standards over years



Data Source: Searle Center Database

Table 8
Summary Statistics of the variables in the time period 2009-2018 for the weighted sample

	Data source	Mean	SD	Min	Max
Patents filed in standard-related classes	PATSTAT	48.8	407.7	0	14,291.0
Patents filed total	PATSTAT	166.3	929.1	0	19,934
Lag1 R&D Expenses (USD billions)	Compustat	214.7	901.3	0	14,863.9
Lag1 Firm Size (thousands)	Compustat	8.8	34.7	0	726.8
Lag1 Sales (USD billions)	Compustat	3,489.3	14,904.6	0	253,347.3
Treat (dT)	SCDB	0.02	0.15	0	1
Standard Age (at the time of declaration)	SCDB	4.5	6.8	-4.0	33.0
Broadness of standard (Total number of IPC classes per standard)	SCDB	13.3	24.0	1	90
Essential patent holders	SCDB	0.6	1.2	0	7.0
Standard documents	SCDB	1.23	2.7	0	14.0
Standard-related patents filed per standard (Total)	6,802.0	11,806.8	9.2	45,363.0	
Essential patents	SCDB	7.1	25.8	0	222.0
Declarations	SCDB	0.6	1.3	0.0	8.0
Number of employees per SEP holder-standard pair (thousands)	50.6	64.0	14.1	391.5	
R&D expenditures per SEP holder-standard pair (billions)	1,777.6	1,975.7	598.8	7,583.6	

Table 9
Treatment firms

Firm Name
ELEKTROBIT
AT&T INC.
INTEL CORPORATION
MOTOROLA SOLUTIONS, INC.
NOKIA
CISCO SYSTEMS INC
ALCATEL-LUCENT S.A.
HUAWEI TECHNOLOGIES
QUALCOMM INC
KYOCERA
AVAYA
FUJITSU LIMITED
RENESAS ELECTRONICS CORPORATION
KAPSCH AG
DIGITAL OCEAN
CSR - CAMBRIDGE SILICON RADIO
BLACKBERRY LIMITED
KPN
PHILIPS
NTT
ALVARION LTD.
NEC CORPORATION
PANASONIC CORPORATION
TEXAS INSTRUMENTS INC
MITSUBISHI CORPORATION
INTERDIGITAL COMMUNICATIONS
SAMSUNG ELECTRONICS CO, LTD
BAE SYSTEMS
CERTICOM
ORANGE SA
TECHNICOLOR
APPLE INC.
SYMBOL TECHNOLOGIES, INC.
TOSHIBA
UNIPER NETWORKS
LG ELECTRONICS
MICROSOFT CORP
SONY CORPORATION
SIEMENS AG
BROADCOM CORP
ARUBA NETWORKS
INTERSIL CORP
ERICSSON AB
HITACHI LTD
ADTRAN, INC
LINEAR TECHNOLOGY CORP.
FREESCALE SEMICONDUCTOR, INC.
AWARE
SANYO
MEDIATEK INC
WI-LAN INC.
NOKIA SIEMENS NETWORKS
TOUMAZ
IBM
EXTREME NETWORKS INC
BROCADE COMMUNICATIONS SYSTEMS, INC.
NUOVA SYSTEMS
HEWLETT-PACKARD COMPANY
COMTECH TELECOMMUNICATIONS CORP.
AGILENT TECHNOLOGIES INC
CIENA

Table 10
Standards and the associated 4-digit IPC classes

Standard	4-digit IPC classes
IEEE 1394	H04J H04L G06F H04B G01R C07K A61K H03K H03M A61M H04N C12N B65D H02M G09F H04Q A61H A63B G01C B29C E04C E06B G08C F23K F02M B62K A47G H04M H05H D04H B25B B25G C12Q C12M G01N B32B D06M A21C F16P D04D A47B A45B B65H H01R C07D B60P B41F H02G G06T G08B B01J C01B C09C G10D G11B E04B E04H A44B A44C B02C B42D B23P F16L A01H C08J C08L G05G H02B A47J A01B F16D G03B F24F C07C C11C C11D F03B B63H A01K A43B A43C E05C H04R G03F H01L
IEEE 1588	G06F H04J
IEEE 1619.1	G06F G11B
IEEE 802.11	H04L H04W H04J H01L C09K H01S C23C A61F B32B D04H C07D A61K A61P F02B C12N C07K C12Q H01R B60L B60K F16F C03B C03C G02B D06F G10K H04R A01N B64D F02C H01B C09D H01C H05B H05K H02P A61L F17C B01J G01R F04B F01N B01D F16H B41J C07C C07B G06F G10D G10G G06Q C07F B22D B65G A61B G01N G01S B64F C08B D06M C07H G07F H04B H03D C12P C12R B60N F16L F24J A43B H05F G06T B28D A61N H02K A61Q C08G C08L G01C G09G G02F B43L G09F B23K B23P F01D A63B H04Q G08C H03M
IEEE 802.11a	H04B H04J H04L B65D G02B B60K C06B H03M H04H D01G H04N D21F G04F
IEEE 802.11aa	H04W H04L H04B
IEEE 802.11ac	H03M H04L H04B H04W H04J H04K H04H C07K A61K G06F B62J H01L H03C C25C H04M C12N C12Q A01H B65G A47J C23C A61H A01D A47C H01R E03D H01Q H04Q H05K B41J A47L A61P C07D F16B G02B A47K C03C G01N F24C B27B G08B H04N B65D B60K
IEEE 802.11g	H04B H04J H04L B65D G02B B60K C06B H03M H04H D01G H04N D21F G04F
IEEE 802.11n	H04B H04L H04W A01N A01P H04N H03M G06F G08C H04J
IEEE 802.11r	H04B H04L
IEEE 802.11s	H04L H04W
IEEE 802.11u	H04W H04B
IEEE 802.11w	H04L H04B H04W
IEEE 802.15.3	G06F H03M
IEEE 802.15.4	H03M H04B H04J H04L
IEEE 802.15.6	H04K H04L H04B H04J E04F E04G
IEEE 802.16	H04J H04L H04H H04M H04N H04W H04B H04Q A61K A61P C07D C07C C07F H03M G06F A61B C06B D01G D21F G01B B60C B60G B60R B60T G08C G01D F16M B23B C12N G06N G01N C12Q F23K F23B
IEEE 802.16a	H03M H04L
IEEE 802.16e	H04L H04W H04J B62D B60R H04B F04B H03M H04H H04N G11B B21D B23P H01L H05K A47F H01B H01R G06F A01K A47C A47G G05F C08F G03F H01J G01L
IEEE 802.17	H04J H04L
IEEE 802.1Q	H04L H04B
IEEE 802.1ah	H04J H04L
IEEE 802.1aq	H04L G06F
IEEE 802.2	H04L H04W H04J
IEEE 802.21	H04W H04L H04M
IEEE 802.22	H04L H04W H04J H03M
IEEE 802.3	H05B H05K

Table 11
Summary Statistics of the Technology Standards

	SEP holders (Total)	Disclosures	standard-related Patents (Total)	Essential Patents (Total)	Age(max)	Employees (mean)	R&D Expenditure (mean)
IEEE 1394	57.0	154.0	312,838.0	2336.0	23.0	164.8	4,589.1
IEEE 1588	8.0	8.0	801.0	144.0	16.0	154.2	5,557.5
IEEE 1619.1	8.0	8.0	78,282.0	40.0	11.0	311.6	4,116.6
IEEE 802.11	69.0	69.0	425,738.0	2544.0	21.0	94.9	2,792.9
IEEE 802.11a	31.0	31.0	72,630.0	750.0	19.0	126.8	2,890.4
IEEE 802.11aa	14.0	14.0	36,110.0	18.0	6.0	59.6	4,838.3
IEEE 802.11ac	108.0	110.0	432,600.0	645.0	5.0	80.5	3,673.8
IEEE 802.11g	32.0	32.0	36,676.0	728.0	15.0	58.7	1,403.4
IEEE 802.11n	74.0	76.0	368,669.0	664.0	9.0	96.0	2,9992.1
IEEE 802.11r	20.0	20.0	52,206.0	44.0	10.0	76.3	4,330.9
IEEE 802.11s	48.0	48.0	225,185.0	128.0	7.0	97.3	3,134.9
IEEE 802.11u	22.0	22.0	64,318.0	64.0	7.0	57.8	3,497.8
IEEE 802.11w	14.0	14.0	45,159.0	28.0	9.0	73.9	6,156.2
IEEE 802.15.3	16.0	16.0	30,122.0	180.0	15.0	81.5	2,586.3
IEEE 802.15.4	16.0	16.0	15,119.0	110.0	15.0	61.2	4,619.4
IEEE 802.15.6	24.0	26.0	60,006.0	46.0	6.0	55.8	3,006.8
IEEE 802.16	86.0	90.0	391,570.0	5026.0	17.0	96.7	3,999.9
IEEE 802.16a	22.0	22.0	7,277.0	100.0	15.0	63.8	2,339.9
IEEE 802.16e	42.0	42.0	403,288.0	696.0	13.0	92.8	2,685.5
IEEE 802.17	16.0	16.0	49,331.0	136.0	14.0	86.9	5,256.4
IEEE 802.1Q	62.0	72.0	88,856.0	1116.0	20.0	100.7	2,667.4
IEEE 802.1ah	12.0	12.0	29,227.0	76.0	10.0	124.9	3,328.6
IEEE 802.1aq	10.0	10.0	8,098.0	42.0	6.0	59.3	2,690.5
IEEE 802.2	24.0	24.0	169,774.0	444.0	33.0	83.2	3,249.7
IEEE 802.21	32.0	34.0	151,167.0	318.0	10.0	94.6	4,072.9
IEEE 802.22	36.0	36.0	142,298.0	276.0	7.0	89.9	3,399.6
IEEE 802.3	38.0	38.0	195.0	826.0	33.0	128.4	2,419.3

Table 12
Effect of IEEE policy change on firm-standard patenting - Full specification

	OLS Weighted	OLS Weighted	OLS Weighted	OLS Weighted
Dependent Variable				
Standard-related Patents (log)				
Independent Variables				
dT				1.503***
				(0.219)
Post	0.383***	0.361***	0.355***	- 0.044
	(0.057)	(0.058)	(0.068)	(0.086)
dT*Post	−0.558***	−0.531***	−0.546***	−0.617***
	(0.071)	(0.072)	(0.079)	(0.092)
Size (Employees)		0.120***		0.281***
		(0.035)		(0.043)
SEP holders per standard (Total)			-0.822	0.388
			(1.656)	(0.421)
Standard documents (Total)			-0.205	-0.078
			(0.940)	(0.189)
Standard-essential patents (Total)			1.178	−0.412**
			(1.248)	(0.187)
Standard Age FE	Yes	Yes	Yes	No
Standard FE	Yes	Yes	Yes	No
Firm FE	Yes	Yes	Yes	No
Number of observations	60,075	59,229	60,075	59,229
adj. R^2	0.92	0.92	0.92	0.14

Note: All variables are in log form, except for $Post$ and $dT * Post$. The dependent variable is the logarithm of the number of patents per firm-standard. The method of estimation is the fixed effect model. Standard errors are in parentheses, and they 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 on firm-standard patenting - Citation-weighted patents

	OLS Unweighted	OLS Weighted	OLS Weighted - Anticipation Effect
Dependent Variable			
Standard-related Citation-weighted patents (log)			
Independent Variables			
Post	0.015	0.565***	1.477***
	(0.015)	(0.114)	(0.236)
dT*Post	−1.041***	−0.811***	−1.209***
	(0.122)	(0.158)	(0.236)
Size (Employees)	0.002	−0.187*	-0.170
	(0.004)	(0.092)	(0.103)
SEP holders per standard (Total)	−1.387***	-1.563	−2.079***
	(0.343)	(3.421)	(0.603)
Standard documents (Total)	0.815**	-0.119	0.506
	(0.355)	(1.828)	(0.578)
Standard-essential patents (Total)	0.883***	1.879	1.987***
	(0.187)	(2.620)	(0.558)
Standard Age FE	Yes	Yes	Yes
Standard FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Number of observations	53,177	53,166	51,953
adj. R^2	0.82	0.91	0.91

Note: All variables are in log form, except for *Post* and $dT * Post$. The dependent variable is the logarithm of the number of citation-weighted patents per firm-standard pair. The method of estimation is the fixed effect model. Standard errors are in parentheses, and they 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 outcomes - 2 Years Lag

	OLS Unweighted	OLS Weighted	OLS Weighted - Anticipation effect
Dependent Variable			
standard-related patents (baseline specification)	−0.465***	−0.406***	−0.526**
	(0.084)	(0.077)	(0.139)
Citation weighted patents (baseline specification)	−0.732**	−0.700**	−0.473*
	(0.218)	(0.214)	(0.186)
Total Patents	−0.358**	−0.405*	−0.348***
	(0.138)	(0.39)	(0.047)

Note: The method of estimation is the fixed effect model. Standard errors are in parentheses, and they allow for serial correlation through clustering by firm-standard pair. The covariates of the primary specification are R&D expenditures, number of employees, number of SEP holders, the total number of patents and number of disclosures per standard, age of the standard, firm, standard, and year fixed effects. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 15
Effect of IEEE policy change on firm-standard patenting over time

	OLS Unweighted	OLS Weighted
Dependent Variable		
Standard-related patents (log)		
dT		
dT*2010	-0.004	0.043
	(0.026)	(0.069)
dT*2011	-0.061	-0.085
	(0.037)	(0.078)
dT*2012	0.008	-0.063
	(0.038)	(0.072)
dT*2013	-0.067	−0.240**
	(0.044)	(0.102)
dT*2014	−0.194*	−0.212*
	(0.058)	(0.129)
dT*2015	−0.409***	−0.459***
	(0.072)	(0.136)
dT*2016	−0.557***	−0.528***
	(0.085)	(0.188)
dT*2017	−0.898***	−0.829***
	(0.086)	(0.159)
dT*2018	−0.998***	−1.094***
	(0.084)	(0.147)
Standard Age FE	Yes	Yes
Standard FE	Yes	Yes
Firm FE	Yes	Yes
Firm Characteristics (Size)	Yes	Yes
Standard Characteristics (Total SEP holders, Total SEPs, Total documents per standard)	Yes	Yes
Number of observations	73,726	73,708
adj. R^2	0.80	0.91

Note: The dependent variable is the number of patents per firm-standard pair. The method of estimation is the fixed effect model. The coefficients of interest are the interaction terms between treatment indicators and year indicators. Standard errors are in parentheses, and they allow for serial correlation through clustering by firm-standard. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ significant levels.

Table 16
Results of the Changes in Changes - Effect of the Treatment on the Treated

	OLS mean log	OLS 25th	OLS 50th	OLS 75th	OLS 90th
Methodology					
Did-log	-0.549	-0.38	-0.45	- 0.56	-0.74
cic disc	-0.420	-0.63	-0.79	-0.16	1.06
cic disc lower bound	-0.441	-0.63	-0.79	-0.16	1.06
cic disc upper bound	-0.401	-0.63	-0.79	-0.16	1.06