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Cooperation and Competition: The Case of Innovation in the Telecommunications Sector

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This paper proposes a novel framework for analyzing collaborative innovation that captures both competition and cooperation among firms, and examines the impact of private appropriation through IP rights licensing on firms' incentives to innovate and on the overall outcome. I show that when developing technology together firms compete and cooperate, and that the intensity of each force depends on their technological similarity and business model. To study the net effect of these forces in equilibrium, I focus on the standardization of mobile telecommunications technologies and use a novel dataset on the development of 3G and 4G standards to estimate my model. I show that enforcing royalty-free clauses reduces the participation and contributions of firms, delaying the completion of the initial release of 4G by almost one year beyond the almost 3 years it took to develop.

KEYWORDS

Innovation in teams, Telecommunications standards, Inter-firm collaboration, Patents, Complementarities, Competition

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Cooperación y competencia: el caso de la innovación en el sector de telecomunicaciones

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Este trabajo propone un marco novedoso para analizar la innovación colaborativa que incorpora, de manera conjunta, la competencia y la cooperación entre empresas, y evalúa cómo la apropiación privada mediante el licenciamiento de derechos de propiedad intelectual afecta los incentivos a innovar y los resultados agregados. Muestro que, en el desarrollo conjunto de tecnologías, las firmas simultáneamente compiten y cooperan, y que la intensidad relativa de cada fuerza depende de su similitud tecnológica y de su modelo de negocios. Para cuantificar el efecto neto de estos mecanismos en equilibrio, estudio la estandarización de tecnologías móviles de telecomunicaciones y estimo el modelo utilizando un nuevo conjunto de datos sobre el desarrollo de los estándares 3G y 4G en 3GPP. Los resultados indican que la exigencia de cláusulas de licenciamiento libres de regalías reduce la participación y las contribuciones de las empresas, y retrasa la finalización de la versión inicial de 4G en casi un año, respecto de los casi tres años requeridos para su desarrollo.

KEYWORDS
Innovación en grupos, Normas técnicas de Comunicaciones, Colaboración entre empresas, Patentes, Complementariedades

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1 | INTRODUCTION

Modern innovations often require the collaboration of firms with diverse technological knowledge. This is particularly true for the development of technology standards, such as the 4G and 5G broadband cellular networks, technologies projected to contribute around $600 billion to the global GDP by 2030 (GSMA, 2022). When developing a common technology standard, firms are interested in including their patented inventions as part of the standard to capture revenue through licensing fees from subsequent users. With the expansion of 5G and other advanced technologies such as the Internet of Things and connected cars, the financial stakes associated with the licensing of these patents have grown enormously, along with their complexity.[1] As a result, several major jurisdictions are now considering regulatory actions to address the issue (EC, 2022).[2]

Moreover, firms may be reluctant to contribute to the development of the common innovation unless they can appropriate most of the value of their contributions. For instance, they may wish to avoid free-riding by other participating firms or competing technologies that may undermine the potential value of their contributions. Firms then face a tradeoff between cooperating to develop a common innovation and competing to include their patented inventions as part of the shared endeavor. Understanding and quantifying firms' incentives to contribute to the development of a common technology standard, and the trade-off they face, is crucial when considering potential regulations on the licensing of standard-related patents that balance the interests of innovators and implementers.

In this paper, I develop a framework to study firms' incentives to contribute to the development of a common technology standard, considering free-riding and competition for the inclusion of patented technologies. I first provide empirical evidence illustrating the relationship between technological diversity among participating firms and the intensity of their cooperation and competition. Furthermore, I develop a structural model to study firms' participation in the groups responsible for developing the standards for the various components of the technology (standardization groups) and the extent of their contributions to each group. Additionally, I use the model to quantify the effect of patent licensing on firms' incentives to innovate and the common outcome, which I model through the time required to develop the full set of standards necessary for implementing the common innovation.

My analysis focuses on the development of 3G and 4G standards. I combine several data sources. I use a novel dataset developed by the Center of Law, Business and Economics of Northwestern University, which contains information on the participating firms, the contributions made by each firm to the development of each component of the technology, and which firms claim to have Intellectual Property (IP) rights over the technologies included in the 3G and 4G standards. I merge these data with information on the firm's patent portfolio, which I obtained from the United States Patent and Trademark Office, and information on the standards themselves, which I scraped from the corresponding standards-setting organization's webpage.

The descriptive analysis reveals three key findings. First, there is an inverted-U relation-

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[1] The number of ongoing disputes over the licensing of these patents is indicative of the enormous stakes involved. According to Lerner and Tirole (2015), as of May 2014, there were at least 50 lawsuits between Apple and Samsung, and 20 between Apple and Google. Galetovic et al. (2018) estimate that royalty revenues from SEP licensing in 2016 were around 14,000 million dollars, and represented 3% of the cost of manufacturing a smartphone.

[2] The US launched two public consultations in December 2021 and April 2022, while the UK launched a public consultation in December 2021. Japan adopted guidelines in 2018, 2020, and 2022. In Europe, the European Commission released a Communication in 2017, "Setting out the EU approach to Standard Essential Patents," and the 2020 action plan on intellectual property.

ship between the number of contributions a firm provides to a standardization group and the average knowledge similarity between the firm and the other contributing firms. The firms' knowledge is inferred from the technological classification of their patents. Second, standards for the technology components develop faster when firms work together, and they develop even more rapidly when firms' knowledge is similar. I refer to this as the cooperation effect. Third, I provide evidence suggesting that firms within standardization groups compete to have their own patented inventions included in the standards. I term this the competition effect.[3]

More specifically, regarding the cooperation effect, when contributions come from firms with a knowledge similarity in the top 20% of the distribution, a 10% increase in contributions reduces the time to develop a component by 1.4%. By contrast, if contributions come from firms with a knowledge similarity in the bottom 20%, this decrease in time is reduced to 0.05% and is not statistically different from 0 at a 5% significance level. Regarding the competition effect, working with other firms that are on average 1% more similar reduces the firms' claims of Standard Essential Patents (SEPs) by 1.3%. Then, contrary to the cooperation effect, the competition effect generates incentives for firms to provide less contributions when teaming up with other firms that are specialized in similar technologies.

Motivated by this empirical evidence, I develop a framework and estimate a two-stage model to examine the incentives that firms face when collaborating to develop telecommunications standards. Profit-maximizing firms make two decisions: (1) which group(s) standardizing a particular component of the technology to participate in, and (2) how many 'contributions' (technological alternatives) to provide within each group. Firms profit from the production of goods using the 3G and 4G standards as inputs, depending on their business model. They also profit from the (cross) licensing of SEPs, which is an endogenous variable modeled as a function of firms' characteristics, the technology component' technological requirements, and the knowledge similarity between participating firms (hereafter, SEP function). Both sources of profits are negatively impacted by the time required to develop each version of the common technology (the full set of standards), which is an endogenous variable in the model. The time to develop the common technology depends on the observed and unobserved characteristics of the component to be standardized, the contributions provided by participating firms, and the complementarities between those contributions, all modeled together as a time production function. The firms are characterized by their technological knowledge and business models, while the standardization groups are heterogeneous in terms of the technological complexity of the components they aim to standardize.

When deciding how many contributions to provide, firms know their marginal cost of contributing and the characteristics of other participating firms in the group (including their knowledge similarity and marginal cost). Firms compute expected profits based on the number of contributions they submit and their expectations regarding the participation and submissions of other firms. Participation costs depends on the match between a firms' technological expertise and that required to develop the component to be standardized.

I identify the key parameters of the model by exploiting the exogenous nature of firms' technological knowledge prior to their participation in the standardization of a component, their business model and the technology required by the components that need to be standardized in each version of the technology. This exogenous match determines the firms' participation decisions and, in turn, their similarity within standardization groups. In addition, I exploit the panel structure of the data, which allows me to account for firms' and component' time-invariant unobservable heterogeneity, as well as the variation in firms'

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[3] Competition between firms to include their preferred technologies has been documented also by Simcoe (2012), Spulber (2013) and Spulber (2016).

contribution decisions in different groups in the same technology version. Furthermore, I construct an instrument to identify the cooperation parameter associated with firms' contributions and the time required to develop a standard (the common output). This instrument is based on the size of each firm's patent portfolio prior to joining the group and the expected probability of each firm's participation, estimated using the exogenous characteristics of firms and the technological requirements of standardized components.

To estimate the parameters , I rely on a three-stage procedure in which I first estimate the parameters in the time production function and the patent equation using standard withing group estimators. Second, I use these estimates and the equilibrium equations of the model to calculate some moment conditions, which I then match to key moments in the data. I rely on a minimum distance estimator to back out this last set of structural parameters. A novel feature of this approach is that it does not require any proprietary data on royalty revenues, profits from standardization, or prices of intermediate goods to estimate the model. Finally, I compute the difference between the profits of the observed participation decision and those of the unobserved ones, imposing a parametric distribution on the participation shock, and estimate the participation parameters by maximum likelihood.

Results indicate that in the 4G standards development, SEP licensing accounts for over 20% of firms' expected standardization profits. Before 4G launch, SEP licensing accounted for between 5% and 10% of firms' total profits, depending on their business model.[4] As a robustness check, I compare my results with those from Qualcomm's earnings reports, which show that from 2010-2016, licensing profits constituted between 63-73% of their total profits, aligning with my model's estimate of 60-66%.[5] [6]

In this context, the impact of enforcing royalty-free licensing is ambiguous.[7] On the one hand, it would shut down the competition effect, aligning firms' private and common incentives and encouraging similar firms to cooperate more to fully leverage their complementarities and expedite the development of common standards. On the other hand, it would also shut down one of the revenue streams, disincentivizing firms from participating and providing contributions. This second channel is particularly important for firms that do not profit from selling products. To quantify this trade-off, I compare the predictions my economic model, using the estimated parameters against those of a model in which patents are licensed for free. In my counterfactual scenario, I allow the number of contributions and participation decisions to vary with the new licensing policies.

I find that, despite an increase of almost 5% in the average similarity between firms in the same standardization group, which boosts the cooperation effect, the overall impact of a change in the licensing rules would be an increase in the time it takes to develop the technology (lower common output) This result can be explained by a decrease of 7% and 18% in average participation and average number of contributions made, respectively.

The change in the licensing rules would also alter the composition of firms interested in developing common standards.Pure upstream firms, which are firms whose business model is to develop technology and license the corresponding IP rights, would rarely if ever participate in this counterfactual scenario, accounting for less than 1% of overall participants. Conversely, vertically integrated firms would take the lead in standardizing mobile network technologies. Firms producing intermediary goods, such as chips and telecommunication equipment, would be the second most affected group, as their participation would decrease by 10%, while the participation of telecommunications operators would remain unchanged.

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[4] This share is not relevant in the case of pure upstream firms and telecommunications operators, since by assumption of the model it would be 100% and 0%, respectively.

[5] See https://investor.Qualcomm.com/financial-information/quarterly-results.

[6] 4G was commercially launched in 2010.

[7] Under royalty-free clauses, firms must license their patents at no cost.

The results are heterogeneous across standards' versions. In the case of the first version of 4G, which took 3 years to develop, forcing firms to license their patents for free would have delayed completion of the first release of 4G by one year. I also calculate the final impact of removing royalties in the downstream part of the market. The final price of mobile handsets would fall by around 11–20 USD, representing between 3%–5% of the average price in 2012.

Overall, my results suggest that even if allowing firms to unilaterally license their standard-related patents induces competition and misalignment of incentives between firms and the group's incentives, this inefficiency is a necessary evil in order to incentivize firms to contribute and avoid free riding.

Contributions to the literature. While the cooperation and competition aspects as well as the inclusion of patented technologies in public standards has been studied theoretically or through reduced form empirical analysis, this paper is the first one to put them together and provide an empirical framework for analyzing the incentives firms face in developing common innovations, quantify the importance of licensing revenues with respect to market revenues, and provide an empirical model that can be used to evaluate counterfactual policies, such as changes in licensing agreements. This paper also makes an empirical contribution to a longstanding academic and policy debate regarding the effect on IPR policy of standards organizations.

Licensing of standards' patents has been mostly analyzed from a theoretical point of view. Shapiro (2000) discusses whether the patent system slows down the commercialization of new technologies, recommending the use of cross-licensing agreements and patent pools. In a similar vein, Lerner and Tirole (2015) study the inefficiencies arising from the lack of price commitments and show how structured price commitments restore competition. Layne-Farrar et al. (2014) assess the effects of different licensing rules on firms' participation in standardization processes and R&D investment. On the empirical side of this literature, using data from W3C and IEEE, two standardization bodies in the ICT sector Simcoe and Zhang (2021) find little evidence that changes in the licensing policies caused a decline in participation by patent licensors or reduced innovation in patent-intensive parts of either SSOs. Rysman and Simcoe (2008) show that when a patented technology is included in a technological standard, the standard-related patents increase their returns. Consistent with the view that inclusion increases a patent's value, Simcoe et al. (2009) show that patents disclosed by a Standard-Setting Organization (SSO) have higher litigation rates, particularly if these patents are issued by small firms. Bekkers et al. (2017) study differences in the rules used by different SSOs and how these influence which patents are disclosed, the terms of licensing commitments, and ultimately long-run citation and litigation rates for the underlying patents.

Baron and Pohlmann (2013) explore how the degree of complementarity and competition between firms participating in the development of ICT standards shapes firms incentives to collaborate. In a similar vein, Bar and Leiponen (2014) find a negative correlation between firms' technological distance and their probability of developing R&D together, and Jones et al. (2021) show that in innovation ecosystems, cooperation with adversaries persists despite conflict. Using the 3GPP as a case study, Jones et al. (2021) find evidence of cooperation between competitors by showing that firms contributing to mobile standards tend to cooperate more after a patent litigation event. Exploring cooperation and competition inside SSOs, Leiponen (2008) finds that firms compete and collaborate at the same time using formal and informal structures. Focusing on informal structures in SSOs, Delcamp and Leiponen (2014) find that technologies that are likely to become part of the UMTS telecommunication system tend to build on technologies developed by firm peers who were members of the same informal structure.

My study relates to team production models. Goyal and Joshi (2003), Ballester et al. (2006), and Benlahlou (2019).[8] develop a theoretical framework that accounts for complementarities and substitutions between players' efforts in a team production function. I use a similar production function but I also include competition among team members for a share of the common output. I also estimate effort complementarities in the team production function, while allowing them to depend on the knowledge similarity of participating firms.

2 | INSTITUTIONAL SETTING

2.1 | The Mobile Telecommunications Market

The market for mobile telecommunications comprises an upstream stage where firms propose and refine the system's technology, and downstream stages where that technology is embodied in intermediate and final goods and services. Upstream activity can generate intellectual-property (IP) licensed downstream through standard-essential patents (SEPs), that is, patents declared by firms to be essential for implementing a standardized technology.[9]

Firms earn revenues through two main channels: the production of intermediate or final goods and the licensing of IP tied to standardized components. Four business types are salient. First, pure upstream licensors focus on research and licensing rather than physical production; examples include InterDigital, universities, and research laboratories. Second, intermediaries produce key components used by others, notably semiconductors (e.g., Qualcomm) and network equipment (e.g., Ericsson, Nokia), typically participating upstream and holding substantial IP portfolios. Third, vertically integrated device vendors both develop technology upstream and sell final devices to consumers; examples include Samsung, Apple, Xiaomi, Huawei, and ZTE.[10] Fourth, telecom operators deploy radio access and core networks and sell service plans (e.g., Verizon, AT&T, Vodafone, Telefónica). Operators contribute to standardization to shape requirements and ensure interoperability but rarely hold large essential IP portfolios.

Under prevailing licensing practices, royalty incidence is concentrated at the device level. Device vendors typically pay royalties to SEP holders. While cross-licensing may offset payments among some vertically integrated firms, it does not exempt them from paying royalties to external SEP holders. Intermediary firms may be involved in specific royalty flows, but they rarely make per-unit payments. Operators are not involved in IP licensing and derive revenue solely from selling services to end users.[11] The analysis throughout the paper focuses on the upstream stage, where firms decide whether and how to contribute technologies that may later be embodied in standardized components and licensed downstream.

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[8] For a survey of the literature on network formation see, e.g., Myerson (1994); Bala and Goyal (2000) and Jackson and Wolinsky (1996).

[9] A patent is standard-essential in the sense that it is impossible to implement the standard without infringing at least one claim of the patent. Essentiality is self-declared under the FRAND policy of 3GPP's Organizational Partners and not verified by the SDO.

[10] Under 5G, many Internet-of-Things and automotive products also implement standardized connectivity and may pay royalties.

[11] This description is positive rather than normative and abstracts from case-specific arrangements at the component or infrastructure level.

2.2 | Mobile Telecommunications System: Generations, Versions, and Components

The mobile system consists of a set of distinct components—such as physical-layer coding, radio link control, antenna configurations, and core network functions—that must operate in coordination for devices to connect to the network. Standardization defines the implementation of each component to ensure that independently developed hardware and software are interoperable. Fully describing the mobile system requires specifying hundreds, and in some cases thousands, of standardized components.[12]

The Third-Generation Partnership Project (3GPP) is the primary organization responsible for providing mobile telecommunications standards to the industry (see **??** for more details). In 3GPP practice, each version of the system corresponds to a *Release*, and each component is documented in one *Technical Specifications*.[13]

Mobile technologies evolve across generations—ranging from 2G to 5G, with 6G currently under development—and, within each generation, through successive versions. These versions do not automatically replace one another; rather, they are updated incrementally and often coexist in the market. Appendix Table **??** presents the different versions and their associated technology generations. These components and versions are formalized through the 3GPP standardization process described in the next section.

2.3 | Standards Development

Numerous standard-development organizations (SDOs) govern interoperability specifications (e.g., IEEE for Wi-Fi, Bluetooth SIG for Bluetooth, IETF for Internet protocols). Each SDO maintains procedures for proposing, discussing, and approving technical work and for handling patent licensing for implementations —often with the goal of mitigating holdout risks. 3GPP develops the cellular standards used by the mobile industry.[14]

In 3GPP, broad technological objectives are articulated and decomposed into specific work items that ultimately translate into technical text for components within each version. Firms prepare and submit *contributions*—technical documents, simulations, or change requests—that propose adding or modifying text for a component in a given version. Contributions are discussed within the responsible working groups; items that reach consensus are incorporated into the component's text for that version. Approval proceeds in stages and is by consensus, defined as the absence of sustained opposition rather than unanimity.[15]

Developing standards is a complex and non-linear process. This paper focuses on firm contributions and their outcomes, rather than on the full sequence of meetings in which discussions unfold. Before submitting a contribution, firms typically conduct in-house research and development, but this internal process falls outside the scope of this analysis. Contributions are submitted within specific components and versions; when adopted, they modify the corresponding technical specifications and may later be declared as SEPs under 3GPP's Fair, Reasonable, and Non-Discriminatory (FRAND) licensing framework. While FRAND serves as a guiding principle for licensing terms, it is not a codified rule; in practice, royalties are often determined through bilateral negotiation or litigation.

To illustrate, consider antenna-related versus signaling components within a given ver-

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[12] For a more in-depth exploration of technology standards, interested readers can refer to Baron and Spulber (2018).

[13] Terminology mapping for clarity: in this paper, "version" refers to a 3GPP Release and "component" to the technical content documented in the corresponding technical specifications.

[14] For a more detailed understanding of the variety of SDO rules, readers can refer to Lerner and Tirole (2006); Baron and Spulber (2018).

[15] Consensus in 3GPP does not require a formal vote or universal agreement; it is achieved when no member maintains sustained, reasoned opposition to a proposal.

TABLE 1 Actors and Revenue Channels in the Mobile Telecommunications Market

Business type	Holds SEPs (typical)	Sells to final consumers	Typical royalty role	Examples
Pure upstream	Yes (main revenue)	No	Receives royalties	InterDigital; universities; research labs
Intermediaries	Yes (substantial)	No, only to other firms	Receive	Qualcomm; Ericsson; Nokia
Vertically integrated device vendors	Yes (varies; often sizable)	Yes	Typically pays at device level; also cross-licenses	Samsung; Apple; Xiaomi; ZTE
Telecom operators	Rarely	Yes	Not involve	Verizon; AT&T; Vodafone; Telefónica

Notes: Under prevailing practice, royalties are typically assessed at the device level. Cross-licensing can net bilateral flows among SEP holders. Exceptions exist (e.g., certain infrastructure or component-level licenses), but these are not the modal arrangements.

sion. For antennas, contributions may propose specific array configurations, beamforming codebooks, or calibration procedures; for signaling, they may propose new random-access procedures, scheduling grants, or handover criteria. Firms often submit contributions aligned with forthcoming silicon capabilities; network-equipment vendors emphasize features needed for deployability and performance; device vendors focus on power and form-factor constraints. Operators contribute requirements and performance feedback to ensure deployability at scale. The interaction of these contributions—complementary in many cases and contested in others—shapes the final text for each component in each version and subsequently the pattern of SEP declarations. Appendix Figure 2.3 shows a simplified example of the development of a hypothetical set of 4G standards that contains only two components: an antenna and a signal protocol. The figure also includes the main payments made in this market. More details and an example of the development of standards in 3GPP can be found in Appendix Section **??**. Finally Table 1 summarizes the market structure and key features of the main actors.

3 | DATA AND EMPIRICAL MEASURES

3.1 | Data Sources

This study combines information from multiple sources to capture firms' technological activities, participation in standardization, and intellectual-property outcomes.

Searle Center Data Base (SCDB). The main source is the dataset developed by the Searle Center on Law, Regulation, and Economic Growth at Northwestern University in collaboration with Qualcomm, Perinorm, and IPLytics, described in Baron and Spulber (2018), Baron and Gupta (2018), and Baron and Pohlmann (2018). The SCDB documents the standardization process of mobile networks within 3GPP from 1999 to 2012, covering nine versions of the technology. It records, for each component of the system, the number of written contributions submitted by each firm, the date of submission, and the outcome (adopted or rejected).[16] The dataset also links these contributions to standard-essential

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[16] Contributions can take the form of technical reports, discussion documents, change requests, or proposals. See Section 2.3 for details on their role in standard development.

patents (SEPs) declared by firms for each component and version. Because SEP declarations are self-reported and not verified by the SDO, they vary in timing and completeness. Firms may declare essential patents during or after standard development.[17] To assign SEPs to components, I follow Baron and Pohlmann (2018) and adopt the broadest matching criterion, which associates each declared patent with all component–version pairs mentioned in the declaration letters sent to 3GPP.

Patent data. Firm-level patent portfolios are obtained from the United States Patent and Trademark Office (USPTO) via the PatentsView database (1970–2014).[18] Each patent is associated with its International Patent Classification (IPC) codes, which allow identification of technological fields and are later used to compute firms' technological proximity.

3GPP online data. To characterize the technological scope of each component, I scraped information on *work items* from 3GPP's public repository. Work items describe the technological goals that motivate additions or revisions to the standardized system. I use the number of work items referencing a component as an indicator of its breadth or complexity.

All datasets were merged using firm names, supported by semi-automated string-matching algorithms and manual validation.[19]

3.2 | Estimation Sample and Variable Construction

During 1999–2012, approximately 280 firms contributed to 3GPP standardization, though the vast majority submitted very few contributions. To study strategic interaction among active participants, I focus on the top 15 contributors per year, yielding a balanced panel of 35 firms. Appendix Tables E.1–E.3 present descriptive statistics for this sample.

Component complexity. Not all components of the mobile system are equally important or innovative. I measure component complexity following 3GPP's working procedures: at the beginning of each version, 3GPP defines a set of technological goals ("work items"), and each component explicitly lists the goals it addresses. My measure of complexity is the number of goals linked to a component. While this proxy captures a component's scope, it may not reflect every aspect of technological difficulty. A component associated with few but demanding goals can be as complex as one addressing many smaller goals. On average, a component is mentioned in 7.18 goals (Appendix Table E.2).

Participation and contributions. A firm is considered to participate in a component–version if it submits at least one contribution to its development. When multiple firms co-author a contribution, each receives equal weight. Because contribution types cannot be distinguished for most records, all are treated as comparable inputs to the standardization process.[20]

Firms' knowledge similarity. To measure technological proximity among firms, I rely on their patent portfolios. For each firm and year, I count patents by IPC subclass and retain the 15 most relevant ICT-related classes following Leiponen (2008). Using these vectors, I compute pairwise cosine similarity as in Jaffe (1986), obtaining a measure of knowledge overlap between any two firms.[21]

Component outcomes. Because all components are ultimately developed within 3GPP,

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[17] Evidence from multiple sources supports this timing heterogeneity: Baron and Pohlmann (2010) find that 56% of declarations to major SDOs occur more than one year after a standard's release; Layne-Farrar (2011) report that 44% of ETSI patents were filed after the standard was frozen; Kang and Bekkers (2015) describe "just-in-time" patenting behavior around meeting dates; and Brismark (2021) show that more than 90% of disclosures for 4G standards were made after the freeze date.

[18] `https://www.patentsview.org`.

[19] Details on the matching procedure, algorithms, and robustness checks are available in Appendix E.3.

[20] Results are robust to alternative weighting schemes when identifiable.

[21] Appendix E details the construction of this measure.

the relevant outcome for a component's development is not obvious. Consistent with 3GPP's stated objective of "using minimum production time for Technical Specifications and Technical Reports from conception to approval,"[22] I define the time to develop a component as the number of days between the first contribution and the date when 90% of its total contributions have been submitted. This measures the speed of the technical process and serves as a performance metric for the component's development. I use 90% rather than 100% because the final 10% typically reflects administrative steps leading to publication rather than substantive technical progress. Robustness checks using 80% and 85% thresholds yield very similar results. Ideally, one would also measure the quality of the component as a second performance dimension, but quality is not directly observable. As a proxy, I examine whether a component is updated in the next version of the technology and how many times it is updated within the next four versions. If a component is high quality, we expect it to persist into subsequent versions; if low quality, it is more likely to be removed from the system. Appendix D.3 provides details and Appendix Table D.3 reports results.

Payments and royalties. Direct information on royalties or product sales is unavailable.[23] I use the number of SEPs declared by a firm as a proxy for its upstream private returns from participation. Downstream revenues depend on firms' business types as described in Section 2.1: device vendors earn from product sales, while upstream and intermediary firms earn primarily through licensing.

4 | EMPIRICAL EVIDENCE

I now present empirical evidence documenting the economic trade-off that arises when firms with similar knowledge work together.[24] I first show the non linear relationship between the number of contributions firms submit to a group and the group's knowledge similarity. I then provide evidence of two effects behind this nonlinearity. I show evidence on the cooperation effect, where firms with similar knowledge speed up the development of a technology component due to complementarities in their contributions, as well as on the competition effect, where the competition over IP rights becomes more intense negatively affecting cooperation.

4.1 | Inverted U-Shaped Relationship Between Contributions and Knowledge Similarity

I start my analysis by plotting the average number of contributions submitted by firms to a given standardization group, on the knowledge similarity of contributing firms. To avoid comparing averages with a different number of observations, I discretized the similarity measure in deciles. See Appendix Figure C for other discretizing criteria.

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[22] 3GPP Partnership Project Agreement, p. 1. `https://www.3gpp.org/ftp/Inbox/2008_web_files/3gppagre.pdf`.

[23] SEPs must be licensed under FRAND principles, and royalties are often set through private negotiations or litigation.

[24] The theoretical framework in Appendix Section **??** describes the primitives behind this trade-off equilibrium result.

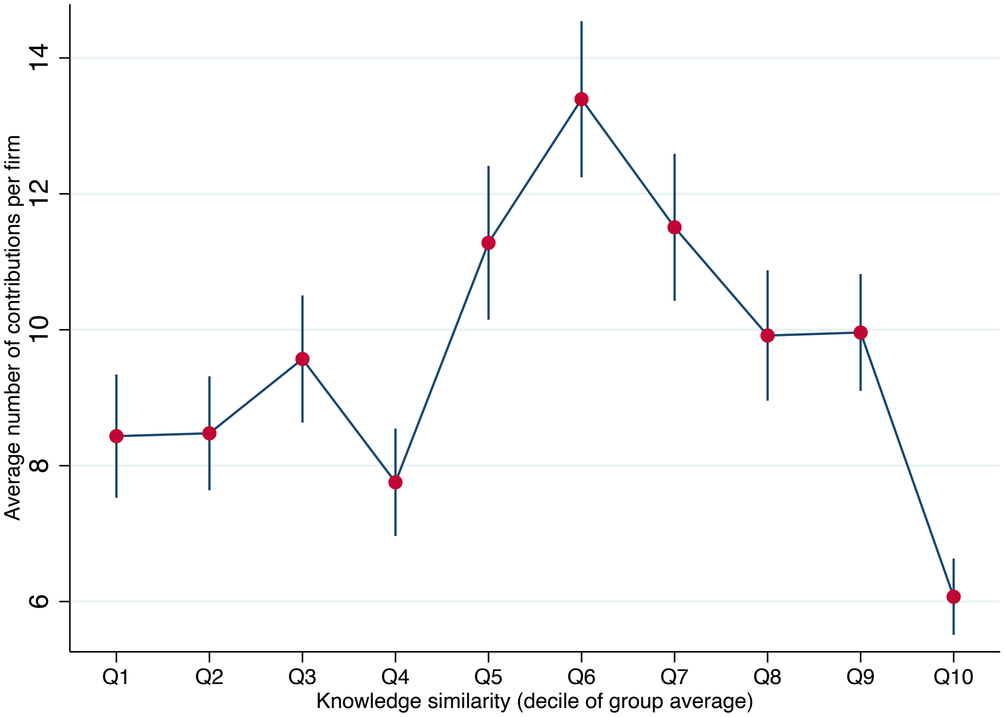

FIGURE 1 Number of Contributions and Similarity of Firms

Notes: The figure below shows the average number of contributions submitted by firms in relation to the average knowledge similarity with other participating firms in the group.

Figure 1 suggests a nonlinear inverted U-shaped relationship between firms' contributions and their knowledge similarity. That is, firms do not submit their maximum number of contributions when teaming up with other firms that are specialized in the same technological area, nor when cooperating with firms with completely unrelated knowledge. The maximum average number of contributions by decile of knowledge similarity is 13.6 contributions per firm and it is achieved in groups in which firms' knowledge similarity is, on average, 0.7 (decile 6 of the similarity distribution). This lower number of contributions at the extremes of the similarity distribution still holds when controlling by component fixed effect, as shown in Appendix Figure C.1, showing evidence that this result is not driven by the unobserved heterogeneity of the component each group is standardizing. Furthermore, the shape of this relationship is also not inherit from the number of participating firms and its relationship with firms' similarity, as can be seen in Appendix Figure C.2.

4.2 | Complementarities in Contributions and Knowledge Similarity

It may be intuitive to think that firms must be working together when there are complementarities between their contributions, but it is not obvious that those complementarities are related to the firms' knowledge similarity, neither the sign of this relationship.

To obtain empirical evidence of complementarities in contributions and their association with firms' knowledge similarity, I estimate a translog production function. I use the number of days required by the group to develop the component standard, normalized by its broadness as output, and the number of contributions provided by each participating firm as inputs. Groups are defined at a component(s)-version(v) level.

I estimate the following fixed-effects model:

$$ttd_{s,v} = \beta_1 \sum^{f\in F} c_{f,s,v} + \frac{\beta_2}{2} \sum^{f\in F} c^2_{i,s,v} + \frac{\phi_0}{2} \sum^{f\in F} \sum^{j\in F} c_{f,s,v} c_{j,s,v} + \mu^S_s + \mu^V_v + \epsilon_{s,v}, \tag{1}$$

where $ttd_{s,v}$ is the time it takes the group to develop the standard for component s in the version v of the technology, normalized by its broadness, in logs.[25] $c_{f,s,v}$ and $c^2_{f,s,v}$ are, respectively, the number of contributions (logs) and the number of contributions squared (logs) that firm f submits. The interaction of firms' contributions is represented by the parameter ϕ_0. A positive ϕ_0 means that firms' contributions are complements, negative ϕ_0 means that the contributions submitted by different firms are substitutes.

I control for unobserved heterogeneity of the technology components by absorbing a set of fixed-effects at the component level μ^S, and include version fixed-effects μ^V. As an extra control I include a dummy variable that takes value 1 if the component is standardized for the first time and 0 otherwise.

Column 1 of Table 2 presents estimates for Equation 1. After adding controls, I find that:(i) there is a nonlinear and concave relationship between the number of contributions and time (adjusted by the standard broadness); and (ii) contributions submitted by different firms are indeed complements. The estimation of parameter β_1 shows that the linear effect of an increase of 10% in contributions decreases the average time to develop a component by 2%, other things being equal.[26]We can see that β_2 is positive with a magnitude of about 0.01%, suggesting decreasing returns in the submission of contributions. The negative and significant value of the estimated parameter ϕ_0 supports finding (ii).

The cooperation effect implies that firms with similar knowledge face lower coordination costs, such as a common expert language, and therefore, the combination of their contributions will speed up the standardization process more than the contributions provided by dissimilar firms.

To explore this hypothesis I estimate two more flexible versions of Equation 1:

$$ttd_{s,v} = \beta_1 \sum^{f\in F} c_{f,s,v} + \frac{\beta_2}{2} \sum^{f\in F} c^2_{f,s,v} + \frac{\phi_l}{2} \sum^{f\in F} \sum^{j\in F} c_{f,s,v} c_{j,s,v} sim_{f,j} + \mu^S_s + \mu^V_v + \epsilon_{s,v}, \tag{2}$$

where $sim_{f,j}$ is the knowledge similarity between firms f and j and therefore ϕ_l captures the linear effect in the complementarities of contributions done by firms with different levels of similarities. Also I estimate,

$$ttd_{s,v} = \beta_1 \sum^{f\in F} c_{f,s,v} + \frac{\beta_2}{2} \sum^{f\in F} c^2_{f,s,v} + \sum_{q=1}^{q=Q} \frac{\phi_q}{2} \sum^{f\in F} \sum^{f\in F} c_{f,s,v} c_{j,s,v} D^q_{f,j} + \mu^S_s + \mu^V_v + \epsilon_{s,v}, \tag{3}$$

where $D^q_{f,j}$ is a set of dummy variables that take value 1 if the similarity between firm f and j is at the qth percentile of firms' knowledge similarity distribution. Then, the set of parameters ϕ_q represent the complementarities between contributions of firms whose similarity falls in the qth percentile of the distribution. Table 2 and Figure 2 present estimates

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[25] I normalize time by dividing it by the broadness of the component, defined as the number of related technological goals (see Section 3.2 for more details on this measure).Normalization is chosen over controlling for the number of technology goals in order to avoid endogeneity issues.

[26] Recall that Equation 1 is defined in terms of $-\beta_1$ and $-\beta_2$.

TABLE 2 Estimates of the Time Production Function

	(1) Restricted model	(2) Linear effect	(3) Nonlinear effects
Contributions (β_1)	-0.200	-0.203	-0.193
	(0.050)	(0.050)	(0.052)
Squared number of contributions ($\frac{\beta_2}{2}$)	0.011	0.012	0.012
	(0.005)	(0.005)	(0.006)
Contributions' interaction term:			
All similarity levels ($\frac{\phi_0}{2}$)	-0.007		
	(0.003)		
Contributions × Similarity ($\frac{\phi_1}{2}$)		-0.013	
		(0.006)	
Q1 similarity ($\frac{\phi_1}{2}$)			-0.005
			(0.003)
Q2 similarity ($\frac{\phi_2}{2}$)			-0.007
			(0.003)
Q3 similarity ($\frac{\phi_3}{2}$)			-0.008
			(0.004)
Q4 similarity ($\frac{\phi_4}{2}$)			-0.011
			(0.004)
Q5 similarity ($\frac{\phi_5}{2}$)			-0.011
			(0.004)
First time dummy	Yes	Yes	Yes
Component FE	Yes	Yes	Yes
Version FE	Yes	Yes	Yes
N	1792	1792	1792
adj. R^2	0.542	0.542	0.544

Notes: The dependent variable is the production time of a component per unit of technological broadness, expressed in logarithms. All explanatory variables are also in logarithms. All specifications include a dummy variable indicating whether it is the first time a component is developed, as well as component and technology–version fixed effects. Robust standard errors are reported in parentheses.

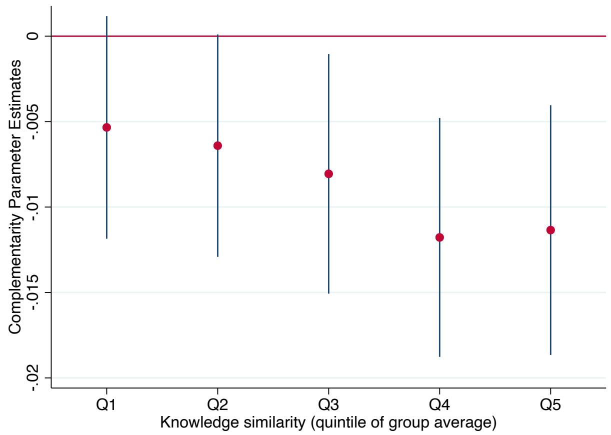

FIGURE 2 Estimates of the complementarity parameter ϕ_q

Notes: The Figure shows estimates of the complementarity parameters Φ_q. 95% confidence intervals bands. Standard errors are robust to heteroscedasticity. Estimation includes component and technology version fixed effects.

using quintiles. See Appendix Section D for robustness checks using other percentiles and variables in levels.

Column 2 of Table 2 presents an estimate of the ϕ_l parameter. The negative and significant estimation of ϕ_l suggests that, given a level of contributions, the more similar the firms providing them, the bigger their complementarities in reducing the time to develop a standard.

Figure 2 shows empirical evidence of a positive relationship between the value of ϕ_q and firms' knowledge similarity when allowing for a more flexible pattern in such relationship. As can be seen in column 3 of Table 2, an increase in the contributions interaction term of 10% decreases the time to develop the standard by 1.4% if the contributions are provided by firms with a knowledge similarity in the top 20% of the distribution. If this same contributions are provided by firms with a knowledge similarity in the bottom 20%, this decrease in time is reduced to 0.05% and it is not statistically different from 0 at a 5% significance level. This evidence and the linear trend estimates, support the hypothesis of a *cooperation effect*, in which contributions are stronger complements the more similar the knowledge of the firms providing them.

For a formal test on the increasing complementarities, I estimate a model including a *quintile trend*, that is, a unique variable that takes the value of the number of contributions made by firms in each quintile of the knowledge similarity distribution. This allows me to see if this trend has a positive coefficient, what will show a positive and increasing relationship between complementarities and similaritiy level. As shown in Appendix Section D this trend is positive and significant, providing extra evidence supporting the cooperation effect.

4.2.1 | Endogenous Number of Contributions

One concern that might arise from the estimation of the previous model is the potential endogeneity of the number of contributions, and of the knowledge similarity of participating firms.

With respect to the number of contributions, one potential concern can be the reverse causality problem, that is, if time is limited in some way firms are pressured to contribute more and develop the standard faster. To address this concern I instrument the number of contributions provided by a firm with the size of its patent portfolio prior to joining the standardization process. Portfolio size prior to the standard development is a good instrument in this setup because: (i) its exogeneity comes from the difference in time with `ttd` and the fact that the size of a firm's patent portfolio is the result of the firm's IP policy, which is a more general decision than its participation in the development of any specific standard component; and (ii) its relevance comes from the fact that the size of such a portfolio can be easily related to the potential to contribute each firm has and it is shown empirically in Appendix Section D.[27]

As an instrument for the contributions' interaction term, I use the interaction between patent's portfolio size of firms multiplied by firms' knowledge predicted similarity. I construct this last measure in two steps. First, I estimate a probit model for firms' participation decision using as independent variables the size of firms' patent portfolio and the broadness of the component to be developed. Since both variables are exogenous in my setup, participation decision predicted by this model, that I name *participation hat* is also exogenous in the `ttd` equation. Secondly, I compute the predicted knowledge similarity between two firms using this predicted participation probability instead of the observed decision. I show in Appendix Section D that this instrument is also relevant to explain contributions' interaction term.

I then estimate Equation 1 by instrumental variables and compute the Wald coefficient. The results remain unchanged. See Appendix Section D.5 for more details on the estimation and results.

4.3 | SEP Competition and Knowledge Similarity

Licensing SEPs is one of the channels through which firms can benefit from participating in the development of standards. Simcoe (2012), Spulber (2013), and Spulber (2016) show that firms in SDOs compete within the standardization of a component to include their preferred technology.[28] Firms have private interests in including certain inventions in a standard, since they often have IP rights over them.

The value of a SEP is difficult to assess since firms usually license the entire patent portfolio and since it is defined in court under FRAND conditions.[29] Therefore, one could think that competition in this market is not over prices, but over the number of patented inventions to be included in the standard. This last statement implicitly assumes that all SEPs are equally valuable. Though this may appear to be a strong assumption, it is based on the essentiality of a SEP: if all SEPs are required to implement the technology, they are then perfect complements. Following a Shapley value approach, it is then reasonable to assume that they have the same value.[30]

My competition effect hypothesis states that firms with similar knowledge, who, by definition, have similar patents, are closer competitors when it comes to introducing their patented inventions into the components' standards and claiming SEPs. As an initial exploration of this hypothesis, in Appendix Figures C.3 and C.4 I plot the average number of SEPs claim by firms for each component of each version of the technology over the

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[27] The decision to participate and its correlation with the firm's portfolio size do not invalidate the exogeneity argument of the instrument due to the time difference between the moments each decision takes place. While firms decide to participate or not in a first stage, they decide how much to contribute in the second one, realizing the time to develop shock at that time. Therefore any potential shock to the time to develop will be uncorrelated with the firm's patent portfolio size not even through the participation decision.

[28] Simcoe (2012) studies the development of Internet standards.

[29] Some of the most well-known cases are Microsoft Corp. vs. Motorola, Inc. and Ericsson, Inc. vs. D-Link Sys.

[30] See Roth (1988) for a detailed description of the Shapley value.

knowledge similarity of contributing firms. Appendix Figures C.3 and C.4 show a negative relationship between the two variables, robust to several controls and specifications.

I then formalize my hypothesis and estimate the following fixed-effects model:

$$\mathtt{Numbersep}_{f,s,\nu} = \alpha + \psi \mathtt{gsimil}_{f,-f,s,\nu} + \beta X_{f,s,\nu} + \omega X_{-f,s,\nu} + \mu_f^F + \mu_s^S + \mu_\nu^V + \epsilon_{f,s,\nu}, \quad (4)$$

where the variable $\mathtt{NumberSep}_{f,s,\nu}$ is the log of the number of SEPs firm f declared to claim in component standard s for version ν, and $\mathtt{gsimil}f, -f, s, \nu$ is the average cosine similarity between the patent portfolios of firm f and all other firms $-f$ participating in the development of component standard s in version ν of the technology, also in logs. I include firm fixed effects to control for unobserved firm heterogeneity, such as experience in standardization and bargaining power, which may also affect the number of SEPs a firm claims. To capture the heterogeneity across technology versions, which may also affect the number of SEPs, I include version fixed-effects. In the same spirit, I absorb a set of component fixed effects to account for the unobserved heterogeneity in their complexity.

Covariates $X_{f,s,\nu}$ control for the number of contributors in the group developing a component-version, for the broadness of the component-version, a dummy variable that takes value 1 if the component is developed for the first time in that version of the technology, and for the portfolio size of the firm. The value of this last variable is computed in the year prior to joining the group, as joining the standardization process might impact firms' patent portfolios. In some specifications, I also control for the average characteristics of other firms in the group, $X_{-f,s,\nu}$, to account for the portfolio size of the competing firms.

The number of contributions submitted by firms in developing a component standard are not included in the main specifications. In this I was guided by anecdotal evidence from engineers attending standardization meetings and previous research, such as Rysman and Simcoe (2008) who show that the inventions finally included in standards developed in SSOs are promising technologies and not the result of vested interests. However, it's worth noting that contributing to the standardization of a component affects the probability of firms claiming SEPs through their extensive margin. In the model, firms need to contribute at least once to participate and therefore claims SEPs.

As a robustness check for my analysis, I estimated the SEP equation including the number of contributions provided by firms to te development of a component. To overcome contributions' endogeneity problem I propose an instrument and estimate by Instrumental Variables. I find that once instrumented, the number of contributions a firm makes to the development of a component standard, conditionally on participating, is statistically insignificant in explaining the number of SEPs a firm claims in that group. The full analysis and results are presented in Appendix Section D.4.

Firms do not always obtain SEPs when participating in the development of a component standard. In fact, in the sample of components on which I have information, 43% of the time firms participate in their development they do not get any SEPs. Given the significant number of zeros in my sample, I also estimate a tobit model for Equation 4.

TABLE 3 SEPs and Firms' Knowledge Similarity

	(1) Baseline	(2) Controls	(3) Other firms controls	(4) Tobit
Firms' knowledge similarity (group average)	-1.723	-0.875	-1.286	-2.470
	(0.418)	(0.520)	(0.528)	(0.693)
Firm's characteristics (Portfolio)	No	Yes	Yes	Yes
Other firms' characteristics	No	No	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Release FE	Yes	Yes	Yes	Yes
Tech. specification FE	Yes	Yes	Yes	No
Standard characteristics (Number of firms, Broadness, First time)	No	Yes	Yes	Yes
Average number of SEPs per firm in a standard	1.5	1.5	1.5	1.5
Firms' average knowledge similarity	0.64	0.64	0.64	0.64
N	2059	2059	2059	2059
adj. R^2	0.137	0.286	0.300	

Notes: The Table shows estimates of the competition parameter. Robust standard errors in parentheses. ***significant at the 1 % level, **5 % level, *10 % level.

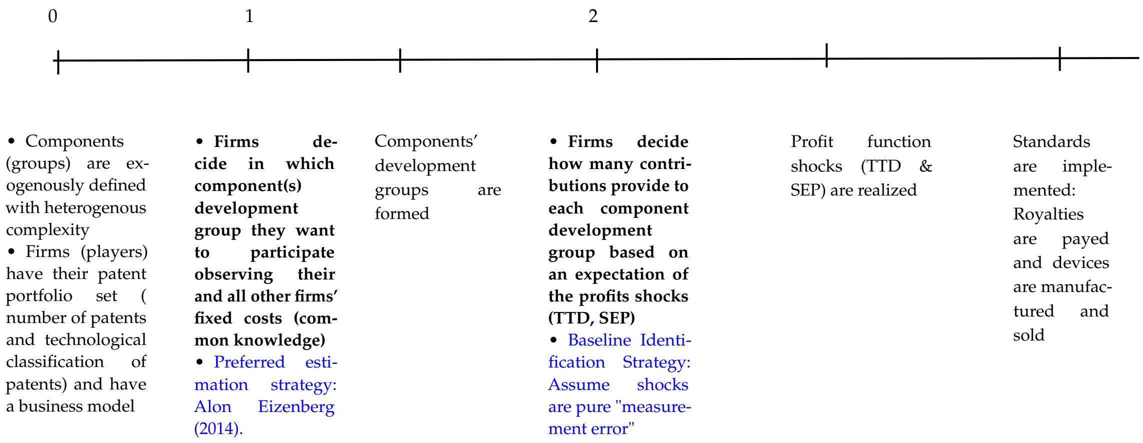
Table 3 shows the estimates of ψ in Equation 4. See Appendix Section D for the complete table including all estimates of Equation 4 and other robustness checks for this analysis. Controlling for firm, component and version of the technology unobserved heterogeneity , an increase of 1% in the average knowledge similarity of firms participating in the development of component standard decreases the average number of SEPs claimed by firms in that group between by 2.47% and 0.875% depending on the model specification. The negative and significant relationship between a firm's number of SEPs and a firm's knowledge similarity in the group is robust to the several sets of controls. This evidence supports the hypothesis of a competition effect, according to which firms with similar knowledge are closer competitors when it comes to introducing their patented inventions in the standardization of a component of the mobile telecommunication system

5 | A MODEL FOR FIRMS' CONTRIBUTIONS AND PARTICIPATION DECISIONS

5.1 | The Setup

This section presents a two-stage model that captures how firms decide in which standardization groups to contribute and how many contributions to provide in each, in order to develop a given version of a common technology standard. At the beginning of the development of each technology version, the components whose standards need to be developed, their broadness, and the technological knowledge of the firm are public information. Firms realize a set of sunk cost disturbances and choose which standardization groups to join. Firms then decide how many contributions to provide to the group, and subsequently realize a set of time production function and patent shocks. Firms solve the problem by working backward from the second stage: they first define the optimal number of contributions and calculate the equilibrium profits that will likely accrue to them under any possible pattern of group participation, and then choose the groups that maximize those profits. Figure 3 shows the timeline of the events. The econometrician solves the problem in the same order.

FIGURE 3 Timeline of the Game



- Components (groups) are exogenously defined with heterogenous complexity
- Firms (players) have their patent portfolio set (number of patents and technological classification of patents) and have a business model

- **Firms decide in which component(s) development group they want to participate observing their and all other firms' fixed costs (common knowledge)**
- Preferred estimation strategy: Alon Eizenberg (2014).

Components' development groups are formed

- **Firms decide how many contributions provide to each component development group based on an expectation of the profits shocks (TTD, SEP)**
- Baseline Identification Strategy: Assume shocks are pure "measurement error"

Profit function shocks (TTD & SEP) are realized

Standards are implemented: Royalties are payed and devices are manufactured and sold

Notes: The timeline of the events is for a given version of the technology. For each version of the technology the game is played the same way.

5.2 | The Second Stage

Each firm f decides the number of contributions c to submit to standardization group s in version v of the technology so as to maximize expected profits, given by

$$\pi_{f,s,v} = \underbrace{\left(MT - TTD_v(c_{f,s,v}, c_{-f,s,v}, sim_{f,-f,s,v}, \epsilon^T_{s,v}, \bar{\theta}^T)\right)}_{\text{Group's outcome}} \times \Big(\underbrace{D_{bm(f)} * BM_{f,v}}_{\text{Downstream profits of using the standards}} + \underbrace{P_{v,bm(f)} * SEP_{f,s,v}(gsimil_{f,-f,s,v}, X_{f,s,v}, X_{-f,s,v}, \epsilon^{SEP}_{f,s,v}, \bar{\theta}^{SEP})}_{\text{Part that can be privately appropriated by licensing IP rights}} \Big) - \frac{mc_f}{2} c^2_{f,s,v}. \tag{5}$$

where MT represents the maximum time to develop a component, after which the component has no value. The function $TTD_v(\cdot)$ is the time it takes participating firms to develop the set of standards in version v, and depends on c, the number of contributions, $sim_{f,-f,s,v}$, the pairwise knowledge similarity between firm f and other firms $-f$, and a set of parameters denoted $\bar{\theta}^T$.

where MT represents the maximum time to develop a component, after which the component has no value. The function $TTD_v(\cdot)$ is the time it takes participating firms to develop the

set of standards in version ν, and depends on c, the number of contributions, $sim_{f,-f,s,\nu}$, the pairwise knowledge similarity between firm f and other firms $-f$, and a set of parameters denoted $\bar{\theta}^T$.

Each firm appropriates a share of the group outcome through two channels. First, downstream profits from using the standards, modeled as $D_{bm(f)} * BM_{f,\nu}$, where $D_{bm(f)}$ captures the average market revenues related to the selling of intermediary or downstream goods and $BM_{f,\nu}$ is a set of dummy variables accounting for the firm's business model. Second, royalty revenues from licensing the standard's SEPs, given by $P_{\nu,bm(f)} * SEP_{f,s,\nu}(\cdot)$. [31]The parameter $P_{\nu,bm(f)}$ is the value of one SEP for firms with business model $bm(f)$ in version ν, and the number of SEPs a firms holds $SEP_{f,s,\nu}(\cdot)$ is a function of the group's average knowledge similarity $gsimil_{f,-f,s,\nu}$, firm characteristics $X_{f,s,\nu}$, the average characteristics of other firms in the group $X_{-f,s,\nu}$, and a set of parameters $\bar{\theta}^{SEP}$.

The functional form of the time penalty component in the revenue function is chosen so that the time to develop the standard (TTD) affects the common output negatively and linearly.[32] While this functional form could theoretically yield a negative value for developing a component if the development takes longer than MT, empirically, MT is set so that this occurs with a probability of 0 in equilibrium.[33] I impose independence between the times it takes to develop the different component s in a given version of the technology ν, therefore the time to develop all components in a given version of the technology TTD_ν is the sum of the time it takes to develop all the components.[34]

Marginal costs. In the model, firms have a quadratic marginal cost mc_f of providing contributions, whereas, conditional on participating, they face no fixed costs. Marginal costs are heterogeneous across firms but constant across component standards and version of the technology. They are also common knowledge for all firms but unobserved by the researcher. I assume that:

$$mc_f \sim lognormal(\mu_f^C, \sigma^2) \tag{6}$$

with an unknown set of parameters μ_f^C and σ^2.

The Time To Develop: the group outcome. Assume that firms participating in the group standardizing component s in version ν of the technology are labeled $f = 1, ..., G$. Then, Equation 7 defines the time production function as

$$TTD_{s,\nu} = \beta_1 \sum^{f\in G} c_{f,s,\nu} + \frac{1}{2}\beta_2 \sum^{f\in G} c^2_{f,s,\nu} + \frac{\phi}{2} \sum_{f\neq j}^{f\in G} \sum_{j\neq f}^{j\in G} c_{f,s,\nu} c_{j,s,\nu} sim_{f,j,s,\nu} + \alpha_s^T + \alpha_\nu^T + \epsilon_{s,\nu}^T, \tag{7}$$

---

[31] Ideally, I would include the value of those SEPs, but this information is unavailable. I then consider only the number of SEPs, and use the model and its equilibrium conditions to back out the value of $P_{\nu,bm(f)}$ and get an estimate of the firms' licensing revenues.There are several problems when dealing with the value of a SEP: (i) firms usually license their entire portfolio of patents; (ii) royalties are usually set in court, are proprietary data, and vary depending on who is the licensee (Abrams et al., 2019); and (iii) even data on royalties collected by firms would not capture the whole value of a SEP due to cross-licensing agreements between vertically integrated firms. See Section 2 for more details on this.

[32] Other, more flexible functional forms can be used to model the common output. However, the model loses valuable characteristics like tractability and a closed-form equilibrium in the second stage of the game.

[33] MT does not interact with c and therefore it does not affect the optimal number of contributions in equilibrium. Empirically MT is set in 3650 days. The maximum TTD observed in the sample is 4030 days.

[34] TTD refers to the number of days it takes all firms to develop the component standards but it does not refer to calendar time since components may be developed parallel in their respective working groups

where $TTD_{s,v}$ is, as in Section 4.2, the number of days it takes the group to develop a component s in version v of the technology, normalized by its broadness.[35] $c_{f,s,v}$ is the number of contributions submitted by firm f, $sim_{f,j}$ is a pairwise measure of the knowledge similarity between firms f and j, α_s^T is a component specific term, that accounts for the unobserved heterogeneity in components complexity, and α_v^T is a version-specific term.[36] All variables in Equation 7 are in levels to make the final model more tractable. The term $\epsilon_{s,v}^T$ is the time to develop shock and accounts for all residual variation in *TTD*. Then, $\epsilon_{s,v}^T$ can be decomposed in

$$\epsilon_{s,v}^T = \sum^{f\in G} \zeta_f^T + \sum^{f\in G} \zeta_{f,s}^T + \sum^{f\in G} \zeta_{f,v}^T + \sum^{f\in G} \zeta_{f,s,v}^T + \sum_{f\neq j}^{f\in G} \sum_{j\neq f}^{j\in G} \zeta_{f,j,s,v}^T + \zeta_{s,v}^T$$

where ζ_f^T is the unobserved component of TTD varying at firm level, accounting for potential heterogeneities in firm's contributions. For example, for the fact that some firms might be more efficient and their contributions might help accelerate the component standard development more than the contributions made by more inefficient firms. Then, $\zeta_{f,s}^T$ accounts for the unobserved components of the TTD varying at firm-component level, accounting for potential heterogeneities in the match between the firm and the component to be standardized. That is, some firms might be more efficient when contributing to the standardization of a given component, and therefore their contributions might speed up the process more than contributions of other firms to that same component. $\zeta_{f,v}^T$ accounts for the error term part varying at a firm-version level. It might be the case that some firms are more involve in the the development of certain version of the technology and therefore their contributions help to develop the component faster in that given version of the technology. Then, $\zeta_{f,s,v}^T$ is the unobserved component of TTD varying at firm-component-version level, representing the potential heterogeneities in the firm-group (component-version) match. $\zeta_{f,j,s,v}^T$ is the part of the error term varying at firm pairwise level and represents potential unobserved heterogeneities in firms pairwise complementaries, as for example, the quality of the match. Finally $\zeta_{s,v}^T$ is the residual error term which is assumed to be i.i.d, following a normal distribution with zero mean.

The parameter ϕ in Equation 7 is an average measure of firms' contributions cross-effects. I allow cross-effects in the number of contributions to vary with firm knowledge similarity $sim_{f,j}$.

SEP function. Different firms may have different technological solutions to meet the technical requirements of the component to be standardized, as explained in section 2. I build on the empirical evidence in Section 4.3 and model the IP rights (number of SEPs) a firm claim to have in the technology of component s inversion v as a function of the technology similarity with the other firms $(-f)$ participating in the development of the component, among other firm and component characteristics, as in Equation 4.

$$SEP_{f,s,v} = \alpha_0 + \psi gsimil_{f,-f,s,v} + \beta_3 X_{f,s,v} + \beta_4 X_{-f,s,v} + \alpha_f^{SEP} + \alpha_s^{SEP} + \alpha_v^{SEP} + \epsilon_{f,s,v}^{SEP}, \quad (8)$$

where the variable $SEP_{f,s,v}$ is the log of the number of SEPs firm f declared to claim in

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[35] I normalize time by dividing it by the broadness of the standard, defined as the number of related technological goals (see Section 3.2 for more details on this measure).Normalization is chosen over controlling for the number of technology goals in order to avoid endogeneity issues.

[36] For notation coherence, I use the same variable α for all sets of fixed effects and ϵ to represent the error term. I then differentiate them between equations by using a superscript.

component s for version ν, and $\mathtt{gsimil}_{f,-f,s,\nu}$ is the average cosine similarity between the patent portfolios of firm f and all other firms $-f$ participating in the development of component standard s in version ν of the technology, also in logs. I include firm fixed effects (α_f^{SEP}) to control for unobserved firm heterogeneity, such as experience in standardization and bargaining power, which may also affect the number of SEPs a firm claims. To capture the heterogeneity across technology versions, which may also affect the number of SEPs, I include version fixed-effects α_ν^{SEP}. In the same spirit, I absorb a set of component fixed effects (α_s^{SEP}) to account for the unobserved heterogeneity in their complexity.

Covariates $X_{f,s,\nu}$ control for the number of contributors in the group developing a component-version, for the broadness of the component-version, a dummy variable that takes value 1 if the component is developed for the first time in that version of the technology, and for the portfolio size of the firm. The value of this last variable is computed in the year prior to joining the group, as joining the standardization process might impact firms' patent portfolios. In some specifications, I also control for the average characteristics of other firms in the group, $X_{-f,s,\nu}$, to account for the portfolio size of the competing firms.

The term $\epsilon_{f,s,\nu}^{SEP}$ is the IP rigths shock and accounts for all residual variation in SEP. Then, $\epsilon_{f,s,\nu}^{SEP}$ can be decomposed in

$$\epsilon_{s,\nu}^{SEP} = \sum^{f \in G} \zeta_{f,s}^{SEP} + \sum^{f \in G} \zeta_{f,\nu}^{SEP} + \zeta_{f,s,\nu}^{SEP}$$

where $\zeta_{f,\nu}^{SEP}$ is the unobserved component of SEP varying at firm-version level, accounting for potential heterogeneities in firms contributions that are not time invariant, but vary with technology versions. As before, It might be the case that some firms are more involve in the the development of certain version of the technology and therefore working with exacting same other firms, having exact the same characteristics their technical proposal are more likely to be part of the selected technology for component s. In the same spirit, $\zeta_{f,s}^{SEP}$ accounts for the unobserved components of the number of SEP varying at firm-component level, accounting for potential heterogeneities in the match between the firm and the component to be standardized. Finally $\zeta_{f,s,\nu}^{SEP}$ is the residual error term which is assumed to be i.i.d, following a normal distribution with zero mean.

Firms' profits. Let $\bar{\theta}^T$ represent the set of parameters in Equation 7, and $\bar{\theta}^{SEP}$ represent the set of parameters in Equation 8.

Combining **??**, Equation 7, Equation 8 and Equation 6, I construct the following empirical firm profit function:

5.3 | Optimal Number of Contributions and Second-Stage Equilibrium

Given their participation decision, firms choose how many contributions $c_{f,s,\nu}$, to provide by maximizing expected profits, assuming that other firms are also maximizing their own profits. I can write the equation for the expected profits as a functions of the contributions submitted by all firms $c_{f,s,\nu}$, observed variables (BM_f, MT) and a set of parameters θ .Then the best-response function for firm f in the group developing component standard s in version ν of the technology is defined by the number of contributions made by the other firms, the observed variables and θ. As shown in Appendix Section **??**, by rearranging terms I can write the optimal number of contributions $c_{f,s,\nu}^*$ of firm f as a linear function of the optimal number of contributions of the other firms in the group $c_{-f,s,\nu}^*$, the observable variables previously defined, and the set of parameters of the model. The Nash equilibrium of this stage of the model is the vector of the number of contributions submitted by each firm.and corresponds to the fixed point on firms' contributions.

As shown in Appendix Section **??**, the reaction function of each firm is linear with respect to the number of contributions from other firms. This linearity enables me to solve the model by simply inverting matrices, as described in the theoretical framework in **??**.

5.4 | Participation Decision

Revisiting the first stage of the model, each firm simultaneously chooses in which group to participate. I model a firm's participation decision based on expected revenues and the fixed cost of participating. Firms generate their expectations over standardization profits according to the model presented in the previous section.

An important component of the fixed cost is the technological knowledge that a firm must possess to participate in the development of the standardization of a given component of the technology. Firms need to invest resources, such as engineers' hours, in order to understand the group's goal and assess its potential for the firm. If the standardization group is working in a field that is completely unrelated to the firm's technological expertise, the fixed cost is higher. Appendix Section F elaborates on the fit between the technological requirements of the standard under development and the firm's technological knowledge. Appendix Table F.1 presents the logit estimates of the participation model, and Appendix Figure F.1 the marginal effects of the group and the firm's characteristics on participation probabilities. These results suggest that the match between the group and the firm is an important factor determining participation decisions. Therefore, I incorporate this friction in my model as a fixed cost.

Moreover, I assume the following structure for the observable part of the firm's fixed costs:

$$\mathsf{FC}_{f,s,v} = \underbrace{\gamma_0^{FC}}_{\mathsf{Constant}} + \underbrace{\mathsf{fit}_{f,s,v}}_{\text{Firm–Component fit}} + \underbrace{\gamma_f}_{\text{Firm-specific FC}}, \tag{9}$$

where:

$$\mathsf{fit}_{f,sv} = M(\mathsf{Broadness}_{s,v}, \mathsf{Portfolio}_{f,v}; \gamma^{\mathsf{fit}}),$$

where γ_0^{FC} represents a constant fixed cost common to all firms in the market, $\mathsf{fit}_{f,s,v}$ is an approximation to the fit between the firm's technological expertise and the component to be standardized technological requirements, and γ_f is a firm-specific constant term accounting for the unobserved heterogeneity in firm's potential capacity to contribute to standardization groups. An example of such unobserved heterogeneity is the number of potential standardization groups in which a firm can participate. I model the fit between the firm and the standardization group as a function M of the component's broadness $\mathsf{Broadness}_{s,v}$ and the firm's technological capacity, proxied by the size of its patent portfolio $\mathsf{Portfolio}_{f,v}$ the year prior to deciding whether to participate or not.

Participation condition (revealed preference assumption): $p_{f,s,v}$ is the participation decision chosen by firm f for component s in version v of the technology, which takes value 1 if the firm decides to participate, and 0 otherwise. For ease of notation I abstract away from the version sub-index v; then,

$$\mathbb{E}(\pi_{f,s}(p_{f,s}, p_{-f,s}) - F_{f,s}(p_{f,s}) + \epsilon_{f,s}^{p_f} \mid \mathcal{I}_f) \geqslant \mathbb{E}(\Pi_{f,s}((1 - p_{f,s}), p_{-f,s}) - F_{f,s}(1 - p_{f,s}) + \epsilon_{f,s}^{1-p_f} \mid \mathcal{I}_f), \tag{10}$$

where $\pi_{f,s}(p_{f,s})$ and $F_{f,s}(p_{f,s})$ are the second-stage profits and fixed costs of choosing $p_{f,s}$ when all the other firms chose $p_{-f,s}$, respectively. The variable $\epsilon^{p_f}_{f,s}$ represents the unobserved (by the researcher) part of fixed costs firm f faces when choosing $p_{f,s}$. This unobserved term accounts for the part of the firm–standard technological match that is not captured by the M function. I assume this information is known by the firm.

Without loss of generality, assume that firm f participates in the development of component standard s in version v. Once again, I abstract away from the v sub-index to ease notation. Then, adding Equation 5, I can write Equation 10 as

$$\begin{aligned}&(MT - \underbrace{TTD(c^*_{f,s}, c^{*p_{f,s}=1}_{-f,s})}_{\text{TTD with participation}}) \times \underbrace{(A^M_{BM} + A^P_{r,BM} SEP_{f,s})}_{\text{Revenues from participation}} - mc_f c^{*2}_{f,s} - F_{f,s} + \epsilon^{part}_{f,s} \\ &\geqslant (MT - \underbrace{TTD(0, c^{*p_{f,s}=0}_{-f,s})}_{\text{TTD without participation}}) \times \underbrace{(A^M_{BM})}_{\text{Revenues from no participation}} + \epsilon^{npart}_{f,s},\end{aligned} \tag{11}$$

where $TTD(c^*_{f,s}, c^{*p_f=1}_{-f})$ is the time it takes to develop the standard if firm f participates in the development of component s in version v, providing the optimal number of contributions $c^*_{f,s}$, and the other firms $-f$ contribute with their optimal number of contributions $c^{*p_f=1}_{-f,s}$. Note that a firm's outside option of participating is not zero. The standard will still be developed in a counterfactual time, $TTD(0, c^{*p_f=0}_{-f,s})$.

I simplify notation in Equation 11 and write the participation condition in component standard s as:

$$p_{f,s} = 1 \iff \Delta(\pi_{f,s}) - FC_{f,s} \leqslant \epsilon^{p_f=0}_f - \epsilon^{p_f=1}_f, \tag{12}$$

where $\Delta(\pi_{f,s})$ represents the difference between the expected second-stage profits if firm f participates and if it does not. Recall that this is a complete information game,[37] and therefore, in equilibrium, expectations equal observed values.

Equilibrium. A Nash equilibrium in this stage of the model is a vector of firm participation decisions for each standardization group. The revealed preference assumption is a necessary condition for any possible Nash equilibrium. It does not rule out multiple equilibria and it does not assume anything about the selection mechanism used when there are multiple equilibria.

6 | ESTIMATION AND IDENTIFICATION

6.1 | Identification Strategy

I identify the key parameters of the model by leveraging the observed characteristics of firms' technological knowledge prior to their participation in the standardization of a component, their business models, and the technology required by the components that need to be standardized in each version of the technology. I assume all of these factors are exogenous to the firms' participation and contribution decisions.

First, the exogenous technological match determines the firms' participation decisions and, in turn, their similarity within standardization groups. To identify the participation decision parameters, I exploit the variation in firms' technological knowledge and compo-

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[37] Althought the game is a complete information one, all firms receive an unexpected shock in the TTD and SEP equations with zero mean.

nents' technological broadness, as well as the panel structure of the data, which allows me to account for time-invariant unobservable heterogeneity in components' complexity.

Second, the number of contributions submitted by each firm is determined by the equilibrium condition in the second stage of the model. To identify the second-stage parameters, I exploit the variation in firms' contribution decisions in different groups (with different levels of similarity with other firms) within and between different technology versions, as well as the panel structure of the data, which allows me to account for time-invariant unobservable heterogeneity of firms.

6.2 | Estimation Procedure

The unknown model parameters $\bar{\theta}$ are: (i) the set of parameters in the time production function parameters $\bar{\theta^T}$ in Equation 7; (ii) the set of parameters in the SEP function $\bar{\theta^S}$ in Equation 4; (iii) the market revenue set of parameters A^M_{BM}, the SEP's price set of parameters $A^P_{r,BM}$; (iv) the set of parameters of the firms' marginal cost distribution μ^c_f and σ in **??** and **??**; and the set of fixed costs parameters $\bar{\gamma}$ in Equation 9. Formally,

$$\bar{\theta} = \{\bar{\theta^T}, \bar{\theta^S}, A^M_{BM}, A^P_{r,BM}, \mu^c_f, \sigma, \bar{\gamma}\},$$

where

$$\bar{\theta^T} = \{\beta_0, \beta_1, \beta_2, \phi, \mu^T_f\}; \bar{\theta^S} = \{\psi, \mu^S_f, \mu^S_r\}; \bar{\gamma} = \{\gamma^R, \gamma^B, \gamma^P, \gamma_f\}$$

To estimate the parameters in my structural model, I rely on a three-stage procedure. I first estimate the parameters in the time production function $\bar{\theta^T}$ and the SEP equation $\bar{\theta^S}$, relying on the conditional exogeneity of the number of contributions and the knowledge similarity of the participating firms for their identification, respectively. I then use those estimates and the equilibrium equations of the model to get some moments, which I then use to identify those parameters. I rely on a minimum distance estimator to back out this last set of structural parameters. Finally, I use all the previously estimated parameters to compute $\Delta\Pi_{f,s}$ and impose a parametric distribution on $\epsilon^{p=1}$ and $\epsilon^{p=0}$ and estimate $\bar{\gamma}$ by maximum likelihood, using the fixed cost of participation as an exclusion restriction to identify the participation parameters from the ones in the profit function. The interested reader may refer to Econometric Appendix A for a more detailed discussion on the identification and estimation of the profit function parameters.

The participation model parameters

The participation model of this paper can be linked to the class of discrete complete information choice models applied to oligopolistic markets. Firms in the model know all about the other firms, and know the distribution of the shocks each of them face. The standard approach to the estimation of this type of entry models relies on assuming that a firm's profits are declining in rivals' decisions (Bresnahan and Reiss (1991b), Bresnahan and Reiss (1990)). This assumption does not hold in my model, since firms can benefit from the presence of other firms in the group due to the complementarities in their contributions. Another standard approach to solving these models is deriving choice probabilities from a theoretical framework and finding the parameter values that maximize the likelihood of entry choice in the data (Bresnahan and Reiss (1991a)). I rely on this last approach.[38]

I rely on a Nash equilibrium concept, and use Nash equilibrium conditions to derive

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[38] While the incomplete information assumption can also make sense in this set up, a model à la Aguirregabiria and Mira (2007) would not be possible to estimate due to the high number of players (35).

firms' (unobserved) choice set. As a standard way of solving for a Nash equilibrium, I start from the observed equilibrium in each group, and consider the vector of observed participation decisions when only one firm deviates at a time as a feasible unobserved group configuration.

I assume that the unobserved participation terms $\epsilon^{part}_{s,v}$ and $\epsilon^{npart}_{s,v}$ in Equation 12 are identically and independently distributed across firms and standards with a type I extreme value distribution. Then, the probability of firm f participating in the development of component standard s in version v is

$$\text{Prob}(p_{f,s,v} = 1) = \frac{exp(\Delta\Pi_{f,s,v} - FC_{f,s,v})}{1 + exp(\Delta\Pi_{f,s,v} - FC_{f,s,v})}, \tag{13}$$

where $\Delta(\Pi_{f,s,v})$ represents the difference between the expected second-stage profits if firm f participates and if it does not, defined in **??**, and FC is the fixed cost defined in Equation 9.

After constructing the counterfactual group configuration for each component standardization group and computing the corresponding $\Delta(\Pi)$, I proceed to estimate the participation parameters in Equation 12 by maximizing the likelihood function corresponding to the probabilities in Equation 13.

For a more detailed discussion on the identification and estimation of the participation parameters, the interested reader may see Econometric Appendix B.

7 | ESTIMATION RESULTS AND FIT OF THE MODEL

Appendix Figures **??** and **??** show the match between data and model moments. The model matches the moments of the data well: notably, it perfectly captures the average number of contributions per firm business model. A broader discussion on the fit of the model and a set of different measures for it can be find at Appendix Section **??**.

Table 4 presents estimates for the direct effect of the number of contributions on the TTD, as well as the estimates for cooperation and competition effects. All average point estimates of the coefficients of interest are significantly different from zero at a 5% confidence level.

The positive sign of the cooperation effect suggests that contributions provided by different firms and their knowledge similarity are indeed complements. The same number of contributions provided by firms that are 0.1 closer technologically reduces the expected time to finish the standard by 0.0068 days. The significant and negative coefficient of $-\beta_2$ suggests that there are decreasing marginal returns from contributions provision. That is, on average, the first contribution reduces standardization time in 0.4014 days,[39] while the second one reduces it by only 0.3906 days. The reduction on standardization time for the average number of contributions in a group, that is 65 contributions, is of 0.06 days.

Column 4 of Table 4 shows that firms working in the same group with technologically similar firms claim to have a lower number of SEPs. The point estimate of the ψ parameter suggests that an increase of 1 p.p in the average similarity of the other firms in the group reduces the expected number of SEPs by 0.7% for each firm. Contrary to the cooperation effect, the competition effect generates incentives for firms to provide less contributions when teaming up with other firms that are specialized in similar technologies.

Appendix Table C.2 presents the structural parameter estimates of the remaining parameters of the profit function. I use 100 simulations to compute each of the model's moments.

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[39] The marginal effect of contributions on time is 0.4068 - 0.0021 * Number of contributions.

TABLE 4 Time Production Function and SEP Estimates

	Individual effect of contributions ($-\beta_1$)	Contributions' squared term ($-\beta_2$)	Cooperation effect ($-\phi$)	Competition effect(ψ)
Estimate	0.4068	-0.0027	0.0068	-5.1673
SE	0.0510	0.0007	0.0027	0.6493
Component charact.	Yes	Yes	Yes	Yes
Release FE	Yes	Yes	Yes	Yes
Firm FE	No	No	No	Yes
N	1,880	1,880	1,880	2,824
R^2	0.5650	0.5650	0.5650	0.08

Bootstrap standard errors (with reposition) at a standardization group level, 1000 samples.

Given the lack of scale in these estimates, I quantify the importance of licensing SEPs for a firm's expected profits by constructing an index that captures the relative importance of royalty revenues with respect to the overall expected revenues from standardization. To that end, I define

$$IL_{v,BM} = \frac{A^P_{v,BM} \times AvgSEP_{v,BM}}{A^P_{v,BM} \times AvgSEP_{v,BM} + A^M_{v,BM}},$$

where $IL_{v,BM}$ is the weight of expected licensing revenues with respect to the total expected revenues from standardization for firms with business model BM for the version v of the technology. The IL index is trivial in the case of pure upstream firms (IL=1) and telecom operators (IL=0). Then I compute it only for intermediary and vertically integrated firms. Figure 4 shows the IL index for those type of firms, per version of the technology. Before 4G (Release 8), the licensing of SEPs had a higher weight in a vertically integrated firms' profit function than in of a firm producing intermediate goods. This changes with 4G, when the licensing of SEPs becomes more important for firms in general and for firms producing intermediate goods in particular. Specially, for those firms, the licensing of SEPs from Release 10 onward represents a up to 30% of the total expected revenues from standardization.

These results implies that royalties' importance increased between 3G and 4G from 4.2% to 25% for the intermediaries and from 8.7% to 23% for vertically integrated firms, consistent with findings in Galetovic et al. (2018). According to the authors estimations royalty revenues increased at least 20% between 3G and 4G.[40]

As another robustness check of the model, I compare my results with those from Qual-

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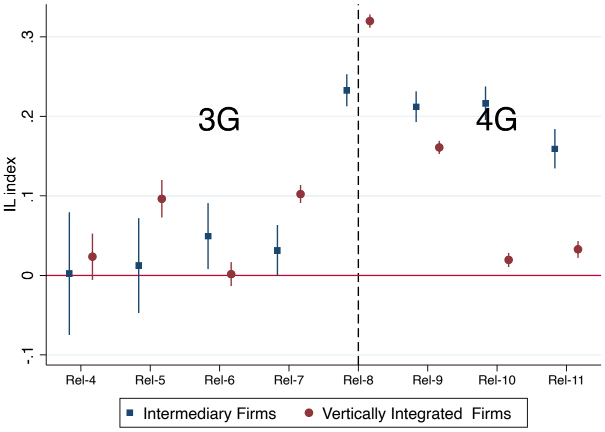
[40] The 20% increase corresponds to comparing the \$67,760 millions in royalties collected between 2008 and 2011 (3G) with the \$37,143 collected in 4G royalties between 2012 and 2016. The \$37,143 are calculated on the conservative basis that 3G royalties in this period equal the 3G royalties of the 2008–2011 period.

FIGURE 4 IL Index for Intermediary and Vertically Integrated Firms



Note: Bands represent 95% confidence intervals. The variance of this index comes from the variance of averaging the number of SEPs per business model and release. Release 4, 5, 6, and 7 are part of the third- generation and Release 8 onward belong to the 4th one.

comm's earnings reports, one of the few firms in the sample reporting separately earnings from licensing and good selling. Qualcomm's reports show that from 2010-2016, licensing profits constituted between 63-73% of their total profits, aligning with my model's estimate of 60-66%.[41] [42]

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[41] See https://investor.Qualcomm.com/financial-information/quarterly-results.

[42] 4G was commercially launched in 2010.

8 | FREE LICENSING: A COUNTERFACTUAL POLICY

In an attempt to curb the monopoly power that they create, 3GPP requires the holders of SEPs covered by the standard to grant licenses on fair, reasonable, and non-discriminatory (FRAND) terms.[43] Needless to say, such loose price commitments have led to intense litigation activity, as discussed in Lerner and Tirole (2015). Nevertheless, as 5G and beyond technologies continue to develop, including the Internet of Things (IoT) and connected cars, the licensing of standard patents becomes increasingly complex. This has led several major jurisdictions to consider regulatory actions, (EC, 2022).[44] Consequently, when considering the regulation of standard-related patents, it is crucial to assess their impact on firms' incentives to innovate.

While free licensing hasn't been discussed in 3GPP, it can be thought of as an extreme case of the potential regulation spectrum for SEP licensing.[45][46]Though an extreme case, it helps us to understand the main mechanisms through which the time it takes to develop a standard might be affected when changing licensing rules as well as their magnitudes in equilibrium.

The impact of enforcing a royalty-free licensing scheme is ambiguous. On the one hand, it would shut down the competition effect, by aligning firms' private and common incentives and encouraging similar firms to cooperate more to take full advantage of their complementarities, so as to develop the standards in less time. On the other hand, it would also shut down one of the potential revenue streams, by disincentivizing firms from participating and providing contributions. This second channel is particularly important for firms that do not profit from selling products. To quantify this trade-off, I compare the predictions of my economic model, using the estimated parameters against an economic model in which patents are licensed for free. In my counterfactual scenario, I allow contributions and participation decisions to vary with the new licensing policies.

For the participation model, enumerating each of the potentially many equilibria is computationally infeasible at present, and so I follow Lee and Pakes (2009) who suggest a learning process to reduce this burden.[47] In short, the program assumes an ordering of decisions based on participation probabilities over all standardization groups. The first firm decides whether to participate or not as a best response to all other firms' participation decisions in the baseline scenario. The second firm similarly best responds, but substitutes the participation decision of the first firm with the first firm own best response. The third firm similarly best responds, but it substitutes the participation decision of the first and second firms with their own best responses. The program cycles through the firms, continually updating the participation decisions until no firm wishes to deviate. The result is a simultaneous-move Nash equilibrium, conditional on a single draw of the sunk costs. I take 100 such draws and report the average outcomes across them. The weakness of this approach is that each "run" results in a unique equilibrium, which is only a small fraction

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[43] See Section 2 for more details on this.

[44] The US launching two public consultations in December 2021 and April 2022, the UK launching a public consultation in December 2021, Japan adopting guidelines in 2018, 2020 and 2022, and the European Commission releasing a Communication in 2017 titled "Setting out the EU approach to Standard Essential Patents" and a 2020 action plan on intellectual property.See EC (2022) for more information.

[45] Under royalty-free clauses, firms must license their patents at no cost.

[46] Other SSOs, such as the 3WC, the organization in charge of the development of HTML protocols, view free licensing as a way to ensure wide implementation of their standards and full realization of the standard's global benefits.

[47] Solving the game requires calculating the potential profits for each firm in each potential group configuration. For each group there are 2^{35} potential configurations. Calculating expected profits for each firms requires solving the model $2^{35} \times 35$ in each group, which is currently computationally unfeasible.

of those possible. The results are robust to completely reversing the order and rerunning the program.

I find that the overall effect of restricting patent licensing would be a delay in the development of the standards. Despite the increase in the similarity of firms working together, which fosters the cooperation effect, the restriction on patent licensing would have a big and negative impact on participation and contribution decisions, as can be seen in Appendix Figure Figure C.3. On average, under a royalty-free licensing policy there would be 7% less firms participating in each standardization group, and they would contribute 18% less.

The results are heterogeneous across firms' business models. While participation of telecom operators remains unchanged, pure upstream firms would barely participate in this counterfactual scenario, representing less than 1% of the total number of participants. Intermediary firms would be the second most affected group, since the restriction of patent licensing would reduce their participation by 10%. Finally, vertically integrated firms would participate 4% less than in a scenario in which they could license their patents.

The results are also heterogeneous across versions of the technology. In the case of the first release of 4G, which took 3 years to develop, forcing firms to license their patents for free would have delayed completion by an additional year.

The Downstream Effect of Free Licensing. Royalties are part of the cost of products sold in the downstream market, such as mobile devices. A free licensing policy would affect the final price of these goods by reducing their costs. To complement my analysis of the effects of a free licensing policy in this market, I calculated the impact on the downstream price of mobile devices in the American market. I assumed Cournot competition downstream to calculate firms' price elasticity and then used the average cumulative royalty yield calculated by Galetovic et al. (2018) nd the industry elasticity estimated by Fan and Yang (2020) to compute the final price reduction of a mobile device in the US. Appendix Section D.7 describes the computing details and Appendix Table D.6 shows the results. Depending on the scenario, free licensing might reduce the final price of a mobile device in the US by approximately3%–5%.

Overall, the free licensing policy would have entailed a delay of an extra year in the completion of the first generation of the 4G standards and a reduction between of 10–20 dollars in the final price of the average mobile device. Comparing how much consumers value each of these reductions is beyond the scope of this paper. Nevertheless, in their paper on the US smartphone market, Fan and Yang (2020) find that for consumers: (i) a one-hour increase in battery talk time is equivalent to a price decrease of $8.40; and (ii) an increase in the screen size by 0.1 inches is equivalent to a price decrease of $15. Though no equivalency is calculated for the time consumers have to wait for a faster generation of mobile networks, we can see that they are willing to exchange relative non-core features for the price reduction that free licensing would result in.

9 | CONCLUSIONS

This paper proposes a novel framework for collaborative innovation between competitors, assessing the effect of private appropriation through the licensing of IP rights on firms incentives to innovate and the common outcome. The analysis combines reduced-form analysis with a structural model of participation and contribution decisions on the development of the 3G and 4G telecommunications standards.

Three key findings arise from the descriptive analysis. First, I show an inverse-U-shaped relationship between the number of contributions provided by a firm to the technology component standardization group and the average knowledge similarity between the firm and the other contributing firms in that group. Second, I provide evidence suggesting that firms can speed up technology development by collaborating, and that this reduction in time is positively dependent on the technological distance between the firms. I refer to this as the *cooperation effect*. Third, I provide evidence indicating that firms compete within standardization groups to have their own technology included in the standards, which I call the *competition effect*.

Drawing on this empirical evidence, I develop and estimate a two-stage model to analyze the incentives that drive firms' participation and contribution to the joint development of telecommunications standards. I find that licensing revenues represent a substantial share of participating firms' revenues, particularly in the context of 4G. For intermediary firms, the licensing of SEPs from Release 10 onward can account for up to 30% of their total expected revenues from standardization. Given the high number of standard-compliant products that are expected to emerge with the introduction of 5G, it is likely that this share will continue to increase, making licensing an increasingly important incentive for firms to engage in the development of telecommunications standards.

I then use the model to assess the effects of a royalty-free policy on the development of telecommunications standards, with the aim of identifying the key mechanisms through which changes in licensing rules can affect the time required for standard development, as well as their magnitude in equilibrium. I find that such policy would delay the development of standards through two mechanisms: (i) a decrease of 7% in the number of participating firms; and (ii) a decrease of 18% in the number of contributions submitted per participating firm. In the case of the first release of 4G, this would have delayed its completion by 1 year beyond the almost 3 years it took to develop the standards. On the other hand, in the downstream part of the market, in the case of the US, the overall effect of a free licensing policy would have been a 3%–5% price reduction of the average mobile device. Though free licensing might be an extreme policy, this paper shows evidence of the quantitative importance of IP revenues for firms developing technology in the telecommunications market.

In summary, this paper sheds light on the intricate economic incentives that govern the joint development of telecommunications standards, a critical and rapidly evolving sector. The findings highlight the significant role that licensing revenues play in incentivizing firms to participate in standardization efforts, particularly in the case of 4G and beyond technologies. Any policy that seeks to cap these revenues must take into account the potential trade-offs and unintended consequences that could arise, such as a slowdown in technology development. It is essential that policymakers carefully consider these implications in order to ensure that any regulatory actions are effective in promoting innovation and competition, while avoiding potential negative consequences.

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Econometric Appendix: Cooperation and Competition: The case of Innovation in the telecommunications sector

A | ESTIMATION AND IDENTIFICATION OF THE PROFIT FUNCTION PARAMETERS

Identification of β_1, β_2, ϕ, ψ , μ_f^S relies on the parametric assumption on the distributions of $\epsilon_{s,\nu}^T$ and $\epsilon_{f,s,\nu}^S$ and the classic moment conditions derived from the orthogonality assumption in Equation 7 and Equation 4:

1. $\mathbb{E}[\epsilon_{s,\nu}^T \mid c_{f,s,\nu}, \alpha_s^T, \alpha_\nu^T, \mathcal{I}_{f,s,\nu}] = 0 \rightarrow$ Contributions are exogenous conditional on participation, and technology component and version fixed effects
2. $\mathbb{E}[\epsilon_{f,s,\nu}^S \mid sim_{f,s,\nu;-f,s,\nu}, \mu_f^S, \mu_\nu^S \mathcal{I}_{f,s,\nu}] = 0 \rightarrow$ Similarity is exogenous conditional on participation and firms and technology version fixed effects

The identification of the remaining parameter of the second stage of the model relies on the set of moments $m(\theta)$. Although the model is highly non-linear in θ, so that (almost) all parameters affect all outcomes, the identification of some parameters relies on some key moments in the data. Keeping this in mind, I use the following $m(\theta)$ moments:

1. The average number of contributions per firm business model, across standards and releases: 1 moment per business model.
2. The average number of contributions per release, across firms and standards: 1 moment per release.
3. The average number of contributions per firm, across standards and releases: 1 moment per firm.

The first set of moments in $m(\theta)$ exploits the variation in the number of contributions across firms' business model and technology version to identify $A_{\nu,BM}^M$. The identification assumption is that revenues of producing goods using the standards as inputs only vary with a firm's business model, and that the business model of a firm only affects its selling revenues. Then, the identification of $A_{\nu,BM}^M$ relies on the idea that the difference between the number of contributions submitted in a given version of the technology by two firms with different business models but otherwise having the same characteristics and expecting to have the same number of SEPs, must be driven by their expected selling revenues.

Identification of $A_{\nu,BM}^P$ comes from the variation of the number of contributions across versions of the technology. Assuming that the value of SEPs is the only component of the profit function that varies exclusively across versions, it follows that the variation across versions should reflect the changes in the value of SEPs.

Finally, I assume that a firm's marginal cost does not vary across components or versions of the technology. Therefore, other things being equal, two firms provide a different number of contributions because of the difference in their marginal costs. Then the identification of μ_f^c comes from the variation in the average number of contributions submitted by each firm across technology components and versions.

Moreover, since the parameters in this model are identified up to a scale factor, I normalize them with respect to the parameter σ of the marginal cost function distribution. Specifically, I use $\sigma = 0.1$.[48]

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[48] Other values of σ can be used for the normalization. For instance, the standard choice $\sigma = 1$ increases significantly the time it takes the algorithm to minimize the distance between the data and the model moments.

To get the point estimates of the parameters, I use a minimum-distance estimator that chooses the parameter vector θ that minimizes the criterion function:

$$\left(m(\theta) - m_d\right)' \, \Omega \left(m(\theta) - m_d\right)$$

where m_d are the corresponding data moments in the sample, and Ω is a symmetric, positive-definite matrix; in practice, I use the identity matrix. Since the moments of this model cannot be easily computed in closed form, I resort to simulation-assisted methods. More precisely, I take 10 random draws from a $\mathrm{lognormal}(\mu_f^c, \sigma^2)$ and for a particular value of θ, I solve the model for each of these simulations.[49] I then average across simulations to obtain the moments of the model for this particular value of θ. I compute standard errors combining the standard delta method with the bootstrap method in order to account for the uncertainty in both stages.

B | IDENTIFICATION AND ESTIMATION OF THE PARTICIPATION MODEL

I rely on a Nash equilibrium concept, and use Nash equilibrium conditions to derive firms' (unobserved) choice set. As a standard way of solving for a Nash equilibrium, I start from the observed equilibrium in each group, and consider the vector of observed participation decisions when only one firm deviates at a time as a feasible unobserved group configuration. Figure B.1 shows a simple example using a three-firm group. In the observed equilibrium, firm A and firm C participate, while firm B does not. Using a one-firm deviation approach, I consider the group in which only firm C or A participates in a potential group configuration, as well as a configuration in which all three firms participate. The number of potential unobserved group configurations under this approach is exactly the number of players, which in my game is 35. Recall that to compute each firm's expected profits, I need to compute the optimal number of contributions of all 34 of the remaining firms in each group. This entails solving the model 35 times per standardization group.

FIGURE B.1 Actual and Counterfactual Group Configurations

Obs. group configuration	**Counterfactual alternatives**		
Firm A = 1	**Firm A = 0**	Firm A = 1	Firm A = 1
Firm B = 0	Firm B = 0	**Firm B = 1**	Firm B = 0
Firm C = 1	Firm C = 1	Firm 1 = 1	**Firm C = 0**

As is standard in deriving conditions for a Nash equilibrium, I don't consider second-round deviations. That is, in example 1, I don't consider the group that would arise if B were to decide to participate after A decides not to participate to be a potential counterfactual group configuration.

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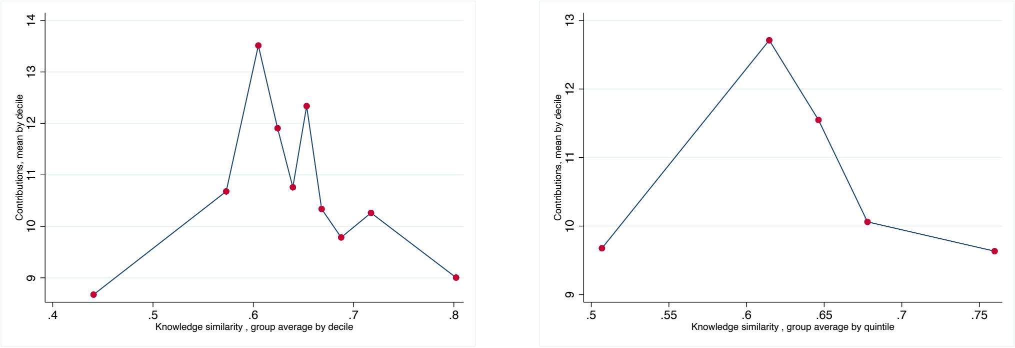
[49] I also computed the moments using 100 simulations. The results were very similar but the computational time increased significantly. While estimating the parameters using 10 draws takes between 1 and 2 hours, using 100 draws increases the computational time to more than 15 hours. Estimating standard errors by bootstrapping using 100 draws would take an incredibly long time.

Tables and Robustness Appendix: Cooperation and Competition: The case of Innovation in the telecommunications sector

C | ADDITIONAL FIGURES AND TABLES

C.1 | Contributions and Firms' Knowledge Similarity

FIGURE C.1 Number of Contributions and Firms' Knowledge Similarity



(a) Contributions and firms' similarity, by similarity's deciles

(b) Contributions and firms' similarity, by similarity's quintiles

Notes: The figures show the average number of contributions submitted by firms with respect to the average similarity of the group of firms working in the standardization group where the contribution was made controlling by firm and component fixed effects, discretized by deciles in the similarity distribution (Panel a) and by quintiles (Panel b).

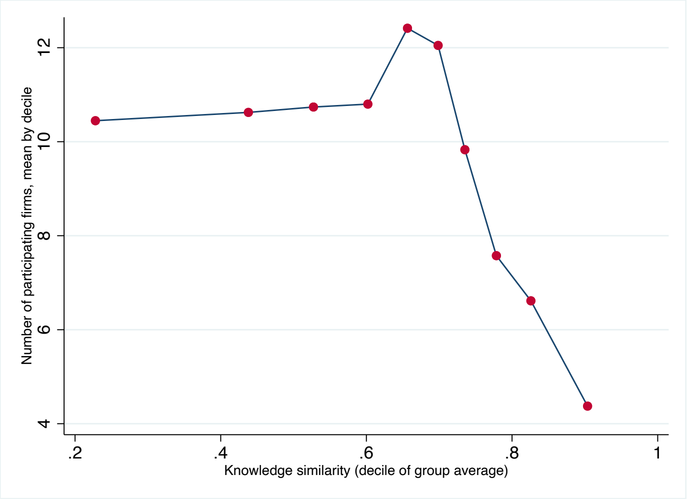
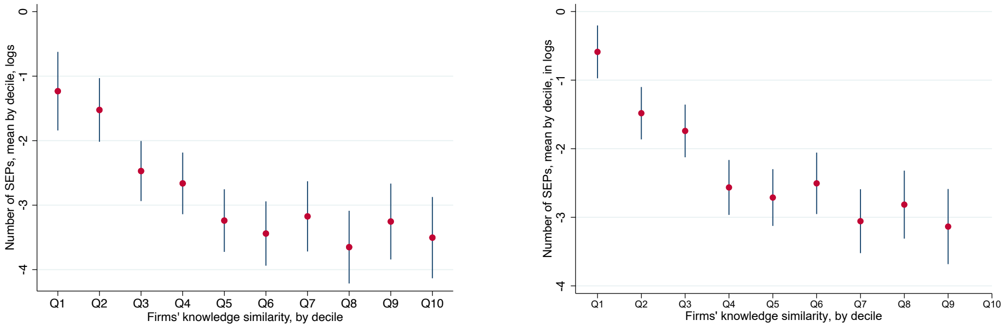


FIGURE C.2 Number of Participating Firms and Firms' knowledge similarity
Notes: The figure shows the average number of participating firms in a component standardization group with respect to their average knowledge similarity, discretized by deciles in the similarity distribution. 95% confidence bands computed with robust standard errors.

C.2 | Seps and Firms' Knowledge Similarity

FIGURE C.3 SEPs and Firms' Knowledge Similarity

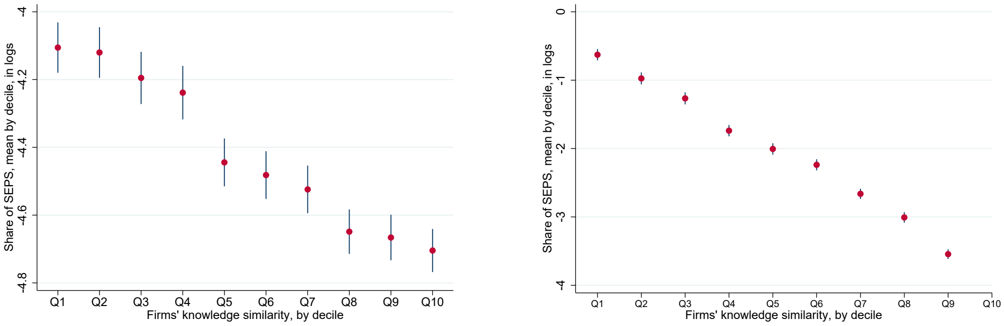


(a) Number of SEPS and firms' knowledge similarity

(b) Number of SEPS and firms' knowledge similarity, including controls

Notes: The Figures shows the average number of SEPs claimed by firm in each component standardization group with respect to the average knowledge similarity of the other firms in the group, discretized by deciles in the similarity distribution. Panel (a) show the results without controls and Panel (b) shows the results when controlling for firm fixed effects and number of firms in the group. 95% confidence bands computed with robust standard errors.

FIGURE C.4 Share of SEPs and Firms' Knowledge Similarity



(a) Share of SEPS and firms' knowledge similarity

(b) Share of SEPS and firms' knowledge similarity, including controls

Notes: The Figures show the average share of SEPs claimed by firm in each component standardization group, defined as the number of claimed SEPs by firm over the total of SEPs related to that component standard, over the average knowledge similarity of the participating firms. Panel (a) show the results without controls and Panel (b) shows the results when controlling for firm fixed effects and number of firms in the group. 95% confidence bands computed with robust standard errors.

Figure C.3 shows a negative and significant relationship between the average number of SEPs firms claim to have in a component standard and the knowledge similarity of the firms, with and without controls. Figure C.4 shows that this relationship still holds when using the share of SEPs, that is, the number of SEPs held by a firm in a given group over the total number of SEPs related to that group. Table C.1 shows the full set of estimates of Equation 4.

Notes: The Table shows estimates of the competition parameter. Robust standard errors in parentheses. ***significant at the 1 % level, **5 % level, *10 % level.

C.3 | Estimation and Counterfactual Results

Table C.2 shows estimates of the downstream revenues and SEP parameters in Equation 5 of the structural model. Figure C.3 shows observed and counterfactual firms' participation and contributions as a function of the broadness of the standard.

TABLE C.1 Estimates of the Competition Effect Parameter

	(1) Baseline	(2) Controls	(3) Other firms controls	(4) Tobit	(5) Tobit
Firms' knowledge similarity	-1.723	-0.875	-1.286	-2.470	-3.204
	(0.418)	(0520)	(0528)	(0.693)	(0.704)
Number of firms	0.956	-0.0437	0.339	1.566	2.027
	(0.119)	(0.247)	(0.246)	(0.233)	(0.252)
Portfolio size		0.131	0.172	0.448	0.495
		(0.210)	(0.212)	(0.431)	(0.430)
Standard's broadness		0.377	0.321	-0.204	-0.248
		(0.125)	(0.123)	(0.125)	(0.126)
		(0.057)	(0.057)	(0.106)	(0.106)
First-time dummy		-0.124	-0.196	0.302	0.223
		(0.223)	(0.220)	(0.289)	(0.288)
Other firms' portfolios			-0.513		-0.260
			(0.233)		(0.256)
Other firms' R&D			1.424		1.735
			(0.199)		(0.349)
N	2059	2059	2059	2059	2059
adj. R^2	0.137	0.286	0.300		
Firm FE	Yes	Yes	Yes	Yes	Yes
Component group FE	Yes	Yes	Yes	No	No
Version FE	Yes	Yes	Yes	Yes	Yes

TABLE C.2 Estimates of the Downstream Revenue and SEP Value Parameters

Panel A: Estimates of the market revenues parameters

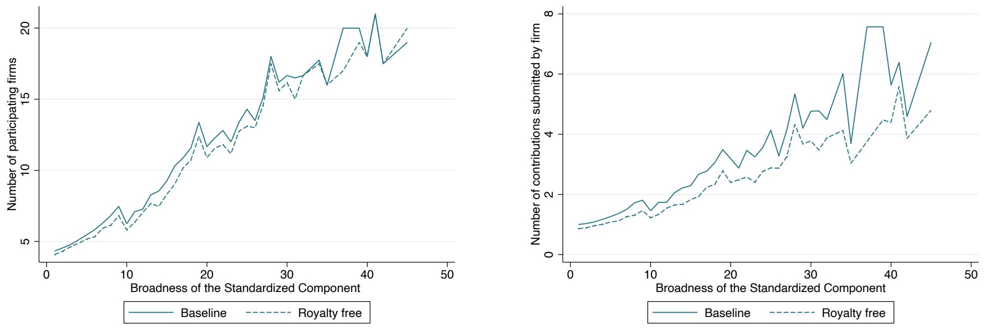
	Pure Upstream A^{M}_{up}	VI A^{M}_{v}	Telecoms A^{M}_{t}	Intermediary A^{M}_{I}
Estimate	0	5.56	5.34	5.46
SE	-	(0.026)	(0.040)	(0.023)

Panel B: Estimates of the SEP value parameters

	Rel-3	Rel-4	Rel-5	Rel-6	Rel-7	Rel-8	Rel-9	Rel-10	Rel-11
Upst.	0.55	0.61	0.71	0.78	0.80	1.17	0.91	1.07	0.75
	(0.000)	(0.001)	(0.001)	(0.003)	(0.012)	(0.014)	(0.019)	(0.018)	(0.017)
VI	0.51	0.55	0.49	0.00	0.33	0.77	0.36	0.20	0.08
	(0.002)	(0.001)	(0.003)	(0.005)	(0.021)	(0.028)	(0.019)	(0.034)	(0.015)
Inter.	0.55	0.55	0.43	0.60	0.56	0.48	0.55	0.55	0.55
	(0.000)	(0.003)	(0.023)	(0.019)	(0.022)	(0.007)	(0.001)	(0.000)	(0.000)

Notes: The Table shows estimate of the downstream revenues and SEP parameters of the structural model. Bootstrapped SE in parentheses. Bootstrap (with reposition) at a standardization group level, 1000 samples.

FIGURE C.5 Number of Participating Firms and Contributions Submitted in the Baseline and Counterfactual Scenario



(a) Number of participating firms, average by the broadness of the standardized component

(b) Number of contributions submitted by firm, average by the broadness of the standardized component

Notes: Panel (a) shows the average number of participating firms in each component standardization group, by broadness of the standardized component, in the baseline and counterfactual scenario. Panel (b) shows the average number of contributions submitted by firm in each component standardization group, by broadness of the standardized component, in the baseline and counterfactual scenario.

D | TEST AND ROBUSTNESS ANALYSIS

D.1 | Test on the Inverse-U-Shaped Relationship Between Contributions and Knowledge Similarity

For a formal test on the inverse-U-shaped relationship between the number of contributions provide by a firm to the standardization group and the average knowledge similarity between the firm and the other contributing firms in that group shown in Figure 1, I estimate the following equations:

$$\mathtt{Contributions}_{f,s,v} = \alpha_1 \mathtt{gsimil}_{(f,-f),s,v} + \alpha_2 \mathtt{gsimil}^2_{(f,-f),s,v} + \epsilon_{f,s,v} \tag{A.1}$$

$$\mathtt{Contributions}_{f,s,v} = \alpha_1 \mathtt{gsimil}_{(f,-f),s,v} + \alpha_2 \mathtt{gsimil}^2_{(f,-f),s,v} + \alpha_3 \mathtt{gsimil}^3_{(f,-f),s,v} + \epsilon_{f,s,v} \tag{A.2}$$

where $\mathtt{Contributions}_{f,s,v}$ is the number of contributions provided by firm f and $\mathtt{gsimil}_{(f,-f),s,v}$ is the average knowledge similarity between firm f and all other firms $-f$ participating in the development of the component standards in version v of the technology, $\mathtt{gsimil}^2$ is the squared average similarity and $\mathtt{gsimil}^3$ the cubic term of the aforementioned variable. All variables are in levels as in Figure 1.

Table D.1 shows the estimates of Equation A.1 and Equation A.2. Estimates of α_1 and α_2 in columns 1 and 2 show that, conditioning on being a second order polynomial, a concave function fits well the data. Column 3 and 4 show results for a third order polynomial approximation of the function. When no controls are added, a third order polynomial approximation can't be rejected by the data, but when firm and release fixed effects are included the third order term of the polynomial (α_3) is no longer significant. These results show evidence in favor of a concave second order polynomial approximation for the relationship between the number of contribution provided by a firm and its average knowledge similarity with the other firms in the group.

TABLE D.1 Contributions and Knowledge Similarity

	No controls	FE	No controls	FE
Knowledge similarity (α_1)	44.12	42.57	-28.82	5.59
	(3.30)	(4.21)	(8.62)	(17.05)
Squared knowledge similarity (α_2)	-38.51	-50.71	180.85	32.78
	(2.81)	(3.73)	(21.10)	(34.37)
Cubic knowledge similarity (α_3)			-108.94	-51.92
			(13.88)	(21.02)
Firm FE	No	Yes	No	Yes
Release FE	No	Yes	No	Yes
N	9265	9265	9265	9265
adj. R^2	0.0079	0.0424	0.0124	0.0430

Notes: The Table shows estimates of the knowledge parameters for different order polynomials approximations. Robust standard errors in parenthesis. All variables are in levels.

D.2 | Test on the Increasing Complementarities with Knowledge Similarity

For a formal test on the increasing complementarities, I estimate a model including a *quintile trend*, that is, a unique variable that takes the value of the number of contributions made by pair of firms in each quintile of the similarity distribution. This allows me to see if this trend has a positive coefficient, what will show a positive and increasing relationship between complementarities and similaritiy level. Formally, I estimate

$$\mathtt{ttd}_{s,v} = -\beta_1 \sum^{f \in F} c_{f,s,v} - \frac{\beta_2}{2} \sum^{f \in F} c^2_{f,s,v} - \gamma \mathtt{trendquintile}_{(f,j)} - \mu^S_s - \mu^V_v - \epsilon_{s,v} \tag{A.3}$$

where $\mathtt{trendquintile}_{(f,j)}$ is the trend variable described above. All the other variables are defined as in Equation 7.

The positive and significant estimate of γ shown in column 1 of Table D.2 provides extra evidence in favor of the complementarity effect.

TABLE D.2 Time Production Function Including Similarity Quintile Trend

	Quintile trend
Contributions ($-\beta_1$)	0.20
	(0.050)
Squared number of contributions ($\frac{-\beta_2}{2}$)	-0.11
	(0.005)
Trend quintile (γ)	0.007
	(0.003)
Standard first time (dummy)	Yes
Standard FE	Yes
Release FE	Yes
N	1789
adj. R^2	0.541

Notes: The Table shows estimates of the time production function parameters including a similarity quintile trend. Robust standard errors in parenthesis. All variables are in logs.

D.3 | Time to Develop and Standard's Quality

The quality of the technology chosen to be the standard is a very relevant outcome when it comes to studying standards development. However, defining quality at a component level is not straightforward and is beyond the scope of this paper. Even assessing the quality of the whole set of standards for a given version of the technology is not trivial. Nevertheless, Spulber (2019) show that given the current rules of the SSO, in equilibrium, standards and market outcomes are efficient, and Rysman and Simcoe (2008) find that SSOs identify promising solutions when studying internet standards. These results suggest quality may be assured by SSOs rules on how to select the technology to be included in the standard.

As an attempt to provide evidence on the relationship between the time to develop a standard and its quality, I use the probability of a standard to be updated in the next release as a proxy of its quality, as well as the number of releases a standard is updated in the ongoing releases. Table **??** shows descriptive statistics of the variables. Formally, I estimate

$$\mathtt{QualityOutput}_{s,v} = \omega_0 + \omega_1 \mathtt{ttd}_{t,v} + \omega_2 \mathtt{Firsttime}_{s,v} + \mu_s + \mu_v + \epsilon_{s,v} \tag{A.4}$$

where $\mathtt{QualityOutput}_{s,v}$ is either a dummy variable that takes the value 1 if the component to be standardized s is updated in the following version of the technology v and 0 otherwise, or the number of versions the standard for that component is updated, considering the following 4 versions. [50] As in Equation 7, $\mathtt{ttd}$ represents the time it takes the group to develop the component standard s in versions v of the technology, normalized by its broadness, in logs. $\mathtt{Firsttime}_{s,v}$ is a dummy variable that takes the value 1 if it is the

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[50] To avoid the censoring problem that arises from the data observability span, when using the probability of a component standard being updated as a proxy for quality, I do not consider the last observed versions and, for the number of versions, I only consider the following 4 and restrict the analysis to the first 5 versions.

first time the component is developed and 0 if it was included in a previous version of the technology. μ_s and μ_v are a set of dummy variables that account for the unobserved heterogeneity of the component and technology version, respectively.

Notes: The Table shows descriptive statistics for the update of the almost 1900 components included in the dataset. *Updated Next Version* is a dummy variable that takes value 1 if the component is updated and included in the next version of the technology and 0 otherwise. *Number of versions updated* is a variable that accounts for the number of times the component was updated and included in the following 4 versions of the technology. To avoid a censoring problem I exclude from the sample the last 4 observed versions of the technology.

TABLE D.3 Time to Develop and Quality

	Updated next version (1)	Number of versions updated (2)	Updated next version (3)	Number of versions updated (4)
Time to develop (ω_1)	-0.035	-0.086	-0.021	-0.019
	(0.012)	(0.045)	(0.021)	(0.080)
First time dummy	No	No	Yes	Yes
Component FE	No	No	Yes	Yes
Version FE	No	No	Yes	Yes
N	1557	1238	1557	1238
R^2	0.03	0.02	0.36	0.45

Notes: The Table shows estimates of the quality function, with and without controls. The time to develop each component is computed in days, adjusted by the broadness of the component to be developed, and expressed in logs. . To avoid a censoring problem when counting the number of following technology version in which the component was included, I exclude from the sample components developed during last 4 observed versions of the technology. Robust standard errors in parenthesis.

Table D.3 shows estimates of Equation A.4. Column 1 and 2 estimates imply a negative and significant correlation between time to develop a component standard, standardized by its level of broadness.[51] Once accounted for the unobserved heterogeneity between components and technology versions, the point estimation of ω_1 remains negative but it is not statistically different from zero. This evidence suggest no trade-off between quality and the time it takes to develop a standard, at least when quality is proxy by its survival probability or the number of releases it will be updated. If any, results suggest that standards developed faster tend to survive more.

D.4 | Patents and Number of Contributions

The SEP function in Equation 4) assumes that the number of contributions submitted by a firm in the development of a component standard has no impact on the probability of the firm ending up claiming a SEP related to that standard, once we account for participation. At first, this assumption might look strong, but it doesn't play a role in the main mechanism of the model and it allows the second stage of the game to be written in matrix form and therefore largely reduces the computational burden of solving it.[52] Moreover, the model

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[51] Estimate of ω_1 using the probability of the standard to be updated in the next release is significant at a 5% level while the estimation using the number of times the standard is updated in the following 4 releases is significant at a 10% level.

[52] This time reduction is key given the estimation strategy based on simulations.

allows for the extensive margin of contributions to have an impact on the expected SEPs a firm can claim. In the model, if a firm does not participate in the component standardization group, which implies submitting at least one contribution to the group, the firm expects to claim zero SEPs related to that component standard. Besides this, in this section I present evidence on why I consider this to be the right way of modeling the probability of a firm to claim a SEP.

In support of anecdotal evidence I collected from engineers attending standardization meetings, Rysman and Simcoe (2008) show that the technology finally included in standards developed in SSOs are promising technologies and not the result of vested interests. It should be borne in mind that contributions in my setup refers to the effort exerted to "create the standard", that is, provide technical solutions, draft the document, attend meetings, and finally decide on the technology to be included in the standard.

From an empirical point of view, showing that the number of contributions, conditional on participation, has no impact on the number of SEPs , implies estimating an equation like Equation A.5.

$$\mathtt{SEP}_{f,s,\nu} = \alpha^{S} + \beta \mathtt{Contributions}_{f,s,\nu} + \psi \mathtt{gsimil}_{f,s,\nu;-f,s,\nu} + \mu^{S}_{f} + \mu^{S}_{s} + \mu^{S}_{\nu} + \epsilon^{S}_{f,s,\nu}, \quad \text{(A.5)}$$

where $\mathtt{Contributions}_{f,s,\nu}$ is the number of contributions made by firm f, to component standard s in technology version ν. The remaining variables are defined as in the main specification.

Nevertheless, inferring the effect of contributions on the number of SEPs from an OLS estimation of that equation would not be valid given that the number of contributions would be endogenous. We only observe SEPs if the firm participated in the development of the standard, and in the empirical analysis participation takes value 1 if the firm provided at least one contribution to the standard. Mechanically, the relationship between the number of contributions and participation decision is going to be significant and different from zero.

To overcome the endogeneity problem in Equation A.5, I rely on instrumental variables. I use as instrument for the number of contributions the number of components the firm is contributing to develop in a given version of the technology. Although the number of component standards the firm is contributing to develop can be related to the effort of the firm since it captures the enthusiasm of the firm in pushing forward the standards, this variable should not be related to the number of SEPs the firm ends up claiming in a particular standard, once I control for the firm's technological capacity (captured by the firm's fixed effects and its patent portfolio size).

TABLE D.4 Number of Contributions and SEPs

	OLS (1)	First stage (2)	IV with control (3)
Group similarity (log)	-0.853	-0.323	-1.141
	(0.500)	(0.181)	(0.687)
Number of contributions	0.338		-0.487
	(0.068)		(0.687)
Number of other components		0.252	
the firm is contributing to		(0.056)	
Component's broadness	0.262	0.292	0.477
	(0.119)	(0.043)	(0.159)
First-time dummy	-0.287	0.652	0.108
	(0.218)	(0.088)	(0.393)
Lagged Portfolio size (log)	0.166	0.127	0.282
	(0.208)	(0.078)	(0.230)
N	2010	2010	2010

Notes: The Table shows estimates of the effect of the number of contributions on the number of SEPs claimed by firm and standardization group. The F statistic for the instrument in Column(2) is 20.16. All specifications include firm, component and technology version fixed effects. Robust standard errors in parenthesis.

Column 1 of Table D.4 shows a positive and significant effect of the number of contributions on the number of SEPs a firm claims, when estimating Equation A.5 by OLS. Column 2 presents the first-stage estimates showing the relevance of the instrument. Finally, Columns 3 shows the results once the number of contributions is instrumented with the number of components the firm is contributing in that version of the technology. Once the endogeneity is addressed I find that there is no effect of the number of contributions submitted to the standardization group of a particular component and the number of SEPs a firm claims in that component standard.

D.5 | IV Estimation of the Time to Develop Function

To address potential endogeneity issues regarding the number of contributions in Equation 1, I instrument it with the size of the firm's patent portfolio the year prior to joining the standardization group. Portfolio size prior to the standard's development is a valid instrument in this setup. Its exogeneity comes from (i) the difference in time with `ttd`, and (ii) the fact that the size of its portfolio is the result of the firm's IP policy, which is a more comprehensive decision than the firm's participation in the development of any specific standard. Its relevance comes from the fact that the size of such a portfolio can be easily related to the firm's size and hence its potential to contribute to standard's development.

While the number of contributions is the only variable I am treating as endogenous in this section of the paper, given the non linearity of Equation 1the variable ends up appearing three times in the equation. The first two times it refers to as the total number of contributions made by all firms to component standard s in version v and its square. The third time it refers to the interaction of the contributions made by firms. To address this difference in the aggregation level of the variable, I propose to estimate two different first stages and calculate the corresponding Wald estimator:

$$C_{s,v} = \pi_0 + \pi_1 \sum^{f\in F} \ln(LPatents_{f,s,v}) + \pi_2 X_{s,v} + \pi^S_s + \pi^V_v + \nu_{1,s,v} \tag{A.6}$$

$$\sum^{f\in F}\sum^{j\in F} c_{f,s,v}c_{j,s,v} = \gamma_0 + \gamma_1 \sum^{f\in F}\sum^{j\in F} c_{f,s,v}c_{j,s,v} + \gamma_2 X_{s,v} + \gamma^S_s + \gamma^V_v + \nu_{2,s,v}, \tag{A.7}$$

where $C_{s,v} = \sum^{f\in F} \ln(c_{f,s,v})$ for every firm f participating in the development of component standard s in version v, $LPatents_{f,s,r}$ is the number of patents in firm f patent portfolio the year prior to participating in the development of the standard , $X_{s,v}$ is a set of control variables as in Equation 1, and π^S_s and π^V_v accounts for component and technology version unobserved heterogeneity, respectively.

Based on the first-stage estimates I compute the OLS predictions of $C_{s,v}$ $C^2_{s,v}$ and $\sum^{f\in F}\sum^{j\in F} c_{f,s,v}c_{j,s,v}$, and compute the IV/Wald estimates.[53] Table D.5 reports the results.

TABLE D.5 Wald Estimates of the Effect of Contributions on the Time to Develop a Component Standard

Time to Develop (-)			Contr..	Interaction Contr..	IV/Wald estimates		
Firms' portfolio effect	Firms' portfolio sq. effect	Firms' portfolios' interaction			Contr..	Contr. sq	Interaction Contr.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0.0112	-0.0001	0.0106	0.0347	2.928	**0.3240**	**-0.0828**	**0.0036**
(0.0047)	(0.00004)	(0.0040)	(0.001)	(0.087)	(0.1389)	(0.0348)	(0.0014)

Notes: The Table shows estimates of the effect of the number of contributions on the time to develop a component standard. The time to develop the component standard is computed in days, normalized by the component broadness, and transform in logs. Results are presented in terms of the negative time to develop to simplify the interpretation. All specifications include the same control variables as in Equation 1. Bootstrapped standard errors are in parentheses.

Columns 1, 2 and 3 of Table D.5 present the reduced-form estimates, while columns 4 and 5 show the first-stage estimates. Finally columns 6, 7 and 8 present the IV/Wald estimates. An increase of 1% in the number of contributions made by firms to a component standard decreased the time to develop it by 0.25%.

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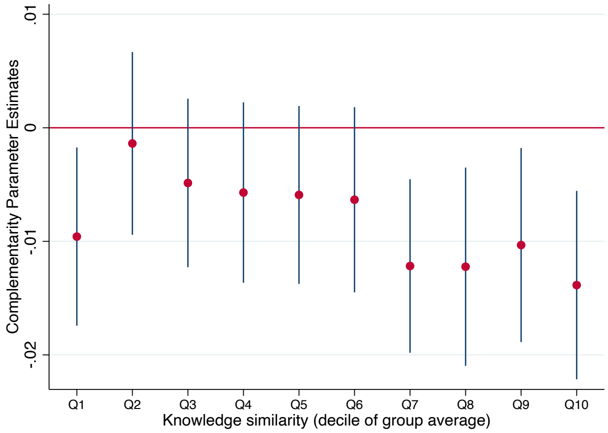
[53] Wald estimates $= \frac{reducedformestimates}{Firststageestimates}$. See Angrist and Pischke (2008) for more details.

D.6 | Alternative Estimation of the Complementarity Parameter

FIGURE D.1 Estimates of the Complementarity Effect, by Similarity Deciles



Notes: The Figure shows estimates of the complementarity parameters Φ_q. 95% confidence intervals bands. Standard errors are robust to heteroscedasticity. Estimation includes component and technology version fixed effects.

D.7 | The Downstream Effect of Free Licensing

Based on the standard price equation for oligopolistic markets, I get

$$\Delta p = \frac{\epsilon_f}{1+\epsilon_f}\Delta mc,$$

where Δp is the variation in the good's final price, ϵ_f is the firm's price elasticity, and Δmc is the variation in the good's marginal cost. I calculate the firm's price elasticity using a Cournot approach; that is, I use the industry elasticity and divide it by the Herfindahl–Hirschman Index (HHI) of the industry.

To calculate the impact of free licensing on the final price of mobile devices, I rely on the average cumulative royalty yield calculated by Galetovic et al. (2018).[54] I take the industry price elasticity from Fan and Yang (2020). I calculate the HHI based on the data in Galetovic et al. (2018). I consider four scenarios resulting from combining 2 options for the average cumulative royalty yield and 2 for the industry price elasticity.

Table D.6 presents the results. Depending on the scenario, free licensing might reduce between 3%–5% the final price of a mobile device. Considering the average smartphone price in 2012 was 387 dollars,[55] this implies a reduction of 11–20 dollars per smartphone. If I consider also feature phones, whose average price in 2012 was 340 dollars, then the reduction would have been around 10–17 dollars per device.

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[54] The cumulative royalty yield calculated by Galetovic et al. (2018)

[55] Consistent with Galetovic et al. (2018) I used from `http://www.statista.com/statistics/309472/global-average-selling-price-smartphones/` accessed 22 october 2021. Statalist relies on data from Worlwide IDC, 2014

TABLE D.6 Free Licensing Impact on Downstream Mobile Device Prices

Scenario	(I)	(II)	(III)	(VI)
Change in marginal cost[1]	3.30%	5.60%	3.30%	5.60%
Industry elasticity[2]	0.75	0.75	0.61	0.61
Firm elasticity	7.99	7.99	6.50	6.50
Pass-through[3]	0.89	0.89	0.87	0.87
Change in price	**2.93%**	**4.98%**	**2.86%**	**4.85%**

[1]Change in the marginal cost equals the reduction in cumulative royalties calculated by Galetovic et al. (2018). [2]From Fan and Yang (2020). [3]Calculated as $\frac{\epsilon_f}{1+\epsilon_f}$

E | DATASET, ESTIMATION SAMPLE AND EMPIRICAL MEASURES

E.1 | Top Contributors and Firms' Business Models

During 1999–2012, a total of around 280 firms contributed to the development of telecommunications standards. But the majority of these firms contributed very little. 265 of these firms contributed, in total, with less than 30,000 written contributions, that is, less than 15% of total contributions. Therefore, and since the goal of this paper is to study strategic interaction between firms, I concentrate my analysis in the top 15 contributors per year, ending up with 35 firms in my sample.To select the top 15 contributions per year I pooled all contributions made each year an selected the 15 companies that contributed the most.

To determine firms' business model I used information available in firms web pages and/or financial reports. During the sample period, 1999–2012 few firms changed their business model. According to their official report, Nokia and Ericsson (and its joint venture with Sony, Sony Ericsson), who were vertically integrated during that period, changed their business model in 2013.[56]

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[56] See `https://www.nokia.com/about-us/company/our-history/` and `https://www.ericsson.com/en/about-us/history/changing-the-world/the-future-is-now/the-problematic-mobile-phone-sector` for more details.

TABLE E.1 Firms Business Model

Firms	Main Business Activity	Business Model
Alcatel Lucent	Vendor	Vertically integrated
Anritsu	Telecommunications equipment	Intermediary
Catt - Chinese Academy Of	Research/Consultancy	Upstream
Cingular	Telecom operators	Downstream
Cmcc - China Mobile	Telecom operator	Downstream
Deutsche Telekom	Telecom operator	Downstream
Ericsson	Vendor/Equipment	VI/Intermediary
France Telecom	Telecom operator	Downstream
Gemalto	Telecommunications equipment	Intermediary
Huawei	Vendor	Vertically integrated
Infineon	Semiconductors	Intermediary
Intel	Semiconductors	Intermediary
Interdigital	Research/Consultancy	Upstream
Koninklijke Kpn N V	Telecom operator	Downstream
Lg	Vendor	Vertically integrated
Lucent	Telecom operator	Downstream
Melco Mobile	Telecom operator	Downstream
Mitsubishi	Telecommunications equipment	Intermediary
Motorola	Vendor	Vertically integrated
Nec	Computer hardware	Intermediary
Neustar Inc	Telecom operator	Downstream
Nokia	Vendor	Vertically integrated
Ntt Docomo	Telecom operator	Downstream
Panasonic	Vendor	Vertically integrated
Qualcomm	Semiconductors	Intermediary
Racal Instruments	Telecommunications equipment	Intermediary
Research In Motion	Vendor	Vertically integrated
Samsung	Vendor	Vertically integrated
Sasken	Semiconductors	Intermediary
Sharp	Vendor	Vertically integrated
Sony	Vendor	Vertically integrated
St Ericsson	Semiconductors	Intermediary
Telecom Italia	Telecom operator	Downstream
Vodafone	Telecom operator	Downstream
Zte	Vendor	Vertically integrated

Notes: The Table shows the name and BM of the 35 firms in the sample. Classification made by the author based on firms' webpage and financial reports. The business model is considered up to 2012. Nokia and Ericsson change their business model in 2013 according to the information provided in their official reports, and therefore, are considered as vertically integrated firms in this study.

E.2 | Firms' Knowledge Similarity

I rely on patented technologies to measure firms' knowledge. Using USPTO data on granted patents, I construct a patent portfolio for each firm in the dataset by counting the number of valid patents in each technological class, as defined by the International Patent Classification (IPC). IPC is a hierarchical system for the classification of patents according to the different areas of technology to which they pertain. Most of the firms in the dataset specialize in Information and Communication Technologies (ICT) and have no patents in classes unrelated to ICT. To avoid "false similarities" driven by zeros in non-ICT categories, I consider only the 15 most relevant classes for this market. To determine relevance, I consider all technological classes of all patents declared to be essential to any standard. I then select the 15 most frequent ones. These 15 classes cover a little over 85% of all essential patents. With the 15 classes for each firm in each year, I follow Jaffe (1986) and use Cosine Similarity (CS) to measure the similarity between any two firms, following . CS is also commonly used in the machine-learning literature as a metric for the similarity between two documents, and is defined as follows:

$$CS(A, B) = \frac{\vec{A}\vec{B}}{\|\vec{A}\|\|\vec{B}\|} = \frac{\sum_{i=1}^{n} A_i B_i}{\sqrt{\sum_{i=1}^{n} A_i}\sqrt{\sum_{i=1}^{n} B_i}}.$$

Since there can only be a non-negative number of patents in any class, CS will take values between 0 (no similarity, vectors are orthogonal) and 1 (completely equivalent, vectors have the exact same direction).

The advantage of CS over the Euclidean distance is that it depends only on the direction, not the length, of the vectors. Here, I consider the classes in which a firm has patents but not how many. Since CS is a pairwise measure, to account for the similarity of a firm in a given group, I average the CS between this firm and all the other firms in the group.

E.3 | Merging USPTO and Searle Center Dataset

Matching information from USPTO and the SCDB is not trivial. Firms can be identified in both datasets only by names, and this name can vary even within a dataset, depending for example, on firms' IP rights policies. That is, some firms register their inventions always under a subsidiary name of the firm specialized in IP rights, while others just register them under the name of the subsidiary that developed the invention. In the majority of cases we observe both strategies. For example, we can find "AT&T INTELLECTUAL PROPERTY I, L.P." but also "AT& TCORP."

I started by cleaning firm names and aggregating all entries under a firm name, independently of the subsidiary. Therefore, in each dataset I end up with only one observation per firm per year. To do so, I relied on the Levenshtein distance to identify entries that potentially refer to the same firm. The Levenshtein distance is a string metric for measuring the difference between two sequences. Informally, the Levenshtein distance between two words is the minimum number of single-character edits (insertions, deletions, or substitutions) required to change one word into the other. It is very often used in computer science to assess the similarity between string variables.

Prior to measuring the distance between two names, I cleaned firms names by capitalizing them, and extracting all common words such as "Corp." and "Inc.". Finally I used the *FuzzyWuzzy* Library of Python to measure the distance between the variables and try different approaches with exact matches and best matches.

I ended up with 290 matches from the original 575 firms that appeared in the SCDB. It should be borne in mind that several of the organizations that appear in the SCDB do not hold any patent at all. That is the case of governments and ministries, for example. For the top 35 firms I use in my analysis, I was able to match them all.

TABLE E.2 Descriptive Statistics

	N	Mean	SD	Min	Max
Panel A: Component characteristics					
Number of participating firms	1,792	6.27	4.53	2	25
Number of contributions	1,792	68.87	163.73	2	2,463
Number of contributions, in logs	1,792	3.04	1.46	0.69	7.81
Time to develop the component (days)	1,792	724.42	642.48	1.58	4,030.34
Broadness (units)	1,792	7.49	10.27	1	173
Time to develop per unit of broadness, in logs	1,792	4.63	1.17	-1.25	8.26
Knowledge similarity among participating firms	1,792	0.55	0.08	0.01	0.67
Number of SEPs declared to the component	946	9.49	19.78	1	175
Panel B: Firms' characteristics (per component)					
Number of patents in the patent portfolio	62,720	5,233.58	9,700.91	0	46,609
Number of standards the firm participates in	62,720	321.20	340.15	1	1,376
Number of declared SEPs	62,720	161.69	335.75	0	1,769
Number of declared SEPs, in logs	62,720	71.16	127.19	0	576.99

Notes: The Table shows descriptive statistics of the estimation sample considering only the top 35 contributors and using SCDB data. The broadness of a component measure the number of initial goals covered by each component of the technology. Panel (B) shows statistics computed at a firm(35)-version(9) level.

TABLE E.3 Descriptive Statistics by Technology Version

Technology Version	Number of components	Participating firms	Average component's broadness
Rel-99	33	21	6.21
Rel-4	42	27	6.36
Rel-5	67	30	8.57
Rel-6	145	31	7.52
Rel-7	234	28	7.15
Rel-8	369	29	6.17
Rel-9	345	28	5.99
Rel-10	318	28	7.77
Rel-11	239	28	11.71

Notes: The Table shows descriptive statistics of the estimation sample by technology version, considering only the top 35 contributors and using SCDB data.

F | PARTICIPATION AND STANDARD–FIRM MATCH

Participation is relatively low in the data, with the overall probability of joining a component standardization group estimated at 16.64%. These decisions are not random, and while the literature provides insides on participation at SSO or consortia level, it sheds little light on why firms choose to participate in the development of each technology's component standard and not others.[57] In an attempt to model participation in a realistic manner, I draw on qualitative survey information, complemented by informal talks with industry practitioners.

In 2003, ConsortiumInfo.org conducted a small survey in which they asked major players in the technology sector about the standardization process in different SSOs. Specifically, they asked, "What are the three most important things that you look for in any standard setting organization in deciding whether to join?'. Firms responded with reasons such as th standard's topic or goals, how relevant a standard was to their technical expertise; IP rights policies, cost effectiveness vis-à-vis alternatives, procedures and group composition, and other members' commitment to investing resources(i.e., paying for engineers'hours).

I group these answers in two categories: (i) the potential overall profits firms expect to get from participation in a standardization group; and (ii) the match between the firm and the standard's goals. Firms are specialized in certain technologies and, therefore, are more willing to participate in groups developing standards involving such technologies. For example, if a group is developing a standard for a new kind of antenna for 5G, then firms working in the fields related to antennas are more likely to participate in that group. I refer to this second point as the *firm–standard match* hypothesis. While (i) is endogenous to all the firms' decisions and characteristics, (ii) is exogenously determined by the technological needs of the standard and the technological knowledge of the firm.

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[57] The reader can refer to Lerner and Tirole (2006), Baron and Pohlmann (2013), and Leiponen (2008) for more information on how firms decide to participate in different SSOs or more informal standardization groups such as consortia.

The empirical challenge of modeling the firm–component standard match is the unobservability of the component' technological needs. Nevertheless, I observe the broadness of a component.[58] Then, if the firm–component technological match hypothesis is true, I should observe that broader components, which require a higher number of distinct technologies, are subject to higher participation. This is because if more technologies are required, it is more likely that one of them will be relevant to a given firm's knowledge and expertise. On the other hand side, if a firm works in several technological areas, it is more likely to be interested in participating in developing more component standards. To capture this empirically, I use patent portfolio size to measure firms' technological capacity.

As an initial exploration of this hypothesis, I estimate the following logit model for participation at the firm- component standard level:

$$p_{f,s,v} = 1\{\beta_p X^p_{f,s,v} + \gamma^p \mathtt{LPortfolio}_{f,v} + \gamma^b \mathtt{Broadness}_{s,v} + \nu^p_{f,s,v} > 0\}, \tag{A.8}$$

where $p_{f,s,v}$ is a dummy variable that equals one if firm f participates in teh development of component standard s in version v, $X^p_{f,s,v}$ is a set of proxy variables for the revenues that f would obtain if it were to participate, $\mathtt{LPortfolio}_{f,v}$ is the number of patents in firm f's portfolio the year prior to version v being released, $\mathtt{Broadness}_{s,v}$ is the broadness of the component to be standardized, $\nu^p_{f,s,r}$ captures the unobserved (by the researcher) determinants of the firm's participation decision, including the quality of the fit between the component technological needs and the firm's technological capacity. As extra controls, I also include a dummy variable that takes value 1 if the component is developed for the first time in version v and 0 otherwise, as well as component and technology version fixed effects.[59]

The matrix $X^p_{f,s,v}$ includes proxies for firms' standardization revenues, including the amount of downstream sales of the firm and firm fixed effects. I rely on downstream sales as a proxy for the size of the firm. Including this covariate allows me to control for the heterogeneity in downstream profits across firms that vary between releases. Firm fixed-effects control for other unobserved firm characteristics, invariant across components, affecting firms' likelihood of participating in a standardization group.

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[58] Another approach would be to look at the technological classes of the component standard's SEPs.. However, these are observed ex-post, and therefore, SEPs' technological classes are likely to match the technological classes of patents held by participating firms.

[59] Given the large number of standards (645) and the small number of observations per standard, estimations of standard fixed effects are biased due to the incidental parameters problem. However, since I am not interested in the estimates of those parameters, I do not adjust for them.

TABLE F.1 Logit Estimates for Participation Decisions

	(1) Baseline	(2) Fixed Effects	(3) Controls
Lagged Portfolio size of the firm (log)	0.134	0.146	0.345
	(0.004)	(0.027)	(0.058)
Broadness of the component	0.038	0.018	.022
	(0.002)	(0.002)	(0.004)
Firm FE	No	Yes	Yes
Standard FE	No	Yes	Yes
Release FE	No	Yes	Yes
Standard and firm characteristics (First time standard, sales)	No	No	Yes
N	59,395	59,395	26,835
Pseudo R^2	0.0415	0.3712	0.3975

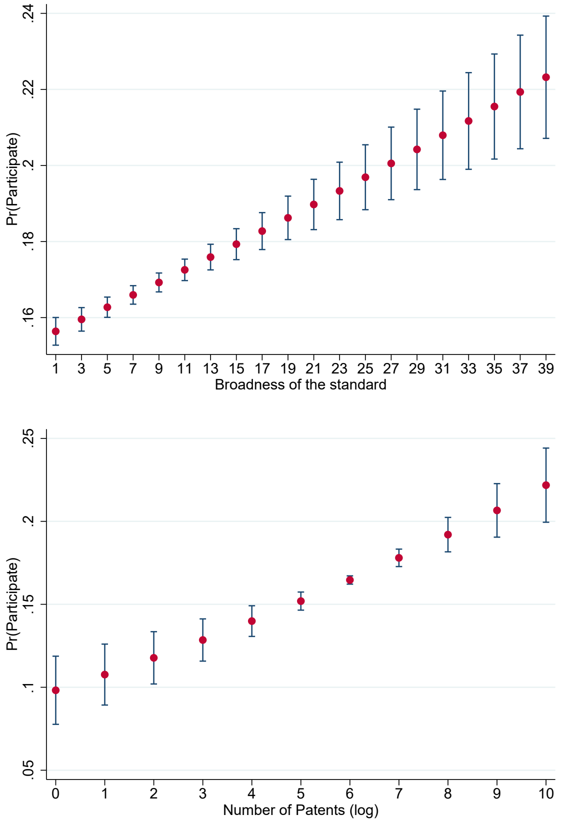
Notes: The Table shows estimates of the participation equation. Robust standard errors in parentheses.

Table F.1 shows estimates for Equation A.8. I find a positive and significant γ_p across all specifications, meaning that firms with bigger portfolios are more likely to participate in a component standardization group, other things being equal. I also find a positive and significant γ_b, suggesting that firms are more likely to participate in the standardization of broader components of the technology.

As is usual in logit models, due to the normalization of $\sigma_\epsilon^2 = \pi^2/3$, parameters are identified up to a scale factor. To quantify the effect of adding an extra patent or broadening a standard by 1 unit, I calculate the marginal effects of those variables on the participation probabilities. Figure F.1 shows the results of this estimation. The probability of a firm participating in a standardization group in charge of developing a standard with a broadness of 30 or more units is almost 30%, double the overall probability of participation of 16%. On the other hand, a firm with a portfolio of 8000 patents (e^9) is twice as likely to participate as a firm with a portfolio of 3 patents (e^1).

These results provide evidence in support of the firm–component match hypothesis. The match between a component and a firm matters for participation and the broadness of a component, which is partially captured by the size of a firm's portfolio.

FIGURE F.1 Marginal Effect of Component Broadness and Firm Portfolio Size on Participation Probabilities



Note: Confidence intervals are at a 95%. Marginal effects computed using the model include firm, release, and working group fixed effects.