Cooperation, Competition and Patents: Understanding Innovation in the Telecommunication Sector *

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Abstract

Many modern innovations depend on interconnectivity, which require technology standards as a common language to successfully link up. This paper develops and estimates a structural model to understand how competition between firms affects their incentives to cooperate by supplying technologies to a common standardization process. I study these incentives empirically by focusing on the standardization of the mobile telecommunications technologies. In the model, firms face two decisions. They decide whether to join a group to develop a component of the system and, in that case, how much effort to exert. When making these choices, firms consider 1) how their effort increases the common value, 2) how much of this common value they can privately appropriate through their patents, and 3) their capacity to profit from the technology in the downstream part of the market. In this setting, patents have an ambiguous effect on the development of a common innovation. On the one hand, they alleviate the free-rider problem and induce firms to exert more effort. On the other hand, they bias firms' participation towards groups with less competition over patented technologies even where their effort may be less valuable. To study the net effect of these forces in equilibrium, I estimate the model using a novel dataset on 3G and 4G technologies. I also show that the enforcement of royalty-free clauses reduces firm participation and effort, ultimately delaying the completion of the initial releases of 4G by almost 1 year.

JEL Codes: O3, L1, L2
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1 Introduction

Many modern innovations depend on interconnectivity. The upcoming 5G network will set the basis for many appliances to communicate with each other, and may, according to the European Commission, represent 10% of the global GDP by 2025.[1] Such an innovative feat requires a diverse set of firms, with different technological specializations and distinct business models, working closely together in order to develop the technology standards guaranteeing such interconnectivity. In the telecommunications sector, firms supply technologies and collaboratively develop these standards. In doing so, participating firms can benefit from their involvement through the sale of resulting products, taking the standards as inputs, or by licensing the patents protecting such technologies. Nevertheless, only some patented technologies will make it into the standard, creating competitive pressures for firms with similar specializations.

Despite the longstanding debate over whether patents foster or hurt innovation, as well as the economic relevance of the mobile telecommunications market, which represented almost 5% of global GDP in 2018, empirical evidence on the effect of patents on this standardized technology is limited. This paper develops and estimates a structural model to understand how competition between firms over including patented technologies in a standard affects their incentives to cooperate and supply technologies to a common standardization process. This study contributes to our understanding of the mobile telecommunications sector, as well as to the debate over patents and innovation in this special but important context.[2]

In this paper, I assess the impact of patent licensing on the number of firms working together, the intensity of their contributions and, ultimately, on the time it takes a group of firms to jointly develop a standard. For that, I propose a framework in which firms develop the full set of standards together but are allowed to individually license the patents protecting the technologies specified on each of them. In my model, firms can choose to work in many standardization groups (extensive margin), each of which focuses on a single part/component of the technological system. On the intensive margin, they also decide how much effort exert to increase the common value of the component/part. In weighing this decision, they consider: (i) how their effort increases the common value, (ii) how much they can privately appropriate from this common value through patents, and (iii) their capacity to profit from the technology in the downstream part of the

[1] Commission (2016)

[2] "One illustration of the enormous stakes in standards has been the ongoing disputes over smartphone patents. Litigation across at least 10 countries enveloped these devices, with at least 50 lawsuits between Apple and Samsung and—until their May 2014 settlement agreement—20 cases between Apple and Google not counting the ongoing lawsuits between Google and the Rockstar Consortium, of which Apple is a partner." See Lerner and Tirole (2015) for the complete quote and details.

market. In this context, patents have an ambiguous effect on the development of a common standard. On the one hand, patents alleviate the free-rider problem, thereby inducing firms to increase their efforts. On the other hand, patents incentivise firms to participate in groups with less competition over patented technologies, but where their efforts may be less valuable. This ambiguity generates a trade off for firms between: (i) participating in groups in which their effort has a bigger impact on the common value but where they can appropriate from a smaller part of the total; and (ii) participate in groups in which their contributions are less valuable but they can appropriate from a bigger part. To study the net effect of these forces in equilibrium, I estimate my model using a novel dataset on the standardization of 3G and 4G technologies. I then use these estimates to evaluate the impact of enforcing royalty-free clauses in this market, a policy in place in some internet standards like HTML. I find that preventing firms from licensing their patents would have reduced firms participation and effort, slowing down the development of the standards. My model implies such a policy would have delayed the completion of the initial releases of 4G by 1 year.

As in other sectors with interconnected components, such as Internet or upcoming smart cars, mobile telecommunication technologies are defined by technology standards. But who sets these standards? Most firms in the Information and Communication Technology (ICT) sector choose to develop their standards cooperatively, in bodies called Standard Development Organizations (SDOs).In the mobile technology industry, the major SDO in charge of developing the industry standards is the 3rd Generation Partnership Project (3GPP), a worldwide organization formed by almost 1000 institutions. Modern innovations are often complex technological systems, requiring a large number of well-defined standards to function. To standardized each component, firms team up in small groups inside SDOs. In these groups, firms submit contributions and collectively decide on what technologies to ultimately include in the standard. A technology is considered essential if any implementation of a standard must use it. Patents protecting the IP rights over such technologies are called Standard Essential Patents (SEP). Several SDOs require SEPs to be licensed under a Fair Reasonable and Non-Discriminatory (FRAND) terms.[3]

This innovation model has proven to be very successful in the telecommunication sector and may be key in the development of other innovations beyond the traditional ICT sector.[4]

[3]FRAND clauses are designed to prevent the exploitation of unearned market power, which firms may gain from the incorporation of their proprietary technologies into industry standards, and avoid potential underinvestment of standards' implementers due to this uncertainty on IP cost (the *hold-up* problem)

[4]Modern innovations often result from a combination of multiple inventions, and therefore require the joint work of firms with different technological specializations. A good example of this are interconnected, or smart, cars. In order for cars to be able to communicate with each other, industries as diverse as cybersecurity providers, cloud vendors and automotive software providers, along with automotive manufactures, need to work closely

The innovation model adopted by firms in the telecommunication market is flexible enough to accommodate the incentives faced by firms with different business models specializing in different technologies. Moreover, the network effects of interconnectivity are large, as are the gains to using a common technological language allowing it.[5] To the best of my knowledge, this work is the first to provide a structural framework for collaborative innovation which can be generalized to analyse firm incentives in the standardization of other technologies.

Understanding the market structure of the mobile telecommunications market is critical to understanding firm behaviour and incentives. In the upstream part of this vertical market, firms collaborate to develop the mobile system's technology, while also protecting their individual IP rights with patents. The technology is then used as an input to produce intermediate and final goods, such as semiconductors, mobile devices, and telecommunication services. This gives rise to 4 different business models: (i) pure upstream firms, whose only revenues come from licensing patents; (ii) intermediary firms, which license patents and produce intermediary goods such as telecommunication equipment; (iii) downstream vendors, which may or may not be vertically integrated and must obtain licenses for the patents necessary to produce their devices; and (iv) telecom operators that buy telecommunication equipment to provide services downstream. Moreover, firms in this market also have *technological knowledge* or a specialization, which I measure using their patent portfolio and the technological classification of their patents. To assess the technological similarity of firms, I rely on the cosine similarity of the corresponding portfolios.[6]

In my framework, firms face a common incentive to develop the technology in the shortest amount of time as they cannot produce or license their IP rights until the whole set of standards is established. Using a novel dataset on the standardization of 3G and 4G, I first show empirical evidence that firms can speed up technology development by providing effort together. To show this, I estimate a time production function for standard development, where the development time is the output and firms' efforts are the main inputs, which I proxy with the number of written contributions submitted by each firm to the group. I find that a 10% increase in a single firm's effort is associated with a nearly 2% reduction in the time it takes to develop a standard. I also show that the effect of greater efforts on the speed of development is higher when the

together.See https://www.rfidjournal.com/articles/view?17632/2 for a complete description of the development of smart cars.

[5]According to the European Commission Guidelines (Commission (2016)), without the interoperability enabled by standards, 40% of the potential benefits of Internet of Things would be lost.

[6]Cosine similarity is a metric used to measure how similar two vectors are irrespective of their size. Mathematically, it measures the cosine of the angle between two vectors projected in a multi-dimensional space. This metric is widely use in machine learning environments, for example, to assess the similarity of two documents.

firms working together are specialized in similar technologies. I call this the *cooperation* effect: if a firm's similarity with the rest of the group is in the top 20% of the knowledge similarity distribution, when that firm increases effort by 10%, the time to complete decreases by an extra 0.2%, on top of the 2% reduction discussed above. On the other hand, when a firm's similarity with the rest of the group is in the bottom 20% of the knowledge similarity distribution, the same increase in effort only decreases development time by an extra 0.075%, which is not significantly different from 0 at a 5% confidence level.

Secondly, allowing firms to license their patents individually generates a private incentive for firms to contribute in teams in which they may obtain a higher number of patents, even if this would slow down development. This can generate a misalignment between the common incentive of developing standards in due time and a firm's particular incentives to contribute more where it can obtain more patents. In my framework, firms contributing to the same standardization group compete for their technology to be included in the standard, and this competition is tougher the closer the firms are in the technological space. I call this the *Competition effect*. I find that for a given firm, working with other firms that are, on average, 1% more similar in terms of knowledge, reduces the expected number of SEPs it holds by 1.3%. This evidence supports the existence of a competition effect.

With this empirical evidence in mind, I develop a two-stage structural model for the incentives firms face in the joint development of mobile telecommunication standards. The model features: (i) firms with heterogeneous knowledge and different business models which choose whether to participate in each standardization group, as well as a level of effort that will maximize profits from standardization; (ii) standards that need to be developed in order to meet technology goals which have been (exogenously) decided. A novel feature of this approach is that it does not require any proprietary data on royalty revenues, on profits from standardization, or on prices of intermediary goods to estimate the model. The timing of events is as follows. First, firms decide whether to participate in each standardization group, depending on the profits they expect to receive and on the match between their technological expertise and the one required to develop the standard. Second, firms decide how much effort to exert in the standardization group, given the participation decisions of the other firms. The time it takes to develop a standard-release depends on the effort exerted and the cross-effects between the efforts of firms with different areas of expertise (*knowledge*).

As usual, I start by solving the second stage of the model. I construct a firm profit function accounting for the revenues from (i) good production with standards as inputs; and (ii) the licensing of SEPs, where both are negatively related to the time it takes to develop the set of standards in a release.[7] For the identification of profit function parameters, I assume revenues from good production using the standard only vary with the business model of the firm, while revenues from licensing SEPs vary with the number of SEPs held by a firm and the standard's release. Finally, I assume firms face a quadratic marginal cost of effort, which is heterogeneous across firms, constant over all standardization projects and unobserved for the researcher up to a parametric distribution with an unknown firm-specific mean and a common variance parameter.

In the first stage of the model, each firm simultaneously chooses in which group to participate. These decisions are not random, but the literature sheds little light on why firms choose to participate in some standardization groups and not others. Guided by qualitative survey information that I complemented with informal talks with industry practitioners, I assume that firms make their participation decision based on (i) the potential overall profits firms expect to get from participation in a standardization group; and (ii) the match between firm and standard goals. Firms are specialized in certain technologies, and therefore are more willing to participate in groups developing standards related to these 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 consider (ii) as a fixed cost of participation. While (i) is endogenous to all firms decisions and characteristics, the second one is exogenously determined by the technological needs of the standard and the technological knowledge of the firm.

To estimate the parameters in my structural model, I rely on a 3-stage procedure in which I first estimate the parameters in the time production function and the SEP equation, using the same empirical strategy as in my empirical evidence section. Second, I use these estimates and the equilibrium equations of the model to calculate the moments, 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. Finally, I use all the previously estimated parameters to compute the difference between the profits of the observed decision and the counterfactual one, imposing a parametric distribution on the participation shocks, and estimate the participation parameters by maximum likelihood.[8]

[7]The faster all standards in the release are finished, the faster firms can start profiting from either of the two channels described above. Time can be implicitly interpreted as a discount factor. Moreover, according to 3GPP program, one of the goals in the standardization process is to develop standards in the smallest amount of time possible, therefore it makes sense to assume that firms profit from lower development times.

[8]I rely on a Nash Equilibrium concept to compute the counterfactual choice set, and derivate logit conditions from the inequalities resulted from a revealed preferences approach.

For a clearer interpretation of the parameters, I construct an index which captures the relative importance of royalty revenues with respect to the overall expected revenues from standardization. My results suggest that in the development of 4G, the licensing of IP rights represents more than 20% of the profits firms expect to get from standardization. Before the first release of 4G, the SEP licensing represented 5% of intermediary firms total profits and less than 10% for vendors.[9] As a robustness check of my results, I compare my estimation of the importance of licensing for Qualcomm, the one firm in my sample that separately reports both type of profits.[10] In my model, from 4G technologies onward, the licensing of patents represents between 60-66% of total profits for Qualcomm. In their annual results, Qualcomm reported, between 2010-2016,[11] licensing profits between 63 -73% of total profits.

In this context, the impact of enforcing a royalty-free licensing scheme is ambiguous.[12] 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 take full advantage of their complementarities, developing the standards in less time. On the other hand, it would also shut down one of the potential revenue streams, disincentivizing firms from participating and exerting effort. 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 effort and participation decisions to vary with the new licensing policies. I find that, despite an increase of the average similarity of almost 5% between firms in the same standardization group, which boosts the cooperation effect, the overall impact is an increase in the time it takes to develop the technology. This result can be explained by a decrease of 7% and 18% in average participation and effort, respectively. Results are heterogeneous across releases. In the case of the first releases of 4G, which took 3 years to develop, forcing firms to license their patents for free would have delayed completion by an additional year.

Contributions to the literature. This paper contributes to various strands of the literature. First, it is related to the growing literature on technology standardization and patents. Licensing of standard's patents has being mostly analysed from a theoretical point of view. Close to my research question, Shapiro (2000) discuss if our patent system is slowing down the

[9]This index is not relevant in case of pure upstream firms or telecommunication operators, since by assumption of the model it would be 100% and 0% respectively.
[10]See https://investor.Qualcomm.com/financial-information/quarterly-results
[11]4G was commercially launched in 2010
[12]Under royalty-free clauses, firms must license their patents at no cost.

commercialization of new technologies by describing the patent thicket problem, a problem that arises when those seeking to commercialize new technology must obtain licenses from multiple patentees, and assess its importance when combined with a hold-up problem, that is, the danger that new products will inadvertently infringe on patents issued after these products were designed. To alleviate those problems they recommend the use of cross licensing agreements and patent pools. In a similar line, Lerner and Tirole (2015) study the inefficiencies attached to the lack of licensing price commitments and show how structured price commitments restore competition. Also related to my reserach question Layne-Farrar, Llobet and Padilla (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, Rysman and Simcoe (2008), show that the inclusion of a patent in a standard increases the patent's return, because it signals its value and influences future adoption of the patented technology. Consistent with the view that inclusion increases a patent's value, Simcoe, Graham and Feldman (2009) show that patents disclosed in SSOs have higher litigation rates, particularly if these patents are assigned to small firms. Both studies focus on the Internet Standards. Related to the standards in the telecommunication market, Bekkers et al. (2017) study differences in the rules used by different SSOs and how this influence which patents are disclosed, the terms of licensing commitments, and ultimately long-run citation and litigation rates for the underlying patents.

Investigating the effects of firm similarity on standard development, Baron and Pohlmann (2013) explore the degree of complementarity and competition between firms participating in the development of ICT standards and how that shapes firms incentives to collaborate. In the same vein, Bar and Leiponen (2014) find a negative correlation between firms' technological distance and their probability of developing R&D together. Using the 3GPP as a case study, Jones, Leiponen and Vasudeva (2018) find that firms contributing to the mobile standard tend to cooperate more after a patent litigation event.

In contrast, this paper is the first one to: (i) provide an empirical framework to think about incentives firms face in this type of collaborations; (ii) quantify the importance of licensing revenues with respect to market revenues; (iii) provide a structural model that can be used to evaluate counterfactual policies; and (iv) asses the impact of enforcing royalty-free clauses on the time of developing standards for the mobile technologies. It also differs from earlier literature on technology development and standardization in that: (i) it estimates a time production function for standards, allowing for cross-effects between the efforts exerted by different firms; (ii) accounts for the heterogeneity in firm knowledge similarity and firms' business models; (iii) uses contributions to 3GPP as inputs for the time production function; and (iv) constructs a revenue function for the firms participating in the development of standards in the mobile telecommunications market, allowing for competition over IP rights of the technologies included in the standard.

This study is also related to the literature on team production models, that is also mainly composed by theoretical contributions. This literature started with the seminal reference of Holmstrom (1982) on moral hazard in teams. More recent theoretical contributions have added a network component to the team production games, including Goyal and Joshi (2003), Ballester, Calvó-Armengol and Zenou (2006) and Benlahlou (2019).[13] The empirical literature on this topic is growing but still narrow. An example is Hsieh et al. (2018) with their empirical model on coauthorship's network. Ballester, Calvó-Armengol and Zenou (2006) and Benlahlou (2019) develop a theoretical framework that accounts for complementarities and substitution between the players' effort in a team production function.

This paper uses a similar production function, but I impose that at least a part of a team's output must be divided between its members. This introduces competition between team members over the largest share of the common output. I also complement earlier studies by empirically estimating effort complementarities in the team-production function, while allowing them to depend on the knowledge similarity of participating firms.

Finally, my analysis also relates to empirical literature on innovation economics. My approach is interesting when revenues and profits are unobserved. Traditionally, papers in this field relied on patents , their citations (Trajtenberg (1990), Hall, Jaffe and Trajtenberg (2001)),their renewal fees Pakes (1984), R&D expenditures, or case studies. More recent papers use administrative data (Aghion and Howitt (1999); Bell et al. (2018); Bell et al. (2019)) or proprietary data provided by Non-Practicing Entities (Abrams et al. (2019)). Notwithstanding, the scarcity and low quality of the data remains a central challenge in studying the economics of innovation.

In this paper, I use a novel data set on standardization, developed by the Searle Center for Innovation at Northwestern University (Baron and Spulber (2018), Baron and Gupta (2018), Baron and Pohlmann (2018)), to develop a structural framework for cooperation within innovation alliances, allowing me to quantify the incentives firms face in jointly developing technology. I can estimate parameters of an empirical revenue function, even while only observing a proxy for the effort exerted by firms. This approach can be very useful for markets in which some variables, such as revenues and prices, are not easily observed due to proprietary conditions or

[13]For literature on network formation see for example, Myerson (1994); Bala and Goyal (2000) and Jackson and Wolinsky (1996).

the difficulty of its accountability.

The rest of the paper proceeds as follows. Section 2 describes the relevant institutional details and data, including the most relevant facts about the mobile telecommunications market and a simplified version of how standards are developed in 3GPP. Section 3 shows empirical evidence on the *competition* and *cooperation effect* than I later include in my model. In section 4, I develop a structural model for firms effort decisions in standardization groups. Estimation procedure and identification strategy is discussed in section 5 and results are presented in section 6. Finally, I conclude in section 7.

2 Institutional setting

2.1 The mobile telecommunications market

The market for mobile telecommunications is vertically integrated. In the upstream part of the market, firms collaborate to develop the mobile system's technology, while also protecting their individual Intellectual Property (IP) rights. The technology is then used as an input to produce intermediate and final goods, such as semiconductors, mobiles, and telecommunication services.

Most of the firms operating in this market produce goods that comply with the technology. These firms can be divided in two groups: those producing final goods and the ones producing intermediary goods. In my study, I consider firms producing intermediary goods as upstream firms, since they don't sell to final consumers. Final consumers in this market are individuals that buy phones and telecommunication operators that buy infrastructure equipment to deploy the mobile network.

Firms selling downstream are mainly phone vendors, such as Samsung, Apple, LG, Huawei and ZTE. The ones producing intermediary goods are firms producing chips, like Qualcomm, and infrastructure equipment, such as Ericsson and Nokia. One of main differences between these two groups is how intensely they use the technology developed upstream for manufacturing their own goods. Vendors need to comply with the whole technological system to produce phones, and therefore must obtain licenses for all patents protecting the technology. Firms producing intermediary goods need to produce goods compatible with the technology, but might not employ all of the system's patents in their product.

Telecommunication operators are another part of this market. In my analysis, these firms are consumers since they buy infrastructure equipment to deploy their network. Though they provide final consumers with mobile communications, this is not germane to my study. These firms rarely develop technology upstream and therefore hold almost no IP rights.

Finally, there are *pure upstream* firms, which I define as a firms which do not produce any goods, but earn most of their revenue by licensing intellectual property. Interdigital, Universities and research centers such as the Chinese Academy of Telecommunications Technology are examples of such firms.

Firms' business models and payments in this market

In this market, there are two channels through which firms can benefit: (i) producing downstream using the technology developed upstream, and (ii) licensing the IP rights. The extent to which firms benefit from each depends on their business model.

Firms in the upstream part of the market, that is, *pure upstream* firms, and those producing intermediary goods, license their IP rights to vendors. IP rights are usually protected by patents, and licensing firms are paid royalty revenues. Firms typically license their entire patent portfolio, and the amount they can charge is set in court. The number of ongoing disputes over the licensing of these patents are 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 (2017) estimates that royalty revenues from SEP licensing in 2016 were around 14,000 million dollars, and represented 3% of the cost of manufacturing a smartphone.

For vertically integrated firms, their downstream business model has implications for the revenues derived from (ii), as they are usually engaged in cross-licensing agreements. These are contracts in which each party is granted rights to a piece of technology, product, research, or other intellectual property. Cross-licensing agreements allow parties to use the technology protected by the other parties' patents without having to pay, in return for allowing the other parties to use their own protected technology. They help prevent litigation over patents infringement disputes.[14]

Finally, phone vendors only operating downstream, such as Apple, Xiomi, and HTC, pay royalties to the firms holding the IP rights for the technology to produce their phones.

Throughout this paper, I focus mainly on the upstream part of the market, only accounting for the downstream activity of firms when considering the incentives they have to innovate.

[14] If a firm undertakes activities that are covered by the claims of a patent without having a license for it, they are said to infringe the patent.

2.2 Technology generations, releases and standards

Mobile telecommunication technology is defined by technological standards, rules defining how related technologies are to be built.[15] More specifically, a standard is a document that describes a feature of a technology. In the telecommunications market, this could be a document describing a characteristic of the antennas required to send a cellular signal. In order to describe the whole system of mobile telecommunications, hundreds or even thousands of standards are required.

Mobile communication technologies evolve over time, and each round or version of standardization is called a *release*. Each release is formed by all the standards necessary to implement a given version of the mobile communication system.

Table 1: Releases and technology generations

Release	Start Year	Generation	Technology
Rel-99	1996	3G	WCDMA
Rel-4	1998	3G	UMTS
Rel-5	2000	3G	IMS HSDPA
Rel-6	2000	3G	HSUPA WLAN
Rel-7	2003	3G	EDGE EVOLUTION
Rel-8	2006	4G	LTE
Rel-9	2008	4G	WIMAX LTE Dual Cell
Rel-10	2009	4G	LTE Advanced
Rel-11	2010	4G	LTE HetNet
Rel-12	2011	4G	ProSe
Rel-13	2012	4G	NB-IoT
Rel-14	2014	4G	LTE Advances Pro
Rel-15	2016	5G	5G system phase 1
Rel-16	2017	5G	5G system phase 1

Each release belongs to a given generation of the technology. There have been 4 generations of mobile standards, each describing a different technology generation, with 5$^{\text{th}}$ generation currently under development. Within each generation, there is heterogeneity in the technology used. A change in generations occurs only when there is a major change in the technology, while a minor evolution of the technology gives place to a new release of the standards inside the same generation of technology. Consider the development of 4G. The first release of 4G was Release-8, describing Long Term Evolution (LTE) technology. Though 4G is still in use, devices can now also connect with LTE advanced Pro, from Release 14.[16]

[15] Though there are standards for many productive activities, such as standards for plugs, TV standards (PAL or NTSC), etc. (even driving on the right side of the street can be considered a standard), this paper only refers to technological standards. These standards are very different from the ones describing mobile telecommunications technologies, and therefore the development procedures described in this paper apply only to mobile technology.

[16] The release of a new version of the technology, such as LTE advanced, doesn't fully replace the previous one.

2.3 Standard Development Organizations

Mobile standards, such those that define the use and implementation of Wi-Fi, Bluetooth and the Internet Protocol, are developed in Standard Development Organizations (SDO). An SDO is any organization active in the development of standards. In some cases, an SDO may endorse a standard it developed. In other cases, standards developed by an SDO may be formally endorsed by a Standard Setting Organization (SSO). Each SDO defines its own standard development procedure, as well as the rules its members have to follow in order to participate. These rules usually refer to the steps and majorities required to approve a standard, as well as how licensing of the patents for standard implementation is handled. For a more comprehensive description of the diversity of SDO rules, the reader might refer to Lerner and Tirole (2006) and Baron and Spulber(2018).

3GPP and the mobile telecommunication standards

The third Generation Partnership Project (hereafter, 3GPP) is the main SDO in charge of supplying mobile telecommunication standards to the industry. It is a private, worldwide organization formed by almost 1000 organizations. This includes anything from phone manufacturers and telecommunication operators to national regulators.[17] Participation in 3GPP is open, up to a fee. It is important to note that being a member of 3GPP does not require any obligation in terms of contributing to the development of the standards. In fact, the majority of their members do not contribute to such development.

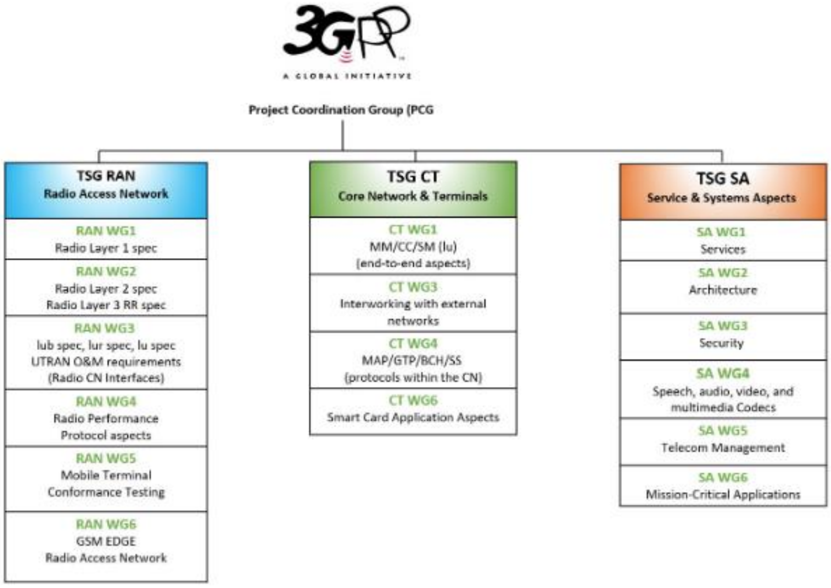
The documents delivered by 3GPP are not proper standards, according to its formal definition, but Technical Recommendations (TR) or Technical Specifications (TS). Once these documents are finished, they are passed to ETSI for its formal endorsement. TS and TR documents may define new proper standards or modify existing ones. Since I am interested in the standard development and not on it endorsement, I simplify my terminology and refer to 3GPP's TS and TR documents as *standards*.

3GPP was created in December 1998 by the signing of "The 3rd Generation Partnership Project Agreement," and since then, they have been in charge of developing standards for the 1st, 2nd, 3rd, 4th and upcoming 5th generation of mobile technology. As can be seen in Figure 1, the work in 3GPP is organized in 3 Technical Specification Groups (TSG) representing the main technical areas: (i) Radio Access Network (RAN), (ii) Core Network & Terminals; and

Usually several technologies coexists in time and their use depends on the deployment of each of them.

[17] Formally 3GPP is formed by 7 national and regional SDOs. These local SDOs, called organizational partners, are: ARIB (Japan), ATIS (USA), CCSA (China), ETSI (Europe), TSDSI (India), TTA (Korea) and TTC (Japan). A firm joins these SDOs by paying a fee, and any member of these organizations can participate in 3GPP.

Figure 1: 3GPP's structure



Source: 3GPP's webpage

(iii) Service and System Access (SA). Inside each TSG, there are Working Groups (WG), which are also defined by their technological scope and organize meetings to develop standards. All of them are coordinated by a unique Project Coordination Group (PCG).

One of the most important rules set out by SDOs relate to the licensing of the Intellectual Property (IP) rights protecting the innovations included in a standard. 3GPP has two main rules regarding IP rights:[18] (i) members should declare the existence of patents protecting any essential technology included in the standard; and (ii) holders of such patents must make licenses available to all interested third parties under fair, reasonable and non-discriminatory (FRAND) terms. The patents mentioned in (i) are called Standard Essential Patents (SEPs), and any entity that wishes to implement the standard must obtain a license for those patents. The use of these clauses allow SDOs to avoid *hold up* problems.[19] By forcing participating firms to license their SEP under FRAND terms, SDOs avoid any potential strategic use of SEPs to prevent competitors from launching rival products. This also encourages the early adoption of a standard by assuring implementers a "reasonable" cost of using it. FRAND is meant to balance

[18]See `https://www.3gpp.org/about-3gpp/3gpp-faqs` for more details on the licensing policies of 3GPP.
[19]See Lemley and Shapiro (1991) for more details on the *hold up* problem.

the tension between providing developers incentives to invest in technology development and ensuring downstream competition.

2.4 Development of standards in 3GPP

The process of developing standards is neither simple nor linear. I present here a simplified version that will help the reader the main steps in the development of a standard in 3GPP.[20]

The first step is to define a technological goal that the system should meet. This initial idea can be presented by any organization as long as it has the support of 4 3GPP members. These initial goals are typically broad and must be broken into smaller ideas and problems that are more concrete and actionable to ultimately attain the broad goal. Each "part" of this idea, generically called *work item*[21] in 3GPP might either give place to a new standard (if there is a completely new feature that must be developed in order to accomplish this goal) or modify an existing one. Each part of this initial idea is allocated to a working group,[22] which is in charge of transforming the idea in a standard.

As a simplifying example, consider a release of only 2 standards with 3 goals: (i) the new mobile technology should allow phones to connect to the network, even in very dense cities; (ii) energy efficiency should be enhanced; and (iii) security of the network should be improved. Each idea is allocated to a different working group depending on the technological requirements. Figure 2 illustrates this example.

Imagine now that the first goal requires a new type of antenna capable of emitting signals in very dense cities. Since this is a new feature it requires a new standard to describe it. Then, the chair of the working group sets up a meeting where all interested firms can show up.[23] Once there, firms provide documents with their ideas for this new antenna. These documents are called *contributions*. Before providing these technical solutions to the group, firms conduct in-house R%D. Firms developing standards typically have a history of R&D activities that determines their *knowledge*. I define *firm knowledge* as the capacities and know-how acquired trough experience and R&D activities.

The process of developing a standard usually requires firms to meet more than once and its approval is done in stages: first it is approved by firms actively contributing to the standard

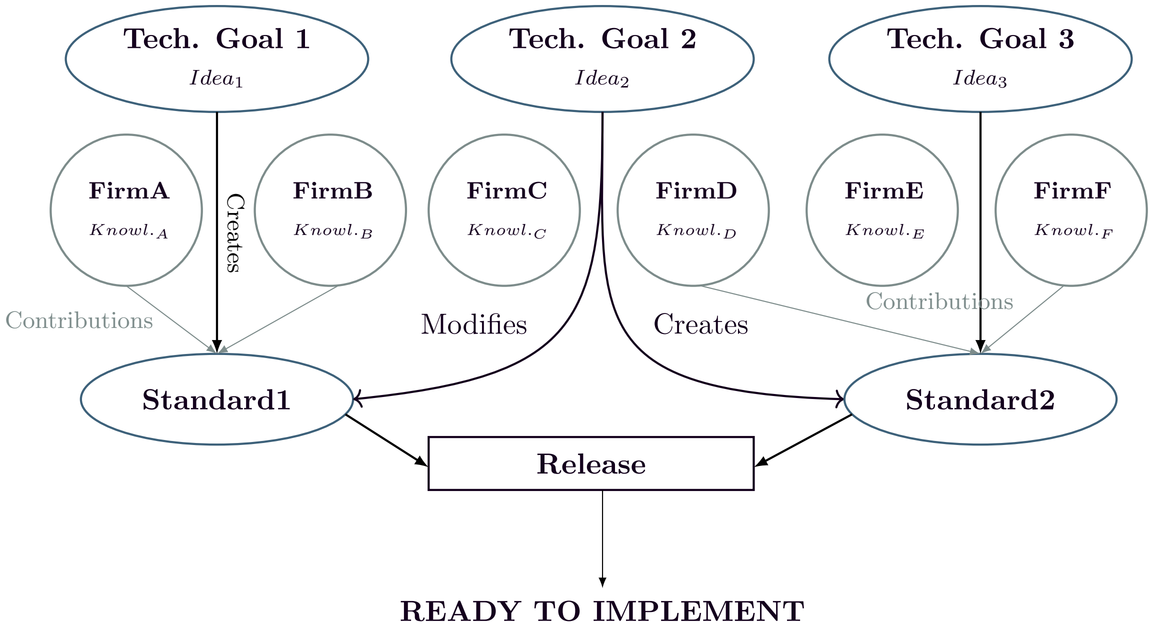
[20] As explained in the previous paragraphs, to simplify terminology I refer to Technical Reports and Technical Specifications as standards.

[21] Formally, there are many categories of work items: study items, features, building blocks and work tasks. See ETSI TR 121 900 p.26 for more details on work items.

[22] See Figure 1 for a description of 3GPP structure.

[23] Working groups have been omitted from Figure 2 to simplify the figure.

Figure 2: Example of the development of a Release with 2 standards



and then by all firms in the corresponding working group. Approval is achieved by consensus.[24] Contributions have different names depending on their type and the stage at which they are submitted: technical reports, discussion documents, change request or proposal. In this paper I assume all contributions equally valuable for the development of the standard.

Consider now idea number (ii). Suppose that to enhance the energy efficiency of the system, two things must be achieved: modify some feature of the antenna previously developed and develop a new way of transmitting signals. The first part of this idea requires to modify Standard 1, while the second one entails the creation of a new one. The procedure for modifying an existing standard is the same as the one for creating one.

To finish my simple example, consider now the third idea. To improve the security of the network, the transmission technology must be modified. This idea only involves modifying standard 2.

Ideas continue arriving until the chair of the Project Coordinator Group judges that most of the work has been done for this release. Then, the release is said to be "frozen" and it can be used by implementers. Firms holding IP rights over technologies that are standard-essential have to declare it at some point of the standardization process. A technology is considered essential if there is no alternative way to implement the standard without using it. Patents protecting IP rights of these technologies are called Standard Essential Patents (SEP).

[24] Consensus in 3GPP is defined as the lack of sustained opposition and might not imply that 100% of members agree with the decision.

3 Data

3.1 Data sources

My main data source is the Searle Center Data Base (hearafter, SCDB), a comprehensive database on technology standards developed by the Searle Center of Northwestern University, in collaboration with Qualcomm, Perinorm, and IPLytics.[25] The database consists on 3 related datasets, one of which contains detailed information on the standardization process of mobile networks in 3GPP, which occurred between 1999 and 2010. During this period I observe 9 releases of 3G and 4G, firms' written contributions to each standard in each release, the date each contribution was submitted, and whether it was approved (or rejected). The database also has information about the meeting in which each contribution was discussed. I combine the information from this database with another dataset on essential patents, from the SCDB. This allows me to see who owns the IP rights over the technologies included in each standard.

For the purpose of my analysis, I also add information on firms' patent portfolio from United State Patent and Trade Office (USPTO). From the Patentview platform, I collected data on firms granted patents from 1970 to 2014, including their technological class, based on the International Patent Classification (IPC).[26]

I complement my analysis with data on *working items* affecting each standard, which I scraped from 3GPP webpage. As explained in 2.4 a working item is a document containing the description of a new feature or a goal proposal that might be included into one or more releases. I call working items "technology goals", since they are the first steps in incorporating new features to the system.

To merge these datasets together, I rely on firm names and algorithms to match string variables. See appendix A for details and robustness checks (TBD).

3.2 Empirical measures and descriptive statistics

Most of the variables I need to conduct my study are not observed. I therefore construct various empirical proxies using the data described in the previous section. More precisely, I construct or define the following measures: (i) Standard heterogeneity; (ii) Effort and participation decisions; (iii) Firm knowledge similarity; (iv) Group outcomes; and (v) Payments.

Standard heterogeneity Not all standards carry equal weight. Some of them describe broader or more complex parts of the system. To account for this, I use information on the technology

[25] see Baron and Gupta(2018) and Baron and Pohlmann(2018) for a more detailed description of the data sets.
[26] patentsview.org.

Table 2: Descriptive statistics by Release

Release	Number of standards in the sample	Average number of firms per standard	Average tech. goals per standard
Rel - 99	54	4.5	4.6
Rel - 4	70	4.9	5.1
Rel - 5	100	4.7	7.1
Rel - 6	194	5.4	6.3
Rel - 7	275	5.9	6.4
Rel - 8	407	7.1	5.5
Rel - 9	389	7.1	5.5
Rel - 10	361	6.9	7.1
Rel - 11	285	6.6	10.4

Source: Table produced using SCDB data

goals for each release. To achieve each goal, new standards might be created and old ones might be modified. Then my measure of a standard's broadness is the number of technological goal documents that mention that standard. For example, a standard that is mentioned in two technological goal documents is broader than one that is mentioned in only one. On average, a standard is related to 7.18 technology goals (see Table 3)

Effort and participation decision. Effort is not directly observable but written contributions to a standard are. I use the number of contributions made by firms to a standard as a proxy for firm effort. If the contribution is submitted by more than one firm, I give equal weight to all participating firms. I consider any firm that submits at least one contribution as a participant of the standard.

Firms' knowledge similarity I rely on patented technologies to measure firm 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 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 similaritie" 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

Table 3: Descriptive statistics

	N	Mean	SD	Min	Max
Panel A: Standardization characteristics					
Number of firms (participating)	1,899	6.09	4.48	2	25
Number of contributions	1,899	65.40	159.69	2	2463
Time to develop the standard (days)	1,899	691.57	649.13	0	4,030
Broadness	1,899	7.18	10.06	1	173
Knowledge similarity of participating firms	1,899	0.67	0.19	0.01	0.99
Number SEP declared to the standard	946	9.49	19.78	1	175
Panel B: Firms characteristics					
Number of standards participating (per release)	315	36.75	55.93	0	313
Number of patents	315	4,476	8,722	0	46,609
Number of SEP	315	18.13	53.30	0	650
Size (sales) per year	115	24,385	24,925	0	116,466
R&D expenditures per year	115	1,803	1,867	0	7,150

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 use Cosine Similarity (CS) to measure the similarity between any 2 firms. CS is 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 amount 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.

Group outcomes and payments According to the project agreement, one of the goals of 3GPP is to "[use] minimum production time for Technical Specifications and Technical Reports from conception to approval".[27] Given that neither value nor quality are observable at a standard level, the time it takes to develop the standard is the closest observable proxy for the success of the group. I define *time of development* as the number of days it takes to accomplish 90% of the standardization work. Say one is the date the first contribution is submitted and the last day is the date when 90% of all contributions have been submitted.

$$\textit{Time to Develop} = \textit{Date when 90\%work is accomplished} - \textit{Date of the first contribution}$$

Payments in this market comes from two sources: selling products or services complying with the standard and from the licensing of SEP (royalty revenues), as explained in 2.1, and any of these variables is observed. SEPs have to be licensed under FRAND terms and therefore there is a cap on the amount a firm can expect to get from licensing it SEP. Even though FRAND is not precisely defined and most of the royalties are set in court, this rule puts a cap on the amount a firm can expect to get from licensing its SEP. Another way for firms to get a benefit from their SEP is through cross-licensing.

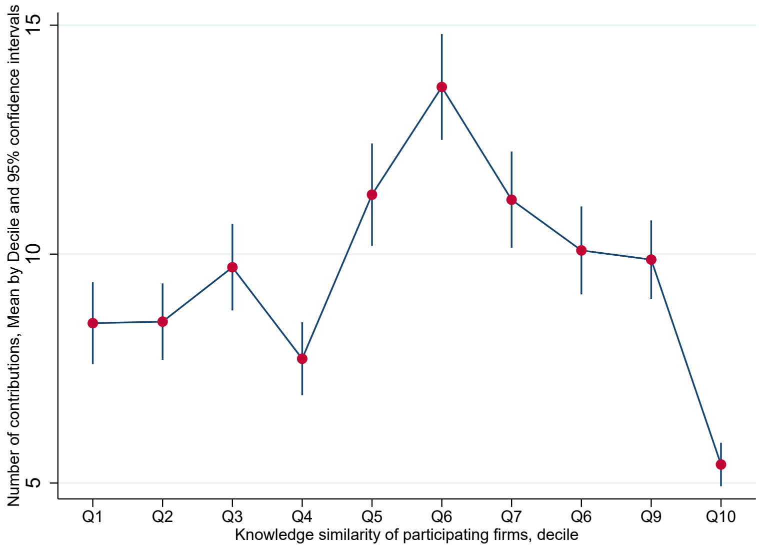
Also no public information on cross-licensing agreements, therefore, even if I had access to data on royalties revenues it will show that firms that don't manufacture goods in the final market are getting the largest benefits from standardization. This is because vendors rely a lot on cross-licensing agreements while pure upstream firms or firms producing intermediary goods choose to license their SEPs. I therefore use the number of SEPs as a proxy of the private upstream revenues a firm gets from participating in a standardization process. Assigning patents to standards is not straightforward. There are several criteria for this in the SCDB. I used the broadest criterion, which assigns all patents declared to be essential to a standard. , even if the information for the match was not perfect.

4 Empirical Evidence

In this section, I present empirical evidence documenting the economic trade-off that arises when firms with similar knowledge work together. I first show the inverted U-shape relationship between the effort firms exert and their knowledge similarity. I then provide evidence of two effects which generate the economic trade-off behind this non-linear relationship. On the one hand, I show that when firms with similar knowledge work together, they speed up the development of a standard because of the positive relationship between complementarities in firms' effort and their knowledge similarity. I call this the *cooperation effect*. On the other hand, when firms have

[27] See 3GPP Partnership Project Agreement https://www.3gpp.org/ftp/Inbox/2008_web_files/3gppagre.pdf, page 1.

Figure 3: Estimates of ϕ_q (95% confidence bands)



similar knowledge, the competition over intellectual property rights of the technologies included in the standard becomes more intense. This is what I call *competition effect*.

4.1 Inverted U-shaped relationship between effort and knowledge similarity

I start my analysis on effort and firms' knowledge similarity by plotting the average number of contributions, my proxy for effort, submit per firm to a given standard, on the knowledge similarity of firms contributing to that standard. To avoid comparing averages with different number of observations, I discretized the similarity measure in deciles. See appendix for others discretizing criteria.

Figure 4 suggest a non linear U-shaped relationship between the effort provided by firms in a group and their knowledge similarity. That is, firms do not exert it maximum effort when teaming up with other firms that are specialized in the same technological area, neither when cooperating with firms with completely unrelated knowledge. The maximum average effort is 13.65 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).

Data also shows that an increase of 1% in the knowledge similarity of firms working together is correlated , in average,with an increase of 0.17% of firms' effort if the average similarity of the group is below 0.7 (groups in the first 6 deciles of the knowledge similarity distribution). That same increase is associated with a reduction of firms' effort of 3.5% if the knowledge similarity of firms in the group was above 0.7.[28]

[28]Those percentages are the slopes of a linear approximations for each side of the inverted U shape curve.

4.2 Complementarities in effort and knowledge similarity

It may be intuitive to think that firms work together because there are complementarities between their efforts, but it is not obvious that those complementarities are related to firms' knowledge similarity, whereas the sign of this relationship is ambiguous.

In order to find empirical evidence of effort complementarities and their link to firm similarity, I estimate a translog production function. As the output, I use the number of days (in logs) it takes the group to develop the standard and as inputs, the effort (in logs), measured by the number of contributions provided by each firm participating. Groups are defined at a standard-release level.

In a first attempt to capture effort complementarities, I estimate the following fixed-effects model at a standard-release level:

$$ttd_{s,r} = -\beta_1 \sum_{i=1}^{i=N} c_{i,s,r} p_{i,s,r} - \frac{\beta_2}{2} \sum_{i=1}^{i=N} c_{i,s,r}^2 p_{i,s,r} - \frac{\phi}{2} \sum_{i=1}^{i=N} \sum_{j=1}^{j=N} c_{i,s,r} p_{i,s,r} c_{j,s,r} p_{j,s,r} - \mu_s^S - \mu_r^R - \epsilon_{s,r} \quad (1)$$

where the dependent variable is the time it takes the group to develop standard s in release r, normalized by its broadness, in logs.[29] The independent variables $c_{i,s,r}$ and $c_{i,s,r}^2$ are the number of contributions (logs) and the number of contributions squared (logs) that firm i submits to develop standard s in release r, respectively. The variable $p_{i,s,r}$ is a dummy variable that takes value 1 if firm i participates in the group developing standard s in release r. The interaction of firm effort is represented by the parameter ϕ. A positive ϕ means that firms' efforts are complements, while a negative ϕ means that the effort put in by different firms are substitutes.

To solve some of the endogeneity concerns that may arise from comparing standards with different characteristics, I control for unobserved heterogeneity in standards by absorbing a set of fixed-effects at a standard level. I include release fixed-effects to account for characteristics of the release that do not vary across standards and which affect the time it takes to develop a standard within the release. For example, it may be that the time it takes to develop standards in the first release of 4G (release-8) is higher that the time it takes to develop a standard in a subsequent release. I include two extra controls, a dummy variable that takes value 1 if the standard is developed for the first time in that release and the average number of patents held by firms participating in each group.

Column 1 of Table 4 presents estimates for Equation 1. After adding controls, I find that: (i) there is a non-linear and concave relationship between effort and time (adjusted by the standard

[29] I normalize time by dividing by the broadness of the standard, defined as the number of related technological goals (see the Data section for more details on this measure).

Table 4: Time production function

	(1) Restricted model	(2) Non-linear Effects
Contributions	0.195***	0.181***
	(0.000)	(0.000)
Squared number of contributions	-0.0107**	-0.00860**
	(0.015)	(0.032)
Joint effort:		
All similarity levels	0.0114**	
	(0.011)	
Q1 similarity		0.00756*
		(0.079)
Q2 similarity		0.0103**
		(0.015)
Q3 similarity		0.0106**
		(0.020)
Q4 similarity		0.0173***
		(0.000)
Q5 similarity		0.0225***
		(0.000)
Firm patent portfolio	Yes	Yes
Standard first time (dummy)	Yes	Yes
Standard FE	Yes	Yes
Release FE	Yes	Yes
N	1792	1792
adj. R^2	0.543	0.544

p-values in parentheses. Errors are robust to heteroskedasticity All values are in logs
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

broadness); and (ii) effort provided by different firms are indeed complements. The estimation of parameter β_1 shows that an increase in contributions of 10% decreases[30] the average time to develop a standard by almost 2%, other things being equal. We can see that β_2 is negative with a magnitude of about 0.1%, suggesting decreasing returns (in terms of the time it takes to complete a standard) in the provision of effort The positive and significant value of the estimated parameter ϕ supports finding (ii).

Estimates of Equation 1 suggest that the efforts provided by different firms are complements, but they do not say anything about the relationship between these complementarities and the similarity of the firms providing the effort. I assume firm knowledge comes from past in-house R&D activities. For example, if a firm has previously done research about antennas, it is likely that its contributions will related to them. As explained in **??**, I use the similarity between firms' portfolios as a measure of firm knowledge similarity.

My hypothesis about the *cooperation effect* implies that if firms have similar knowledge, they will face lower coordination costs, such as common expert language, and therefore, their joint effort will speed up the standardization process more than the effort provided by dissimilar firms.

To explore this hypothesis I estimate a more flexible version of Equation 1:

$$ttd_{s,r} = -\beta_1 \sum_{i=1}^{i=N} c_{i,s,r} p_{i,s,r} - \frac{\beta_2}{2} \sum_{i=1}^{i=N} c_{i,s,r}^2 p_{i,s,r} - \sum_{q=1}^{q=Q} \frac{\phi_q}{2} \sum_{i=1}^{i=N} \sum_{j=1}^{j=N} c_{i,s,r} p_{i,s,r} c_{j,s,r} p_{j,s,r} D_{i,j}^q - \mu_s^S - \mu_r^R - \epsilon_{s,r} \tag{2}$$

where $D_{i,j}^q$ is a set of dummy variables that take value 1 if the similarity between firm i and j is at the qth percentile of the firm knowledge similarity distribution. The set of parameters ϕ_q represent the complementarities between efforts of firms whose similarity falls in the percentile q of the distribution. Table 4 and Figure 4 present estimates using quintiles. See Appendix for robustness checks using other percentiles and variables in levels.

Figure 4 shows empirical evidence of a positive relationship between the value of ϕ_q and firm knowledge similarity. According to column 2 of Table 4, an increase in efforts' interaction term of 10% reduces the time to develop the standard by 2.25% if the effort is provided by firms with a knowledge similarity in the top 20% of the distribution. If this same effort is provided by firms with a knowledge similarity in the bottom 20%, this decrease in time is reduced to 0.75% and it is not statistically different from 0 at a 5% significance level. This evidence supports the

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

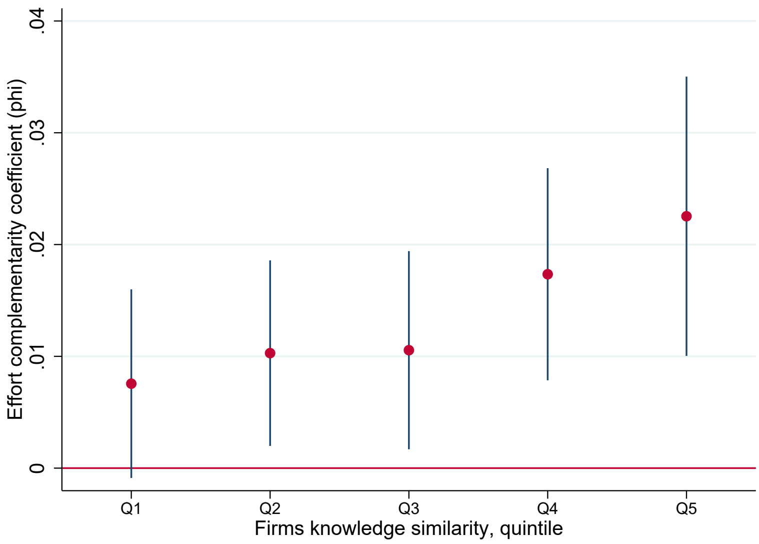


Figure 4: Estimates of ϕ_q (95% confidence bands)

hypothesis of a *cooperation effect*, in which efforts are stronger complements the more similar the knowledge of firms providing it.

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. As documented by Simcoe(2012) and by Spulberg(2013) and Spulberg(2016), firms in SDOs compete within standards to include their preferred technology.[31] Firms have private interests in including certain technologies in a standard, since they often have IP rigths over them. Rysman and Simcoe (2008) show that SEPs receive twice as many citations as the average patent, implying that patents gain additional value when included in a standard.[32]

The value of a SEP is difficult to asses since firms usually license the entire patent portfolio and since it is defined in court under FRAND conditions.[33] Therefore, one could think that competition in this market is not on prices, but on the number of patented technologies to be included in the standard. This last statement is implicitly assuming 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 innovation, they are then perfect complements. Following a *Shapley value* approach, it is then reasonable to assume that they have the same value.[34]

[31] Simcoe(2012) studies the development of Internet standards.
[32] For their empirical study, Rysman and Simcoe (2013) use data on 4 SSOs: ANSI, IEEE, IETF and ITU.
[33] Some of the most well-known cases are Microsoft Corp vs Motorolla Inc and Ericsson Inc vs D-Link Sys.
[34] See Roth (1988) for a detailed description of the *Shapley value*.

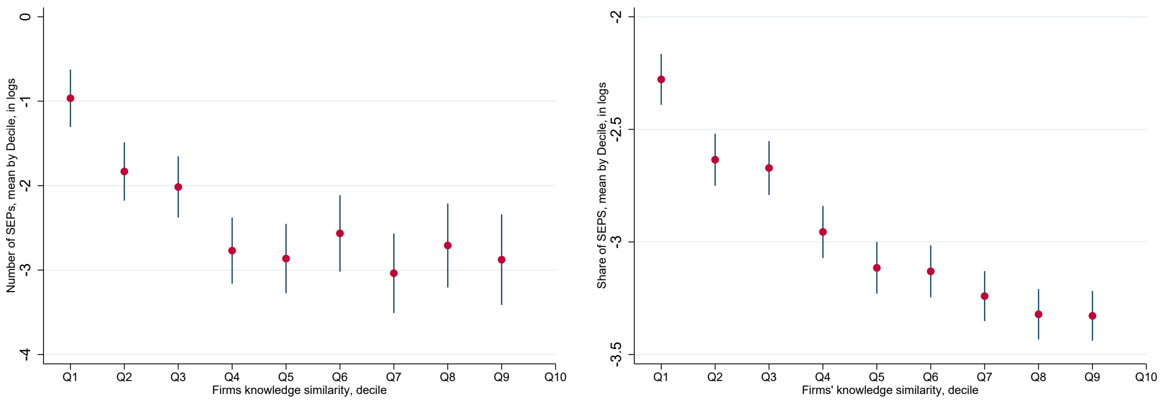


Figure 5: Number of SEPs (Left) and Share of SEPs (Right) over firms' knowledge similarity (95% confidence bands)

My *competition effect* hypothesis states that firms with similar knowledge, which by definition have similar patents, are closer competitors for getting a SEP. As an initial exploration of this hypothesis, I plot the average number of SEPs firms got in each standard-release over the knowledge similarity of contributing firms.

Figure 5 shows a negative and significant relationship between the number of SEPs firms have in a standard-release and the knowledge similarity of firms contributing to that standard-release. The right figure in Figure 5 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 standard-release over the total number of SEPs for that standard-release. In both pictures, means are adjusted by firm fixed-effects. See Appendix for robustness checks without fixed effects, controlling by the number of contributors and variables in levels.

Though these figures account for firms' unobserved heterogeneity, there are other endogeneity issues that must be resolved. For example, across different standard-releases, with different broadness levels, different numbers of firms will participate , something that must be accounted for to draw conclusions about competition inside groups. To address some of these concerns, I formalize my hypothesis and estimate the following fixed-effects model:

$$numbersep_{f,s,r} = \alpha + \psi similarity_{f,-f,s,r} + \beta X_{f,s,r} + \omega X_{-f,s,r} + \mu_f^S + \delta_r^S + \gamma_s^S + \epsilon_{f,s,r} \quad (3)$$

where the variable $NumberSepf, s, r$ is the number of SEPs firm f has in standard s for release r, and $similarity_{f,-f,s,r}$ is the average cosine similarity between the patent portfolios of firm f and all other firms $-f$ participating in standard s in release r. I include firm fixed-effects to account for unobserved firm heterogeneity, such as experience in standardization and bargaining power, which may also affect the number of SEPs a firm can get. In order to capture the heterogeneity across releases that may affect the number of SEP, I also include release fixed-effects. In the same spirit, I absorb a set of standard fixed-effects.

Covariates $X_{f,s,r}$ control for the number of contributors in the standard-release, the broadness of the standard-release, a dummy variable that takes value 1 if the standard is developed for the first time in that release, and the portfolio size of the firm and its expenditure in R&D activities. The value of these last two variables is computed in the year previous to joining the standard, as joining the standardization process might impact firms' patents portfolio and their R&D activities. In some specifications, I also control for the average characteristics of other firms in the group, $X_{-f,s,r}$, to account for the portfolio size and R&D expenditures of the competing firms.

Firms do not always get SEPs when participating in the development of a standard-release. In fact, in the sample of standards for which I have information, 43% of the times firms participate they do not get any SEPs. Given the significant number of zeros in my sample, I also estimate a tobit model for Equation 3.

Table 5: SEPs and firm knowledge similarity

	(1) Baseline	(2) Controls	(3) Other firms controls	(4) Tobit
Firms' knowledge similarity	-1.723***	-0.875*	-1.286**	-2.470***
	(0.000)	(0.093)	(0.015)	(0.000)
Firm characteristics (Portfolio, R&D)	No	Yes	Yes	Yes
Charact. other firms in the group	No	No	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Release FE	Yes	Yes	Yes	Yes
Standard FE	Yes	Yes	Yes	No
Standard- release characteristics (Numb of firms,Broadness, First time)	No	Yes	Yes	Yes
Average SEP per firm-standard-release	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	

p-values in parentheses. Errors are robust to heteroskedasticity. All values are in logs
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5 shows estimates of ψ in Equation 3. See Appendix for the complete table including all estimates in Equation 3. An increase of 1% in the average knowledge similarity of firms in the group decreases the number of SEPs obtained by firms in that group between 2.47% and 0.875% depending on the 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 set of controls detailed in the previous paragraph. This evidence supports the hypothesis of a *competition effect*, according to which firms with similar knowledge are closer competitors when it comes to obtaining SEPs.

4.4 Participation and standard-firm match

Participation is relatively low in the data, with the overall probability of joining standardization group at 16.64%. These decisions is not random, but the literature sheds little light on why firms choose to participation in some standardization groups and not others. In an attempt to model participation in a more realistic manner, I relied on qualitative survey information, complemented with informal talks with industry practitioners.

In 2003, ConsortiumInfo.org conducted a small survey on standardization and SSOs, which asked major players in 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 topic and goals, how relevant a standard was to their technical expertise; IP rights policies, cost effectiveness vis-à-vis alternative, the procedures and group composition, and other members' commitment of engineering resources.

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 firm and standard 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 fit*hypothesis. While (i) is endogenous to all firms decisions and characteristics, the second one is exogenously determined by the technological needs of the standard and the technological knowledge of the firm.

The empirical challenge of modelling the firm-standard match is the unobservability of the standard topic or goal. Nevertheless, I observe the broadness of a standard.[35] Then, if the firm-

[35]Another approach could be to look at the technological classes of the patents declared to be essential to the standard. However, this is observed ex-post, and then patents' technology class are likely to match the classes of

standard technological fit hypothesis is true, I should observe that broader standards, 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 will be relevant to a given firm's interest and expertise. On the flip side, if a firm works in several technological areas, it is more likely to be interested in more standard. To capture this empirically, I use patent portfolio size to measure firm technological capacity. If the firm-standard fit hypothesis is true, I should observe that firms with bigger portfolios are more likely to participate in standardization groups.

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

$$p_{f,s,r} = \mathbb{1}\{\beta_p X^p_{f,s,r} + \gamma^p Portfolio_{f,r} + \gamma^b Broadness_{s,r} + \nu^p_{f,s,r} > 0\} \quad (4)$$

where $p_{f,s,r}$ is a dummy variable that equals one if firm f participates in standard s in release r, $X^p_{f,s,r}$ is a set of proxy variables for the revenues that f would obtain if it were to participate, $Portfolio_{f,r}$ is the number of patents in firm f's portfolio the year prior to release r, $Broadness_{s,r}$ is the broadness of standard S in release r measured by the number initial goals affecting the standard, and $\nu^p_{f,s,r}$ captures the unobserved (to the researcher) determinants of the firm's participation decision, including the quality of the fit between the standard's technological needs and the firm's technological capacity. As extra controls, I also include a dummy variable that takes on value 1 if standard s is developed for the first time in release r, as well as release and standard fixed-effects.[36]

$X^p_{f,s,r}$ includes proxies for firms' standardization revenues, including the amount of downstream sales of the firm and firm fixed-effects. The first accounts for the size of the firm, controlling for the heterogeneity in downstream profits across firms and firm's size. Firm fixed-effects control for other unobserved firm characteristics, invariant across standard and release, affecting their likelihood of participating.

Columns 1, 2 and 3 present estimates for Equation 4. I find a positive and significant γ_p across all specifications, meaning that firms with bigger portfolios are more likely to participate in a standardization group, everything else constant. I also find a positive and significant γ_b, suggesting that firms are more likely to participate in broader standards.

As is usual in logit models, due to the normalization $\sigma^2_\epsilon = \pi^2/3$, parameters are identified up to a scale factor. To quantify the effect of adding an extra patent or broadening a standard

patents held by participating firms.

[36]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 (Neyman and Scott (1948)). Nevertheless, since I am not interested in the estimates of those parameters, I do not adjust for them.

Table 6: Logit estimates for participation decisions

	(1) Baseline	(2) Fixed Effects	(3) Controls
Portfolio size of the firm (log)	0.134 ***	0.146***	0.345 ***
	(0.000)	(0.000)	(0.000)
Broadness of the standard	0.038***	0.018***	.022**
	(0.000)	(0.000)	(0.000)
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

p-values in parentheses. Errors are robust to heteroskedasticity
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

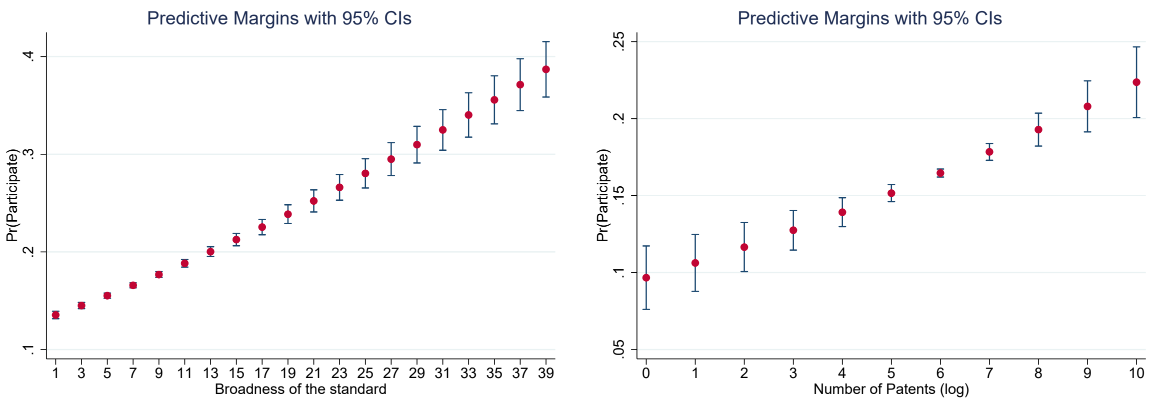
by 1 unit , I calculate the marginal effects of those variables on the participation probabilities. Figure 6 shows the results of this estimation. The probability of a firm participating in a group with a broadness of 30 or more units is almost 30%, double the overall probability of participation of 16%. On the other hand, a firm with a portfolio of 8000 patents (e^9) are twice as likely to participate than firms with portfolios of 3 patents (e^1).

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

4.5 The need for a model

Results in the preceding sections suggest that the presence of IP rights generate vested interests that could slow down the standardization process. On the one hand, competition over IP rights generates incentives for firms to team up with firms specialized in different technologies, as shown in subsection 4.3. On the other, I show in subsection 4.2 that firms which are closer in the technological space develop standards faster due to the large complementarities between them. Notwithstanding, IP rights are a monetary incentive for firms to participate and exert effort. That is especially true for pure upstream firms, since IP licensing is their only revenue

Figure 6: Marginal effect of standard broadness and firm portfolio size on participation probabilities



Note: Marginal effects computed using the model include firm, release and working group fixed-effects.

channel. The scarcity of data on IP rights revenues or other sources of standardization profits makes quantifying the effect of IP rights on standardization processes difficult. To evaluate the overall impact of a policy restricting IP rights payments beyond the current FRAND clauses, it is necessary to account quantitatively for all the incentives firms faces when deciding whether to participate and how much effort to exert. In the rest of the paper, I develop and quantify a structural model for firms' effort and participation decisions in the standardization process of mobile telecommunications. Such a framework allows me to overcome the empirical limitations of this unobserved data, enabling me to evaluate the effect of a change in IP rights policy on the amount of time it takes to develop collaborative standards.

5 A model for firms' effort and participation decision

5.1 Set-up

In this section, I present an empirical model that captures the most relevant trade-off firms face when deciding whether to participate and how much effort to exert in each standardization group. The model predicts: (i) Firms' participation decision in each standard-release; (ii) the level of effort firms exert by standard-release; (iii) the number of SEPs held by each participating firm; and (vi) the time to develop a standard. I later estimate this model and use it as a tool to simulate counterfactual policy analysis.

The model focuses on the participation and effort decisions taken by *firms* in each standardization *group* and how their *knowledge similarity* shapes those decisions. A group is defined by the standard-release its members are there to develop. The goal of the group is to develop the standard-release "[using] minimum production time". [37] A *firm* in this empirical model is any of the 35 organizations actively contributing to 3GPP.[38] The concept of *knowledge similarity* refers to the technological specialization or know-how firms have prior to joining any standardization group.

The timing of events is as follows. First, firms decide whether to participate in each standardization group, depending on the profits they expect to get and on the match between their technological expertise and the one required to develop the standard. Second, firms decide how much effort to exert in the standardization group, given the participation decisions of the other firms. The time it takes to develop a standard-release depends on the effort exerted and the cross-effects between the efforts of firms with different areas of expertise (*knowledge*). Third, members of 3GPP decide on which technologies to include in the standard-release. Then,firms owning IP rights over these technologies claim their SEPs.[39] Finally, when all standards in the release are finished, implementers manufacture phones or deploy the network to provide telecommunication services. SEPs holders also license their patents at this stage.

5.2 Group Outcomes

I model the time it takes to develop a standard-release, $TTD_{s,r}$, as a function T of the effort exerted by each firm, the complementarities between these efforts, and standard and release characteristics.

$$TTD_{s,r} = T(E_{s,r}, E^2_{s,r}, X^S_s, X^R_r; \theta^T)$$

where $E_{s,r}$ represents the effort exerted by all firms developing standard s in release r, $E^2_{s,r}$ is the sum of the squared efforts and X^S_s and X^R_r are a set of variables representing standard and release characteristics, respectively. Finally, θ^T represents the set of parameters in T.

To take this model to the data, I assume a linear specification for T and proxy for firm effort for each standard-release using the number of contributions they submit to each group. Assume that firms are labeled $f = 1...N$. Then, Equation 5 defines the time production function as:

[37] 3GPP Partnership Project Agreement.

[38] 3GPP has hundreds of members, but I consider only those that submit at least 5 contributions during the period 1999-2012. See 3.1 for more details on this.

[39] SEPs are actually *declared* by their owners. Once the technological solutions are chosen firms holding patents protecting the IP rights of those selected technologies have to declare it to 3GPP.

$$TTD_{s,r} = \beta_1 \sum_{f=1}^{f=N} e_{f,s,r} p_{f,s,r} + \frac{1}{2}\beta_2 \sum_{f=1}^{f=N} e_{f,s,r}^2 p_{f,s,r} + \frac{\phi}{2} \sum_{f \neq j}^{N} \sum_{j \neq f}^{N} e_{f,s,r} p_{f,s,r} e_{j,s,r} p_{j,s,r} s_{f,j} + \alpha_s^T + \alpha_r^T + \epsilon_{s,r}^T \tag{5}$$

where $e_{f,s,r}$ is the effort exerted by firm f toward the development of standard s for release r, $p_{f,s,r}$ is a dummy variable that takes value 1 if firm f participates in the development of s in release r, $s_{i,j}$ is a measure for the knowledge similarity between firms i and j, α_s^T is a standard-specific term that accounts for the unobserved heterogeneity in standard complexity and α_r^T is a release-specific term. The term $\epsilon_{s,r}^T$ is standard-release specific and accounts for all residual variation in TTD. The parameter ϕ in Equation 5 is an average measure of firm effort cross-effects. If $\phi > 0$, then the efforts are on average strategic complements. If instead $\phi < 0$, then they are substitutes. Keeping in mind the empirical evidence on the interaction between complementarities and firm knowledge similarity, I allow complementarities in effort to vary with firm knowledge similarity $s_{i,j}$.

Moreover, I assume that:

$$\mathbb{E}[\epsilon_{s,r}^T \mid e_{f,s,r}, \mathcal{J}_{f,s,r}] = 0 \tag{6}$$

where $\mathbb{E}$ denotes the expectation of $\epsilon_{f,s,r}^T$ conditional on firm effort, and $\mathcal{J}_{f,s,r}$ is the information set of firm f when deciding how much effort to exert for standard s in release r

5.3 Revenue function

There are two channels through which firms can benefit: (i) producing downstream using the technology developed upstream, and (ii) licensing the IP rights. The main differences between these benefits are whether they accrue upstream or downstream and the rivalry each entails. To profit from the implementation of the standard, a firm must operate downstream or produce intermediary goods. Then, since many vertically integrated firms can produce downstream at the same time, there is no rivalry on the implementation of the standard. On the other hand, each SEP is a rival good because only one firm can own it.

To account for both channels in my model, I include: (i) a set of dummy variables representing the business model of the firm; and (ii) a SEP equation that models firm competition over SEPs in the standardization group. The first term represents the non-rivlarous part of the team's output value, which firms can appropriate by using standards as inputs to produce downstream. The second term represents the part of the team's output that can be privately appropriated by firms through IP rights on the essential technologies.

The time it takes to develop the standard also (negatively) affects firms' revenues. The faster all standards in the release are finished, the faster firms can start profiting from either of the two channels described above. Time can be implicitly though of as a discount factor in my model. Recall that one of the goals in the standardization process is to develop standards in the smallest amount of time possible, therefore it makes sense to assume that firms profit from lower development times. As a simplifying assumption, I impose independence between the times it takes to develop different standards. That is, there are no externalities between standards in a release.

I then construct the following empirical function, R, to proxy for a firm's revenue function:

$$R_{f,s,r} = R(TTD_{s,r}, BM_f, SEP_{f,s,r}; \theta^B)$$

where BM_f is a set of dummy variables representing firm f's business model, and $SEP_{f,s,r}$ is a function modelling the number of SEPs firm f has in standard s in release r. Ideally, I would include the value of those SEPs, but because this variable is unavailabile, I consider only the number of SEPs.[40] Finally, θ^B represents the set of parameters in R.

To take this function to the data, I assume both components of the revenue function and the time enter linearly. Then, the firm revenue function becomes:

$$R_{f,s,r} = \underbrace{(MT - TTD_r)}_{\text{Time Penalty (-)}} \times (\underbrace{A^M_{BM} BM_f}_{\substack{\text{Downstream}\\ \text{profits of}\\ \text{using } s}} + \underbrace{A^P_{r,BM} * SEP_{f,s,r}}_{\substack{\text{Value of } s \text{ that can}\\ \text{be privately appropri-}\\ \text{ated by IP rights}}}) \tag{7}$$

where :

$$TTD_r = \sum_{s \in r} TTD_{s,r}$$

The term MT represents the maximum time to develop the set of standards, after which they have no value. The parameter A^M_f accounts for the market revenues related to the implementation of the standard, while $A^P_{r,BM}$ is the average value for a firms with BM BM of a SEP in release r.

5.4 SEP function

Most of the technologies included in 3GPP standards are protected by SEPs. Some of these technologies were already developed, patented and ultimately included in the standard, while

[40]There are several problems when dealing with value of a SEP: (i) firms usually licence their entire portfolio of patents; (ii) royalties are usually set in court, are propietary data and vary depending 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 2.1 for more details on this.

others were developed specifically to meet the standard's goals. Moreover, different firms may have different technological solutions to meet the standard requirements. I assume that the more similar the firms' knowledge, the more they compete for their solution to be included in the standard. This idea is in line with the negative correlation I showed in section 4 between the number of SEPs a firm has in a given standard and its knowledge similarity with the other firms participating.

With this in mind, I define the following equation for the number of firms:

$$SEP_{f,s,r} = S(simil_{f,s,r;-f,s,r}, X_f^S; \theta^S)$$

where $similf, s, r; -f, s, r$ is the knowledge similarity between f and all other firms $-f$ participating in the development of standard s in release r, X_f^S are firm characteristics and θ^S represents all parameters in S.

To take S to the data, I assume a lineal specification. I also include a set of dummy variables μ_f to account for unobserved firm heterogeneity, such as patenting experience and bargaining power, and for release fixed-effects. I also add an error term $\epsilon_{f,s,r}^S$ that accounts for the measurement error in $SEP_{f,s,r}$ and an unexpected normal shock in the SEP function. Then the SEP function is defined by:

$$SEP_{f,s,r} = \alpha^S + \psi simil_{f,s,r;-f,s,r} + \mu_f^S + \mu_r^S + \epsilon_{f,s,r}^S \tag{8}$$

Moreover, I assume that:

$$\mathbb{E}[\epsilon_{f,s,r}^S \mid s_{f,s,r;-f,s,r}, \mathcal{J}_{f,s,r}] = 0 \tag{9}$$

where $\mathbb{E}$ denotes the expectation of $\epsilon_{f,s,r}^S$ conditional on firm knowledge similarity prior to joining the group, and $\mathcal{J}_{f,s,r}$ is the information set of firm f when deciding how much effort to exert in standard s for release r

5.5 Marginal costs and Firms profits

In my model, firms have a quadratic marginal cost c_f of exerting effort, whereas conditional on participating, they face no fixed cost. Marginal costs are heterogeneous across firms but constant across standards and releases. They are also common knowledge for all firms but unobserved to the researcher. I assume that:

$$c_f \sim lognormal(\mu_f^C, \sigma^2) \tag{10}$$

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

Combining Equation 7, Equation 8 and Equation 10, I construct the following empirical firm profit function:

$$\Pi_{f,s,r} = (MT - TTD_r) \times (A_{BM}^M BM_f + A_{r,BM}^P * (\psi s_{f,s,r;-f,s,r} + \mu_f^S + \mu_r^S + \epsilon_{f,s,r}^S)) - \frac{c_f}{2} e_{f,s,r}^2 \quad (11)$$

$$\Pi_{f,s,r} = \sum_{s \in r} (MT - TTD_{s,r}) \times (A_{BM}^M BM_f + A_{r,BM}^P * (\psi s_{f,s,r;-f,s,r} + \mu_f^S + \mu_r^S + \epsilon_{f,s,r}^S)) - \frac{c_f}{2} e_{f,s,r}^2$$

$$\begin{aligned}\Pi_{f,s,r} = \Big(&- \beta_1 \sum_{s \in R} \sum_{i \in S} e_{i,s,r} - \frac{\beta_2}{2} \sum_{s \in R} \sum_{i \in S} e_{i,s,r}^2 - \frac{\phi}{2} \sum_{s \in R} \sum_{i \in S} \sum_{j \in S} e_{i,s,r} e_{j,s,r} s_{i,j} - \mu_s^S + \mu_r^R - \epsilon_{s,r}^T \Big) \\ &\times (A_{BM}^M BM_f + A_{r,BM}^P * (\psi s_{f,s,r;-f,s,r} + \mu_f^S + \mu_r^S + \epsilon_{f,s,r}^S)) \\ &- \frac{c_f}{2} e_{f,s,r}^2 \end{aligned} \quad (12)$$

5.6 Optimal effort

Given their participation, firms choose how much effort $e_{f,s,r}$ to exert by maximizing expected profits, assuming that other firms are also maximization their own profits. Combining Equation 12 with Equation 6 and Equation 9, I can write the following equation for the expected profits:

$$\begin{aligned}E(\Pi_{f,s,r} \mid I_{f,s,r}) = (&- \beta_1 \sum_{s \in R} \sum_{i \in S} e_{i,s,r} - \frac{\beta_2}{2} \sum_{s \in R} \sum_{i \in S} e_{i,s,r}^2 - \frac{\phi}{2} \sum_{s \in R} \sum_{i \in S} \sum_{j \in S} e_{i,s,r} e_{j,s,r} s_{i,j} - \mu_s^S + \mu_r^R) \\ &\times (A_{BM}^M BM_f + A_{r,BM}^P * (\psi s_{f,s,r;-f,s,r} + \mu_f^S + \mu_r^S + \epsilon_{f,s,r}^S)) \\ &- \frac{c_f}{2} e_{f,s,r}^2 \end{aligned} \quad (13)$$

Then the best response function for firm f in standard s for release r is defined by:

$$\frac{\partial E(\Pi_{f,s,r} \mid I_{f,s,r})}{\partial e_{f,s,r}} = (-\beta_1 - \beta_2 e_{f,s,r} - \frac{\phi}{2} \sum_{j \neq f j \in S} e_{j,s,r} p_{j,s,r} s_{f,j}) * (A^M_{BM} BM_f + A^P_{r,BM} * SEP_{f,s,r}) - c_f e_{f,s,r} = 0 \tag{14}$$

Rearranging, I can write the optimal effort $e^*_{f,s,r}$ of firm f as a function of the optimal efforts of the the other firms in the group $e^*_{j,s,r}$, the observable variables previously defined, and the set of parameters of the model. That is:

$$\begin{aligned} e^*_{f,s,r} = & -\beta_1 \frac{A^M_{BM} BM_f + A^P_{r,BM} * (\psi s_{f,s,r;-f,s,r} + \mu^S_f + \mu^S_r + \epsilon^S_{f,s,r})}{c_f + \beta_2 (A^M_{BM} BM_f + A^P_{r,BM} * (\psi s_{f,s,r;-f,s,r} + \mu^S_f + \mu^S_r + \epsilon^S_{f,s,r}))} \\ & - \frac{\phi}{2} \sum_{\substack{i \in S \\ i \neq f}} \frac{A^M_{BM} BM_f + A^P_{r,BM} * (\psi s_{f,s,r;-f,s,r} + \mu^S_f + \mu^S_r + \epsilon^S_{f,s,r})}{c_f + \beta_2 (A^M_{BM} BM_f + A^P_{r,BM} * (\psi s_{f,s,r;-f,s,r} + \mu^S_f + \mu^S_r + \epsilon^S_{f,s,r})} e^*_{j,s,r} p_{j,s,r} s_{f,j} \end{aligned} \tag{15}$$

Then the matrix representation of the game becomes:

$$\underbrace{\begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_{N_s} \end{bmatrix}}_{\mathbf{E}_{N_s \times 1}} = \underbrace{\begin{bmatrix} -\beta_1 C_1 \\ -\beta_1 C_2 \\ \vdots \\ -\beta_1 C_N \end{bmatrix}}_{K_{N_s \times 1}} - \underbrace{\begin{bmatrix} \frac{\phi}{2} C_1 \\ \frac{\phi}{2} C_2 \\ \vdots \\ \frac{\phi}{2} C_N \end{bmatrix}}_{\mathbf{V}_{N_s \times 1}} \circ \underbrace{\begin{bmatrix} 1_{1,1} & \dots & 1_{1,N_s} \\ 1_{2,1} & \dots & 1_{2,N_s} \\ \vdots & \ddots & \vdots \\ 1_{N_s,N_s} & \dots & 1_{N_s,N_s} \end{bmatrix}}_{\mathbf{Ones}_{N_s \times N_s}} \circ \underbrace{\begin{bmatrix} s_{1,1} & \dots & s_{1,N_s} \\ s_{2,1} & \dots & s_{2,N_s} \\ \vdots & \ddots & \vdots \\ s_{N_s,N_s} & \dots & s_{N_s,N_s} \end{bmatrix}}_{\mathbf{S}_{N_s \times N_s}} \times \underbrace{\begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_{N_s} \end{bmatrix}}_{\mathbf{E}_{N_s \times 1}} \tag{16}$$

where

$$C_f = \frac{A^M_{BM} BM_f + A^P_{r,BM} * (\psi s_{f,s,r;-f,s,r} + \mu^S_f + \mu^S_r + \epsilon^S_{f,s,r})}{c_f - \beta_2 (A^M_{BM} BM_f + A^P_{r,BM} * (\psi s_{f,s,r;-f,s,r} + \mu^S_f + \mu^S_r + \epsilon^S_{f,s,r})}$$

Then I can write the game as:

$$\mathbf{E}^*{}_{N_s \times 1} = \mathbf{K}_{N_s \times 1} + \mathbf{W}_{N_s \times N_s} \circ \mathbf{S}_{N_s \times N_s} * \mathbf{E}^*{}_{N_s \times 1} \tag{17}$$

where

$$\mathbf{W}_{N_s \times N_s} = \mathbf{V}_{N_s \times 1} \circ \mathbf{Ones}_{N_s \times N_s}$$

5.7 Second stage equilibrium

The Nash equilibrium of this stage of the model is the vector of efforts exerted by each firm, for which every firm is maximizing its expected profits given that all other firms in the group are doing so. Taken participation as given, in equilibrium each firm is exerting the effort that maximises its profits given that all the other firms are also playing their best response. This corresponds to the fixed point on firms' efforts.

As can be seen in Equation 15 the reaction function of each firm are linear on others firms' effort. This allow me to solve the model just by inverting the matrices in Equation 17. Then the equilibrium of the model becomes:

$$\mathbf{E^*}_{N_s \times 1} = (\mathbf{I}_{N_s} - \mathbf{WS}_{N_s \times N_s})^{-1} * \mathbf{K}_{N_s \times 1} \tag{18}$$

5.8 Participation decision

Revisiting the first stage of the model, each firm simultaneously chooses in which group to participate. In line with the empirical evidence presented in subsection 4.4, I model a firm's participation decision based on: (i) expected revenues; and (ii) the fixed cost of participating. Firms generate their expectations over standardization profits according to the model presented in the previous section.

Firms face a fixed cost of participating in each standardization group. An important part of this fixed cost is the technological knowledge a firm must have to participate in the development of a given standard. Firms have to invest resources (engineers' hours) in order to understand the group goal and assess its potential for the firm. If the standardization group is working in a field completely unrelated to a firm's technological expertise, the fixed cost is higher. As I show in subsection 4.4, the fit between the technological need of the standard under development and the firm's technological knowledge is an important determinant of firm participation. I therefore 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:

$$FC_{f,s,r} = \underbrace{\gamma_0^{FC}}_{Constant} + \underbrace{fit_{f,s,r}}_{\text{Firm-Standard fit}} + \underbrace{\gamma_f}_{\text{Firm specific FC}} \tag{19}$$

where:

$$fit_{f,s,r} = M(Broadness_{s,r}, Portfolio_{f,r}; \gamma^{fit})$$

where γ_0^{FC} represents a constant fixed cost common to all firms in the market, $fit_{f,s,r}$ refers to the fit between the firm's technological expertise and the standard's requirements, and γ_f is a firm-specific constant term accounting for the unobserved heterogeneity in firm standardization capacity. An example of such unobserved heterogeneity is the number of potential groups in which a firm might be able to participate. Keeping in mind the evidence presented in subsection

4.4, I model the fit between firm and standard as a function M of the standard's broadness $Broadness_{s,r}$ and the firm's technological capacity, proxied by the size of its patent portfolio $Portfolio_{f,r}$.

Participation condition (Revealed Preference assumption): If $p_{f,s}$ is the participation decision chosen by firm f in standardization group s, then

$$\mathbb{E}(\Pi_{f,s}(p_{f,s}) - F_{f,s}(p_{f,s}) + \epsilon_{f,s}^{p_f} \mid \mathcal{J}_f) \geq \mathbb{E}(\Pi_{f,s}(1-p_{f,s}) - F_{f,s}(1-p_{f,s}) + \epsilon_{f,s}^{1-p_f} \mid \mathcal{J}_f) \quad (20)$$

where $(\Pi_{f,s}(p_{f,s})$ and $F_{f,s}(p_{f,s})$ are the second-stage profits and fixed costs of choosing $p_{f,s}$, respectively. $\epsilon_{f,s}^{p_f}$ represents the unobserved part (to the researcher) 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.

Without lost of generality, assume that firm f participates in standard s. Then, adding Equation 11 I can write Equation 20 as:

$$\begin{aligned}&(MT - \underbrace{TTD(e_f^*, e_{-f}^{*p_f=1})}_{\text{TTD if part.}}) \times \underbrace{(A_{BM}^M + A_{r,BM}^P SEP_f)}_{\text{Revenues of part.}} - c_f e_f^{*2} - F_f + \epsilon_{f,s}^{part} \\ &\geq (MT - \underbrace{TTD(0, e_{-f}^{*p_f=0})}_{\text{TTD if no part.}}) \times \underbrace{(A_{BM}^M)}_{\text{Revenues of not part.}} + \epsilon_{f,s}^{npart}\end{aligned} \quad (21)$$

where $TTD(e_f^*, e_{-f}^{*p_f=1})$ is the time it takes to develop the standard if firm f participates, exerting optimal effort e_f^*, and, given that firm f participates, the other firms $-f$ exert their optimal effort $e_{-f}^{*p_f=1}$. Note that a firm's outside option of participating is not zero. The standard will still be developed in a counterfactual time, $TTD(0, e_{-f}^{*p_f=0}$, given that firm f would exert no effort and the other firms in the group would exert their optimal effort $e_{-f}^{*p_f=0}$ accounting for the non-participation of firm f.

I simplify notation in Equation 21 and write the participation condition as:

$$p_{f,s} = 1 \iff \Delta(\Pi_{f,s}) - FC_{f,s} \leq \epsilon_f^{p_f=0} - \epsilon_f^{p_f=1} \quad (22)$$

where $\Delta(\Pi_{f,s})$ represents the difference between the expected second stages profits if firm f participates and if it does not. Recall that this is a full information game, 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 equilibria. It does not rule out multiple equilibria and it does not assume anything about the selection mechanism used when there are multiple equilibria. To overcome the problem of multiple equilibria, I assume that only one equilibrium is played out in the data, following most games of incomplete information (see Bajari, Hong and Nekipelov (2013) for a survey on game estimation)

6 Estimation and Identification

The unknown model parameters $\bar{\theta}$ are: (i) the set of parameters in the time production function parameters $\bar{\theta^T}$ entering Equation 5; (ii) the set of parameters in the SEP function $\bar{\theta^S}$ in Equation 8; (iii) the market revenues 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 entering Equation 7 and Equation 17; and the set of F fixed costs parameters $\bar{\gamma}$ in **??**

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

where:

$$\bar{\bar{\theta^T}} = \{\beta_0, \beta_1, \beta_2, \phi, \mu^T_f\}$$

$$\bar{\theta^S} = \{\psi, \mu^S_f, \mu^S_r\}$$

$$\bar{\gamma} = \{\gamma^R, \gamma^B, \gamma^P, \gamma_f\}$$

To estimate the parameters in my structural model, I rely on a 3-stage procedure. I first estimate the parameters in the time production function$\bar{\theta^T}$ and the SEP equation $\bar{\theta^S}$, relying on Equation 6 and Equation 9 for their identification. I then use those estimates and the equilibrium equations of the model (Equation 18) to calculate the moments, which I then match to key moments of the data. 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 to $\epsilon^{p=1}$ and $\epsilon^{p=0}$ and estimate $\bar{\gamma}$ by maximum likelihood.

Estimation and identification of the profit function parameters

Identification of β_1, β_2, ϕ, ψ , μ^S_f relies on the parametric assumption on the distributions of $\epsilon^T_{s,r}$ and $\epsilon^S_{f,s,r}$ and the classic moment conditions derived from the orthogonality assumption in Equation 5 and Equation 8:

1. $\mathbb{E}[\epsilon^T_{s,r} \mid e_{f,s,r}, \mathcal{J}_{f,s,r}] = 0$

2. $\mathbb{E}[\epsilon^S_{f,s,r} \mid s_{f,s,r;-f,s,r}, \mathcal{J}_{f,s,r}] = 0$

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 choose the following $m(\theta)$ moments:

1. The average effort per firm business model, across standards and releases: 1 moment per business model.

2. The average effort per release, across firms and standards: 1 moment per release.

3. The average effort per firm, across standards and releases: 1 moment per firm.

The first set of moments in $m(\theta)$ exploits the variation in effort across firm's business model to identify A^M_{BM}. I assume that the 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^M_{BM} relies on the idea that the difference between the effort exerted by two firms with different business model, but otherwise have the same characteristics and expect to have the same number of SEPs, must be driven by their expected selling revenues.

Identification of $A^P_{r,BM}$ comes from the variation of effort across releases. Assuming that the value of SEPs is the only component of the profit function that varies exclusively across releases, then the variation across releases should reflect the changes in the value of SEPs.

Finally, I assume that a firm's marginal cost does not vary across standards or releases. Therefore, everything else equal, two firms exert different levels of effort because of the difference in their marginal costs. Then the identification of μ^c_f comes from the variation in average firm effort across standards and releases.

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 cost function distribution. Particularly, I use $\sigma = 0.1$.[41]

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

$$(m(\theta) - m_d)'\Omega(m(\theta) - m_d)$$

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

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

be easily computed in closed form, I resort to simulation-assisted methods. More precisely, I take 10 random draws from a $lognormal(\mu_f^c, \sigma^2)$ and for a particular value of θ, I solve the model for each of these simulations.[42] I then average across simulations to obtain the moments of the model for this particular value of θ. I compute standard errors following combining standard delta method with bootstrap method in order to account for the uncertainty in both stages.

Participation model

The participation model of this paper can be linked to the class of discrete full information choice models applied to oligopolistic markets. The standard approach to the estimation of this type of entry models relies on assuming that firm profits are declining in rivals' decisions(Bresnahan and Reiss (1991*b*), 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 efforts. Another standard approach to solve this 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 (1991*a*)). I rely on this last approach. I rely on Nash equilibrium concept, and use the observed equilibrium to derive firms' (unobserved) choice set. Starting from the observed equilibrium in each group, I consider the vector of observed participation decisions when only 1 firm deviates at a time as a feasible unobserved group configuration. Figure 7 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 local deviation approach, I consider the group in which only firm C or A participates as a potential group configuration, as well as a configuration in which all three firms participate. The number of potential unobserved group configurations following this approach is exactly the number of game players, which in my game is 35. Recall that to compute each firm's expected profits, in each group, I need to compute all the remaining 34 firms optimal effort decisions. This means solving the model 35 times per standardization group

Figure 7: Actual and counterfactual Group configurations

Obs. goup configuration	**Local deviation alternative**		
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**

[42] I also computed the moments using 100 simulations. 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 increased the computational time to more than 15 hours. Estimating standard errors by bootstrapping would take an incredible time using 100 draws.

Estimation of the participation model parameters

I assume unobserved participation terms $\epsilon_{s,r}^{part}$ and $\epsilon_{s,r}^{npart}$ in Equation 22 are identically and independently distributed across firms and standards with a type I extreme value distribution. Then, the probability of firm f participating in standard s is:

$$Prob(p_{s,r} = 1) = \frac{exp(\Delta\Pi_{f,s} - FC_{f,s})}{1 + exp(\Delta\Pi_{f,s} - FC_{f,s})} \tag{23}$$

where $\Delta(\Pi_{f,s})$ represents the difference between the expected second stage profits if firm f participates and if it does not, defined in Equation 7, and FC is the fixed cost defined in Equation 19. To compute $\Delta(\Pi_{f,s})$.

After constructing the counterfactual group configuration for each standardization group and computing the corresponding $\Delta(\Pi)$, I proceed to estimate the participation parameters in Equation 22 by maximizing the likelihood function corresponding to the probabilities in Equation 23.

7 Estimation Results and fit of the model

Table 7 shows estimates for the direct effect of effort and the cooperation and competition effects. All average point estimates of the coefficients of interest are significantly different from zero at a 5% confidence level.

Table 7: Time production function and SEP estimates

	Individual effect of effort ($-\beta_1$)	Effort's 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
Standard charact.	Yes	Yes	Yes	Yes
Release FE	Yes	Yes	Yes	Yes
Standard FE	No	No	No	No
Firms FE	No	No	No	Yes
N	1,880	1,880	1,880	2,824
R^2	0.5650	0.5650	0.5650	0.08

Errors are robust to heteroskedasticity.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The positive sign of the cooperation effect suggest that efforts exerted by different firms and their knowledge similarity are indeed complements. The same amount of effort provided by firms that are 0.1 closer technologically reduces the expected time to finish the standard by 0.0075 days. I also find that each contribution reduces the expected standardization time non-linearly. The significant and negative coefficient of β_2 suggests that there are decreasing marginal returns in the effort provision. That is, on average, the first contribution reduces standardization time in 0.2243 days,[43] while the second one only saves 0.2201 days. Standards require time to be developed, and the effort provided by participating firms can reduce it up to a point. Given that the time it takes to develop a standard reduces potential revenues from sales, the *cooperation effect* here generates an incentive for firms to exert more effort when teaming up with other firms specialized in similar technologies.

Column number 4 of Table 7 shows that firms working in the same group with technologically similar firms expect to have a lower number of SEPs. The point estimate of the ψ parameter suggest that an increase of 1% in the average similarity of the other firms in the group reduces the expected number of SEPs by 0.41% for a firm. Contrary to the *cooperation effect*, the *competition effect* generates incentives for firms to exert less effort when teaming up with other firms that are specialized in similar technologies.

Table 8: Downstream revenues and SEP value estimates

Panel A: Estimates of the market revenues parameters

	Pure Upstream A^M_{up}	Vendors 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

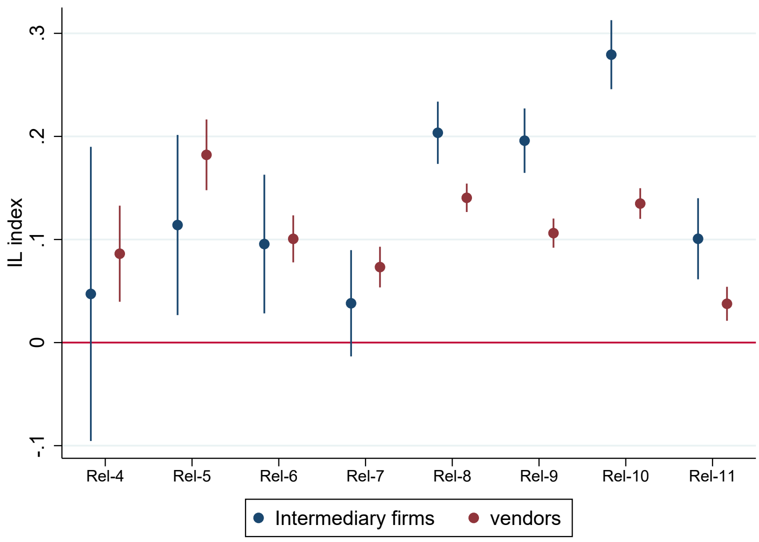
	Rel-3	Rel-4	Rel-5	Rel-6	Rel-7	Rel-8	Rel-9	Rel-10	Rel-11
Upst.	0.55	0.61	0.71	0.78	0.80	1.17	0.91	1.07	0.75
	(0.000)	(0.001)	(0.001)	(0.003)	(0.012)	(0.014)	(0.019)	(0.018)	(0.017)
Vend.	0.51	0.55	0.49	0.00	0.33	0.77	0.36	0.20	0.08
	(0.002)	(0.001)	(0.003)	(0.005)	(0.021)	(0.028)	(0.019)	(0.034)	(0.015)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

Note: Bootstrapped SE in parenthesis. Bootstrap (with reposition) at a standardization group level, 1000 samples.

For the estimation of the remaining parameters of the profit function, I rely on a minimum

[43] The marginal effect of effort on time is 0.2285 - 0.0021 * Number of contributions.

Figure 8: IL index for vendors and intermediary 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

distance estimator as explained in section 6. I use 100 simulation to compute each of the model's moments. Table 8 presents the structural parameter estimates.

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 which captures the relative importance of royalty revenues with respect to the overall expected revenues from standardization. I define,

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

where $IL_{bm,r}$ is the importance of expected licensing revenues with respect to the total expected revenues from standardization for firms with business model bm in release r. Figure 8 shows the IL index for vendors and intermediary firms, per release. As can be seen in Figure 8, before 4G (from release-8 onwards), the licensing of SEPs had a higher weight in a vendor's profit function compared to that of a firm producing intermediary goods. This changes with 4G, when the licensing of SEPs become more important in general, and particularly for firms producing intermediary goods,for which represents a maximum of almost 30% of the total expected revenues from standardization in release 10.

7.1 Fit of the model

Table 9 compares the empirical moments and the moments calculated from the model at the estimated parameters. Overall, the model matches the moments of the data well: notably, it perfectly captures the average effort per firm business model. Similarly, as can be seen in Figure 9, the model perfectly captures the average firm effort for most of the firms in the sample.

Figure 10 also plots the observed average effort per decile of firms' similarity in the data and the average effort computed from the model at the estimated parameters. Considering that those moments are not targeted when estimating the parameters, the model predicts the non-monotonic relationship between effort and firms' knowledge similarity remarkably well.

Table 9: Model fit - targeted moments

	Data	Model
Upstream firms average effort	0.04512	0.04512
Vendors average effort	0.90027	0.90026
Operators average effort	0.16442	0.16442
Intermediary firms average effort	0.21695	0.21695
Average firms' effort in release-4	0.02075	0.01980
Average firms' effort in release-5	0.02641	0.02696
Average firms' effort in release-6	0.07082	0.07090
Average firms' effort in release-7	0.11904	0.11931
Average firms' effort in release-8	0.31930	0.31969
Average firms' effort in release-9	0.32449	0.32489
Average firms' effort in release-10	0.27032	0.27072
Average firms' effort in release-11	0.16146	0.16162
Average firms' effort in release-R99	0.01417	0.01286

Figure 9: Difference between average effort per firm in the data and the model

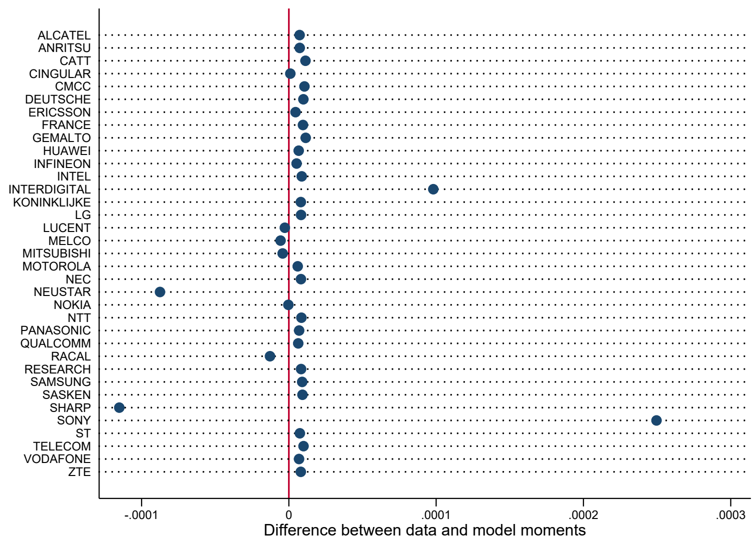
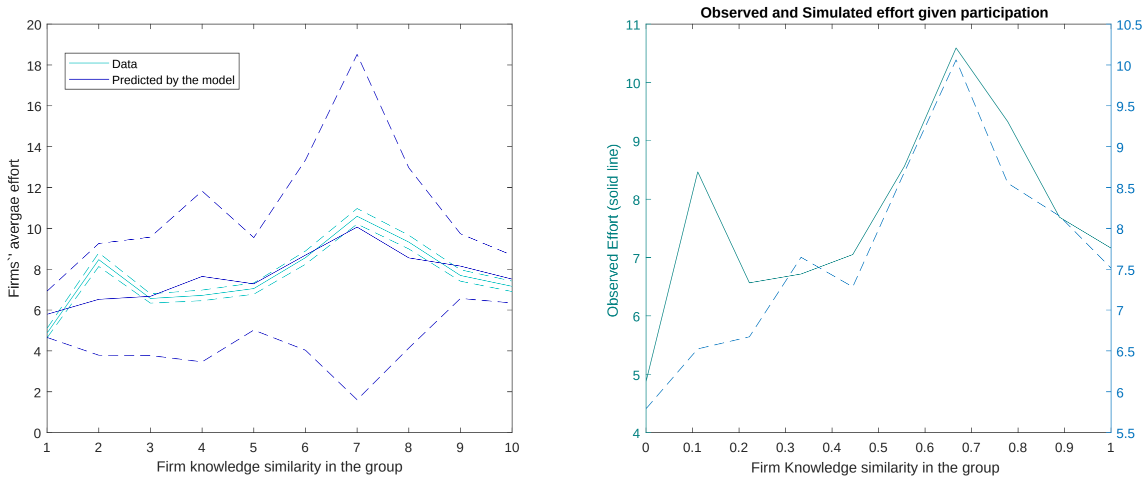


Figure 10: Untarget moments - Effort per firms' similarity decile



8 Counterfactuals

For each counterfactual policy, I compare the predictions of my economic model using the estimated parameters against an economic model in which patents are licensed under different licensing policies but the current FRAND ones. In my counterfactual scenario I allow effort abut also 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, so I follow Lee and Pakes (2009), who suggest a learning process to reduce this burden.[44] In short, the program assumes an ordering of decisions based participation probabilities over all standardization groups. The first firm whether to participate or not as a best response to all other firms' participation decision in the baseline scenario. The second firm similarly best responds, but substitutes participation decision of the first firm with its best response. The third firm similarly best responds, but it substitutes the participation decision of the first and second firm with their best responses. The program cycles through the firms, continually updating the participations decisions, until a 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, a small fraction of those possible. 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

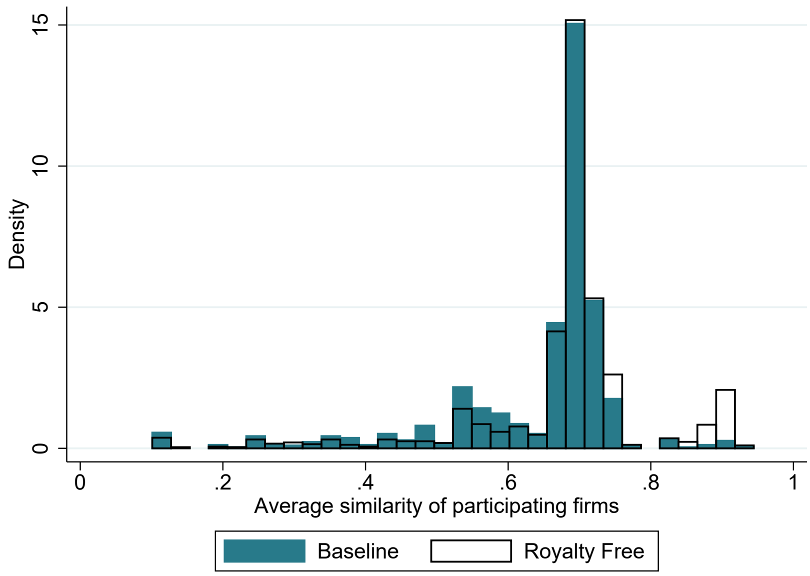
[44]Solve the game implies calculate the potential profits for each firm in each potential group configuration. For each group there are 2^35 potential configuration. Calculating expected profits for each firms implies solving the model $2^35 \times 35$ in each group, which is currently computationally unfeasible.

of the standards. Besides the increment of similar firms working together as can be seen in Figure 11 that fosters the cooperation effect, the restriction on patent licensing would have a big and negative impact on participation (see page 49) and effort decisions. In average, under a Royalty-free licensing policy there would be 7% less firms participating in each standardization group, and they would contribute 18% less.

This results are heterogeneous across firms' business models. While participation of telecomm operators remain unchanged, pure upstream firms would barely participate in this counterfactual scenario, representing less than 1% of overall participants. Intermediary firms would be the second most affecting group, reducing their participation in 10%. Finally, vendors would participate 4% less than in a scenario in which they could license their patents.

This result in an overall increase in standardization time. In the case of the initial releases of 4G, implementing a Royalty-free policy would have delayed its completion by 1 year beyond the 4 years it took to develop it.

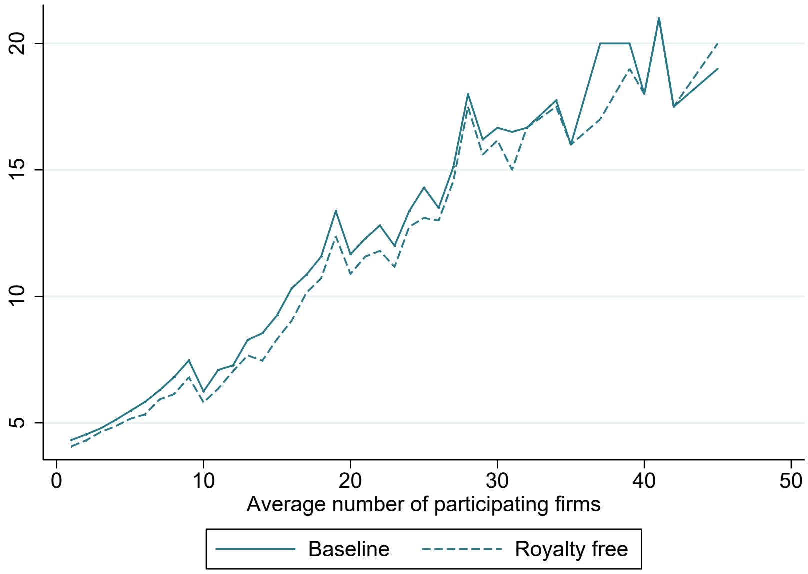
Figure 11: Distribution of average similarity between firms in a standardization group



9 Conclusions

The future of technology is in interconnected gadgets. In order to successfully deploy this interconnectvity, firms in the ICT sector cooperatively develop technological standards in SDOs, many of which include technologies that are protected by patents. The exclusivity provided by these rights may become an impediment to the implementation of standardized technology.

Figure 12: number of participating firms per standardization group



Nevertheless, licensing revenues provide incentives for firms to actively contribute in the development of these standards. This debate over whether such patents cause more harm or good is of special interest for policy-makers, who have so far chosen not to impose any regulation on the licensing of the IP rights for standard-essential technologies. I provide new insights to this debate by developing and estimating a structural model that captures the incentives firms face in the joint development of mobile telecommunication standards. I find that enforcing a Royalty-free policy would delay the development of standards. In the case of the first release of 4G, it would have delayed its completion by 1 beyond the almost 4 years it took to develop them.

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10 Appendix

Figure 13: Estimates of ϕ_q using similarity deciles (95% confidence bands)

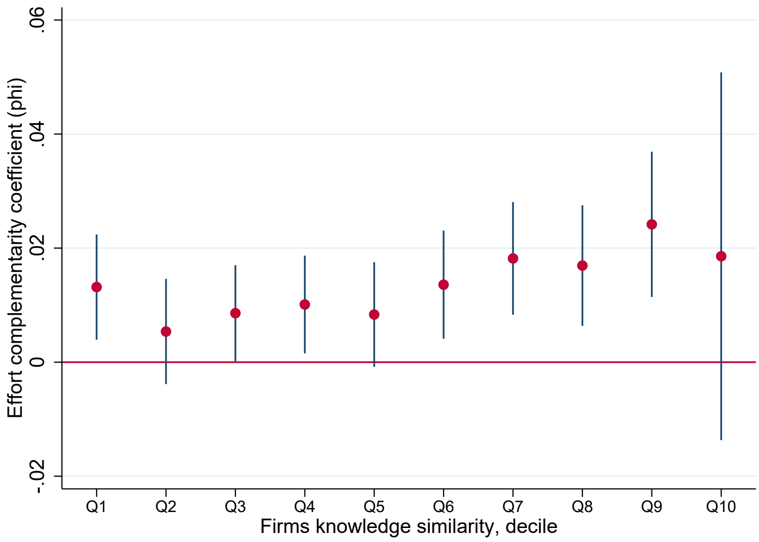

Figure 14: Estimates of ϕ_q using all variables in levels (95% confidence bands)

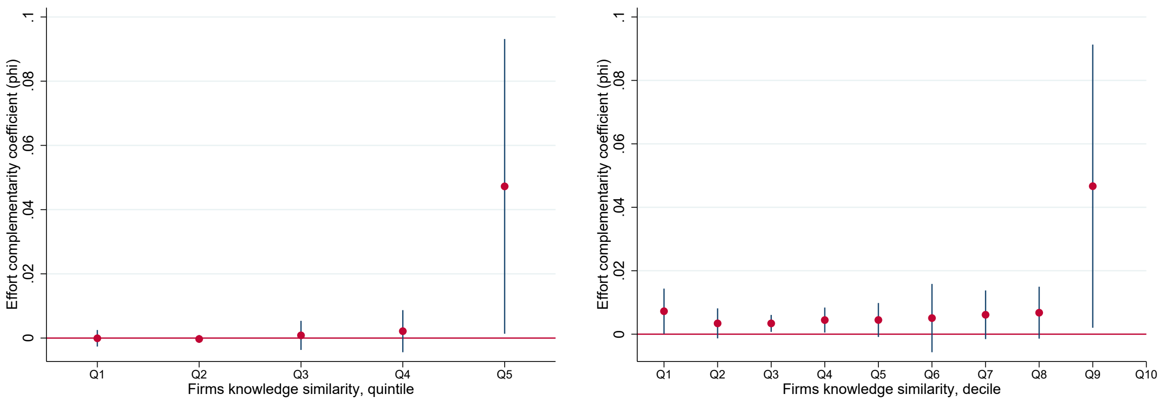

Figure 15: Number of SEPs (Left) and Share of SEPs (Right) over firms' knowledge similarity, no controls (95% confidence bands)

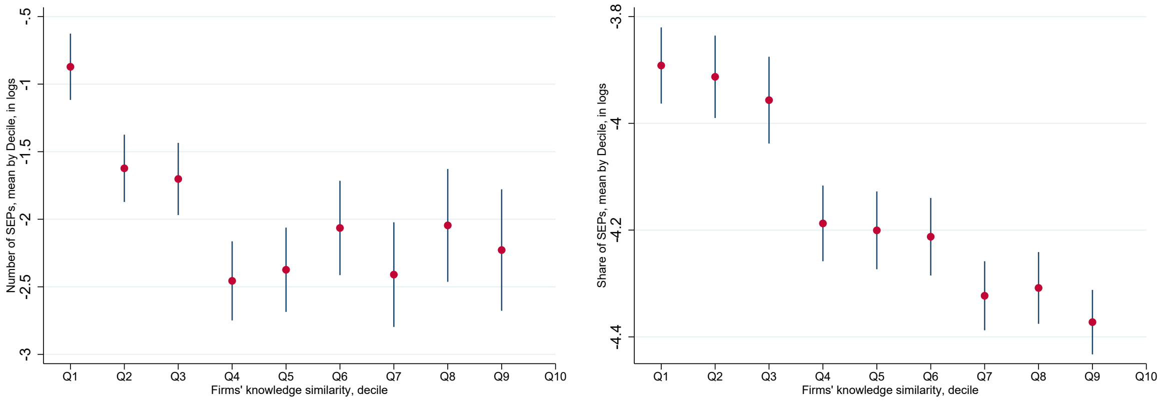

Figure 16: Number of SEPs (Left) and Share of SEPs (Right) over firms' knowledge similarity, controlling by firms fe and number of firms in the group (95% confidence bands)

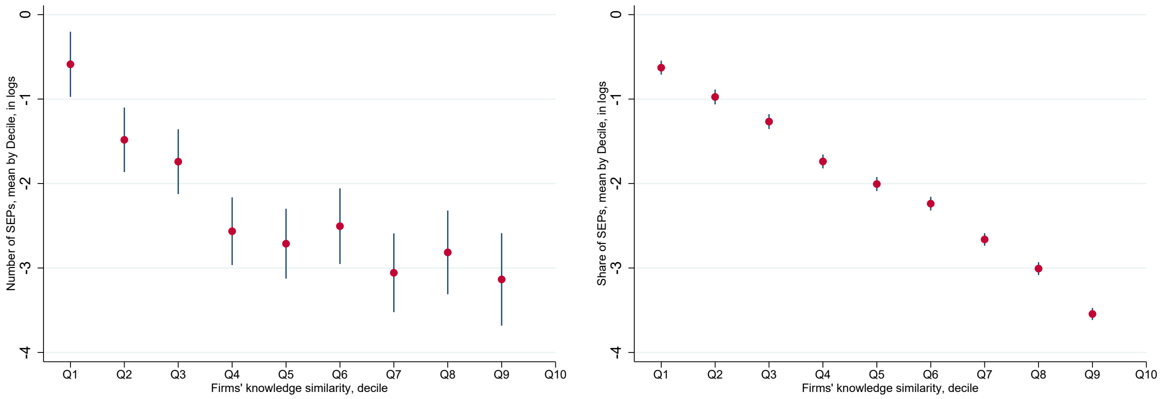

Table 10: SEP and firms knowledge similarity, all coefficients

	(1) Baseline	(2) Controls	(3) Other firms controls	(4) Tobit	(5) Tobit
Firms'knowledge simlarity	-1.723***	-0.875*	-1.286**	-2.470***	-3.204***
	(0.000)	(0.093)	(0.015)	(0.000)	(0.000)
Number of firms	0.956***	-0.0437	0.339	1.566***	2.027***
	(0.000)	(0.860)	(0.169)	(0.000)	(0.000)
Portfolio size		0.131	0.172	0.448	0.495
		(0.534)	(0.418)	(0.315)	(0.282)
Standard's broadness		0.377***	0.321***	-0.204*	-0.248**
		(0.003)	(0.009)	(0.092)	(0.042)
R&D expenditures		0.0924	0.129**	0.0327	0.0672
		(0.103)	(0.023)	(0.767)	(0.543)
First time dummy		-0.124	-0.196	0.302	0.223
		(0.577)	(0.374)	(0.283)	(0.426)
Other firms portfolio			-0.513**		-0.260
			(0.028)		(0.324)
Other firms R&D			1.424***		1.735***
			(0.000)		(0.000)
N	2059	2059	2059	2059	2059
adj. R^2	0.137	0.286	0.300		
Firm FE	Yes	Yes	Yes	Yes	Yes
Release FE	Yes	Yes	Yes	Yes	Yes
Standard FE	Yes	Yes	Yes	No	No

p-values in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$