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Abstract

The introduction of the fifth generation of mobile technology (5G) is expected to bring immense changes. These changes may be much more pervasive than any previous introduction of new mobile "generations", and they are expected to influence the whole economy. For this reason, the global rush for 5G technology is not only considered crucial in economic or technological terms, but also for its implications in terms of policy, geopolitics, and national security issues.

This paper presents an analysis of the patents in the most relevant fields of specialization connected to the 5G development. The period under investigation is from 2010 to 2019, and the data are extracted from the U.S. Patent and Trademark Office (USPTO) database. The analysis shows how the technologies and the specialisations needed to develop 5G are in the hands of a few countries around the globe, and that single European countries, taken in isolation, are not among these leading players. However, Europe, considered as a whole, competes well with the US and Asia in terms of patented innovations, suggesting the economic and strategic relevance of strong cooperation within the EU.

Keywords

5G; Complexity; Patents

JEL CODES

L96, O30, O33

1. Introduction

The debate regarding the 5G development, implementation and disruptiveness is gathering growing attention. This new mobile infrastructure will provide the basis for digitization in many areas of our lives, hence influencing a broad spectrum of sectors (Cave, 2018, Campbell et al., 2017; Rao et al., 2018). The full realisation of the Internet of Things (IoT), which is often called the next Industrial Revolution, relies on 5G development. IoT can be described as a globally distributed network (or networks) of physical objects that are capable of sensing or acting on their environment and that are able to communicate with each other. At present, its adoption is accelerating across different sectors (transportation, manufacturing, agriculture, etc.) where an abundance of smart, connected devices and platforms that are integrated into a wide range of applications, are emerging. As a consequence, *interoperability* stands out as a key concept in the current policy debates concerning the digital economy, since the expected benefits of the Internet of Things and Industry 4.0 hinge on smooth “communication” between objects, networks, software and data.

While IoT adoption is maturing in Europe, with the IoT industry’s spending estimates reaching 127 billion of Euros in 2019[1], the debates related to the 5G leadership are on fire on both sides of the Atlantic. Key concerns emerge because of the growing complexity of 5G technology, which may act as a barrier to new entrants, and because of the vast amount of resources needed to access the growing numbers of patented technologies that are involved in the development of 5G.

In this respect, it is not yet clear how many actors really hold the necessary capabilities, and how difficult it may be for others to acquire ownership of, or access to, them. These aspects may also have policy and strategic implications, both in term of geopolitics and industrial competitiveness, not to mention in relation to national security (Brake, 2018).

The current landscape sees a handful of companies actively involved in the development of the 5G standard. In this respect, there is an increasing debate regarding who is really leading the development of this technology. Many studies rely on the simple counting of patents to determine just who are the leaders in 5G development (see, as example, Pohlmann et al., 2020)[2]. However, this procedure has clear limitations, in fact, other recent studies and reports point out that it is not the simple number of patents that may define who is the leader in relation to this technology, but it is necessary to go beyond this elementary measure and to try to really understand which patents are more or less relevant (Noble et al., 2019; Tsilikas 2020).

This paper addresses the complexity of the technological and business environment of the 5G ecosystem and the related implications for competition and innovation. There exists a growing literature on Economic Complexity (EC) (Hidalgo and Hausmann, 2009; Hartmann et al., 2017; Morrison et al., 2017), which is especially related to knowledge or technological complexity (Balland and Rigby, 2017; Petralia et al. 2017; Broekel, 2019; Balland et al., 2020). Following the seminal works by Hidalgo and Hausmann (2009), the literature on EC suggests that the sophistication of a country’s (or a region’s) productive structure can be analysed by combining information on the *diversity*, in terms of the products exported (how many different products are exported), and their *ubiquity* (how many countries/regions can export that same products). In this paper, this approach was applied to the technologies by looking into the embodying patents: like products, some technologies are also more difficult to develop or to replicate than others. This has to do with the number of different specialisations needed to develop them and to the relative rarity of these specialisations.

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1 IDC Worldwide Semi-annual Internet of Things Spending Guide, 2019. The study is available at the website: https://www.idc.com/getdoc.jsp?containerId=IDC_P29475

2 Who is leading the 5G patent race? A patent landscape analysis on declared 5G patents and 5G standard contributions, Iplytics, November 2019, p. 4.

The present study will exploit these ideas in order to explore some aspects as diverse as the technologies, ubiquity and complexity of 5G that may amplify the difficulties in accessing the technology, so as to effectively go beyond previous studies that use the counting of patents to identify which company or country is leading in the development of 5G (Pohlmann et al., 2020). In particular, our work investigates whether the technological complexification is likely to lead to a situation in which only a few actors around the globe develop, and hold the keys to, 5G.

The work is organised as follows. After this introduction, Section 2 presents a brief account of the "generations" of mobile technologies that preceded 5G; the concept of complexity is also introduced. Section 3 illustrates the research design of the study, describing the data sources and the construction of the indicators. Section 4 presents and discusses the main results of the analysis. Section 5 concludes, and also suggests leads for further research.

2. Background to 5G

2.1 The evolution of "Generations" of technologies in mobile communication

The evolution of the technological path of wireless communication technology started at the end of the nineteen seventies with a network that had only voice call capabilities. This was defined as 1G only after the development of the following generation (2G), probably the most enduring mobile generation. 2G played a critical role in evolution and diffusion, as the popularity of mobile technologies experienced and presented the first huge growth in terms of the numbers of users. This second-generation continued to be dominant, with few advancements, until the introduction of the 3G generation at the beginning of the 2000s. The introduction of 3G was very important, causing sizable technological advancements in the networks, especially in relation to data transmission. In fact, the speed of transmission with the implementation of 3G increased to an average of 1.5Mbps, a dramatic increase in respect of the previous generation. The effect was that this increase in speed enabled wider use of the technology and, particularly, the first rise in the diffusion of smartphones, instruments able to use e-mails, fast browsing, communications and streaming videos. At the end of the first decade of the last millennium, 4G was introduced. The Long Term Evolution (LTE) 4G standard, offered a huge increase in the mobile networks' speed (up to 150 Mbps), enabling the arrival of new sectors of activity for millions of consumers with a host of new services (live gaming, conferencing, high definition video streaming, etc.). However, due to the fact that the latency of 4G technology is around 50ms, and is hence still too slow for real-time responses, researchers started to develop 5G almost simultaneously with the introduction of the 4th generation.

In all cases, during the last three decades, the telecommunication industry experienced a dynamic equilibrium, which was characterised by frequent additional updates of the technological "generations", which happened almost every decade (Cave, 2018). This dynamic was sustained by a widespread technological change (Oughton et al., 2018; Curwen and Whalley, 2004; Han and Sohn, 2016) obliging the operators of the telecommunication industry to continuously innovate and adapt to the new technologies (Asimakopoulos and Whalley, 2017). Nonetheless, even if the industry is used to technological change and new generation developments, sometimes with more than incremental improvement in term of performances, the fifth generation of mobile telecommunication promises to offer a much deeper change than has ever previously occurred (Teece, 2018).

The discussion on the strategical relevance of 5G is flourishing, and many scholars suggest that this generation will lead a new industrial revolution, well beyond the mobile telecommunications industry, for the pervasive dimension of this technological jump (Cave, 2018; DCMS, 2018; Oughton et al., 2018; Teece, 2018). In particular, the implementation of 5G, due to the tremendous increase in the speed of transmission (see Table 1), its larger bandwidth and, particularly, the improvements in relation to latency, which will cause a five-fold reduction (on average, from 50ms to 10ms), is expected to enable the development of new fields of application, favouring the rising of IoT solutions (Teece, 2018).

***Table 1.* Speed of the different "generations"**

Generation	2G	3G	4G	5G
Max speed	0.3Mbps	7.2Mbps	150Mbps	1-10Gbps
Average speed	0.1Mbps	1.5Mbps	10Mbps	?

While the contours of the revolution may still be fuzzy, it appears clear that 5G technology is expected to introduce immense changes beyond the telecommunication industry, which are expected to be much more pervasive and disruptive than those experienced after the introduction of any previous "generation" (Cave, 2018). These pervasive changes are expected to reach and influence the whole economy: for this reason, 5G competition is not considered only a matter of economic, or of technological competition among companies, but also has huge implications in terms of policy, geopolitics and national security issues (Brake, 2018).

The exact areas in which the 5G will show its major relevance are still being debated and, as was true for previous generations, the applications will certainly cover more fields than had been expected (Campbell et al., 2017). However, there is a relatively unanimous consensus regarding the application to the following rising fields that will be enabled by the new "generation" of networks. In the first place, the IoT's application to services, and the growing interest in devices, will be able to facilitate our lives in the so-called smart home and smart city domains (Aazam et al., 2018, Goudos et al., 2017). It is expected that, in the next few years, we will employ more than 20 billion objects needing fast connections (Hung, 2017). Other specific sectors of activity where 5G is considered to be a key enabling technology are healthcare, the automation of vehicles, industrial manufacturing, logistics and smart farms (Anwar and Prasad 2018). In addition, the increased speed and the lower latency will support more efficient data transmission through improved network coverage and capacity, and thus will foster the efficiency of tools, such as augmented reality, and many other activities and personal experiences that need strong data transmission that were limited by insufficient speed, stability and latency with 4G (Hsieh, 2018; Chang, 2019).

In conclusion, it is possible to affirm that 5G is the first mobile technology that has emerged that has a General-Purpose-Technology (GPT), one that almost has the same standing as electricity or the Internet. According to the economic literature, GPTs are characterized by their pervasiveness across most sectors of the economy, by their fast evolution, and by the ability to enable further products' or process's innovation. In general terms, these technologies are developed in ways that can be employed by different potential downstream licensees and that can accommodate their different strategies.

For firms with important knowledge assets, the development of general-purpose technologies has emerged as a novel alternative to applied, specialized, commercially mature technologies, boosting new 'markets for technology', in which firms will sell rights that are related to their IP, rather than products and services that are based on their knowledge capital. Markets for technology, in the case of 5G and IoT, are evolving quickly and are expected to grow at a swift pace in the next few years.

2.2 The increasing complexity of 5G technologies

The growing globalisation, leading to a decrease in transportation and mobility costs, continuously changing labour markets, advancements in the information and communication technologies and growing purchasing power, has led, particularly in the advanced world, to a shift from competition that is based on price, to a more advanced competition that is mainly based on innovation and design. This means that a growing number of specialisations are needed in order to remain competitive (Hartmann, 2014). This state of affairs has led to more and more complex and specialised organisation of production, with leading companies, particularly in such innovative fields as mobile telecommunication, specialising in new and increasingly complex technologies so as to climb the ladder of technological complexity (Petralia et al., 2017). This increased complexity may represent an additional obstacle for countries that lag behind, severely limiting their capability to join the race. In general, only a handful of countries have been actively developing new technologies. The United States, some Western European countries, Japan and South Korea, host a small fraction of the world's population, but they are responsible for most of the technological advances, and if we include China in the group, almost one-third of the world's population is responsible for practically the entire scope of relevant innovations. This is particularly true for the most strategic technologies, such as 5G. In this case, few countries and, particularly, only a few companies, hold the necessary technological capabilities.

Many scholars have attempted to study the knowledge and technological evolution, and the subsequent competition, following the idea of "*complexity*" (Romer, 1990; Hidalgo and Hausmann, 2009; Petralia et al., 2017; Balland and Rigby, 2017; Broekel, 2019). During the last ten years, starting from theories developed by Hidalgo and Hausmann (2009) regarding economic complexity, an increasing stream of research has focused on the growing technological or knowledge complexity (Balland et al., 2020; Petralia et al., 2017) and the tendency of the most complex technologies to be concentrated in only a few countries, and particularly in large cities (Balland and Rigby, 2017).

The concept of complexity, following Hidalgo's seminal work, is based on two main characteristics*: diversity and ubiquity*[3]. The idea is that if many different technological specialisations are needed in order to advance a particular technology, and if these specialisations are also rare, the complexity of the technology will be high. However, among scholars, there is not yet a strong consensus on computational methodology and technical issues, which are still under debate (Tacchella et al., 2012; Inoua, 2016; Broekel, 2019). There are many different ways to define and measure technological complexity (Fleming and Sorenson, 2001; Pintea and Thompson, 2007; Broekel, 2019; Balland et al., 2020), ranging from the simple counting of patents, to the study of the diversity, or the relationship between diversity and ubiquity (Balland and Rigby, 2017), to the structural analysis of networks (Broekel, 2019).

While there is a clear consensus regarding the increasing technological complexity, particularly of such strongly innovative fields as mobile telecommunication, there are a lack of studies connecting complexity to access to technologies. If more complexity will unavoidably lead to a small number of actors around the globe developing and holding crucial technologies, such as 5G, is a matter for both research and policy concerns. For this reason, the present paper aims to explore the nexus between complexity and global competition, following the literature mentioned above, and adopting the research strategy that will be described in the next Section.

3. Research Design for analysing 5G complexity and competition

3.1 The database

The economic literature is still debating many technical issues relating to how to best measure innovation. Patents, notwithstanding the acknowledged limitations that they do not account for all the innovations produced, are largely recognised as being a good proxy for innovation at the aggregate level (Acs et al., 2002; Burhan et al., 2017). Several studies are inquiring into the relevance of technological specialisations for the market development of specific 5G technologies, such as the "5G photonic" (Chang, 2019), or the "network function virtualization" (Hu and Guo, 2019), however, to the best of our knowledge, there are a lack of studies that are related to the technological development of 5G using a

[3] *Diversity* indicates how many different technological specialisations are present in an area, region or country, while *ubiquity* defines how rare these technological specialisations are.

broader perspective (Noh et al., 2016). For this reason, we have decided to focus our research on all the patents that are related to several families of technologies which are relevant to 5G.

The data that we have used were collected from the U.S. Patent and Trademark Office (USPTO) database. While this choice represents a serious limitation to our work, given the imperfect representation of the worldwide patents granted, and the overestimation from the sample of US patents, the USPTO database is often used for global analysis, and is recognised as a reliable proxy for global innovation activities. The US is still the largest commercial market in the world, and many companies seeking IP protection apply to the USPTO, in addition to applying to the patent office of their country of residence. Moreover, with respect to other sources, the USPTO is also considered to be the most relevant repository for emerging markets, if compared to other patent offices (Jaffe and Trajtenberg, 2002; Ivanova et al., 2017). Finally, the aim of this study is not to offer a complete representation of all worldwide patents on 5G, but to have a consistent dataset that is sufficient to investigate the technological specialisations used in building this technology. Analysing the distribution of patents and the increasing complexity of the technology, we investigate how this may lead to increasing difficulties for countries that are lagging behind in joining the global race to 5G.

The first phase of the study is devoted to the identification of the most relevant technological categories of patents for the development of the 5G. Of course, the selection of technological categories is tricky, as many different technologies may be useful for the development and the implementation of a GPT like 5G. Being such a pervasive technology, few studies have attempted to elaborate a complete taxonomy for investigating this technology and, until now, there is no consensus on its precise boundaries (Noh et al., 2016; Chang, 2019; Hu and Guo, 2019). For this reason, we have first reviewed the research that already defines technological categories that are relevant to 5G, or to particular fields of 5G technology, and we downloaded all the patents that were assigned during the period 2010-2019 under these codes.

Many of the available studies agree on the focal relevance of certain of the categories of the Cooperative Patent Classification (CPC), namely, those falling under the classes of "electric communication technique", which is coded as H04, "computing; calculating or counting", which is coded as G06, plus those related to data processing "basic electric elements" and "basic electronic circuitry", which are coded as H01 and H03[4].

We then ran a co-occurrence analysis on the technological categories of these classes of selected patents in order to enlarge the database by adding other categories that occurred frequently in relation to patents that are related to 5G. The extraction from the database produced around 750,000 items.

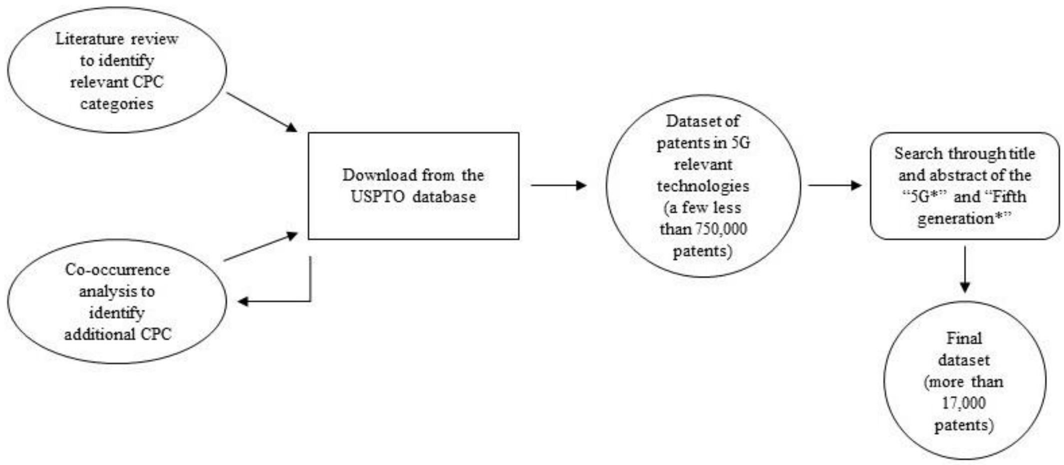
At this point, we finally selected only those patents explicitly referring to 5G in either the title or the abstract, we decided to use the strictest possible keywords to identify the patents that were relevant to 5G, for this reason, we used "5G*" and "Fifth generation*"[5]. In practice, this resulted in a database of those patents granted by the USPTO during the period 2010-2019, derived from all the potential CPC categories that were "5G relevant", but that were **explicitly identified as dedicated to 5G technology,** which gave around 17,000 results. In addition to all the technological categories of each patent, the database includes information regarding the assignee, the country of the assignee, the year of assignment and the univocal patent number.

A summary of the database selection process just described is shown in the following Table.

4 These CPC classes are reported at the 3-digit level (e.g., H04), while the following analysis is performed at the 4-digit level (e.g., H04B): this enhanced level of granularity is necessary in order to clearly understand which are the technological classes that are most involved in the development of 5G.

5 The "*" means that the plural terms and appendices to the keywords were also used.

***Table 2*. Database construction framework**



3.2 Measure of technological specialisation

A critical aspect of measuring competition in technologies is related to how to attribute patents to countries, and many studies on the geography of knowledge using patent data rely on inventors' residence in order to attribute the patent to a specific country, region or city, while other studies prefer to rely on the assignees' residence (Kuan et al., 2011; Nagaoka et al., 2010). In our case, given that the primary aim of the study is not to map where the knowledge is produced, but to identify who holds the patents and is able to translate innovation into production, we choose the location of the assignee, instead of the residence of the inventors, so as to attribute patents to countries.

The next steps in our analysis is to use our database of patents dedicated to the 5G in order to produce a measure of concentration, and then to apply it to the technological categories. This concentration measure will show a picture of how diversified the countries are - with respect to 5G technologies - and how their specialisations are rare, and therefore difficult to autonomously develop by late comers.

Following the literature on technological specialisations and concentration, we measure the *Relative Comparative Advantage* (RCA) of a certain country for a technology with the Balassa formula:

$$RCA_{ct} = \left(\frac{P_{ct}/_{P_c}}{P_t/_{P}} \right) \qquad (1)$$

where P_{ct} represents the number of patents of country c in the technology t, P_c the total number of patents in all the considered technologies for country c, while P_t represents the total number of patents of all the considered countries in technology t and, finally, P represents the total number of patents.

A country showing a value higher or equal to 1 has a comparative advantage in the considered technology, *t*, with respect to other countries. In synthesis, a country is considered to have an RCA in technology, *t*, if it owns more patents than the world average for that sector.

The RCA is at the basis of many of the measures of complexity, regarding products (Hidalgo and Hausmann, 2009; Hartmann et al., 2017; Zhu and Li, 2017), technologies (Balland et al., 2017; Petralia et al., 2017) or industries (Chavez et al., 2017; Innocenti et al., 2020). By using these measures, one can compute the diversity (how many different technological specialisations there are in the basket of each country) and the ubiquity (how rare are these specialisations, on average) of the countries considered.

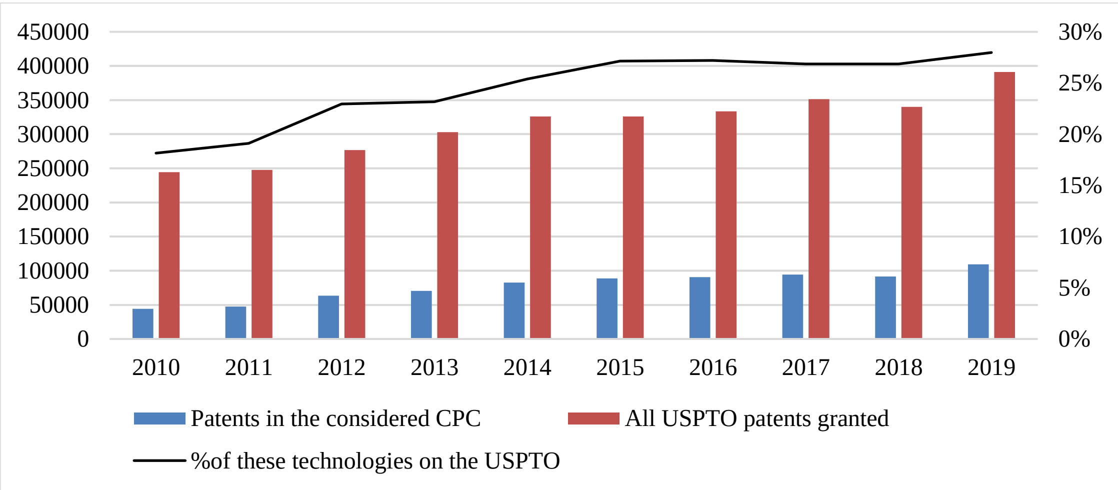
In conclusion, looking at the relationship between the diversity and ubiquity of the selected patents granted during the period 2010-2019 gives us a view on how the 5G technological specialisations are distributed around the world, and which countries hold most of them, especially the rarest.

4. Results and discussion

The number of patents that are somehow related, but not specific, to the 5G technology, as explained above, is close to 750.000, but considering that each patent has, on average, two technological categories, this leads to a total of about 1.5 million records. Since one focus of the present analysis is to examine the entire technological universe related to 5G, we first used this larger database with the purpose of comparing the evolution of these technologies with all the USPTO patents.

Graph 1, below, shows the representativeness of our dataset with respect to all of the patents granted by the USPTO during the period 2010-2019. It is possible to notice that the number of the patents granted by the USPTO strongly increased during the period considered, almost doubling in less than ten years. This trend, however, is even more pronounced for those technologies that are somehow related to 5G, which, at the end of the period, more than double the values of 2010. In percentage, the patents related to technological specializations that are relevant to 5G increased from less than 20% to close to 30% of all the patents granted. An increase that is not surprising, given the spread of the technological competition in these sectors.

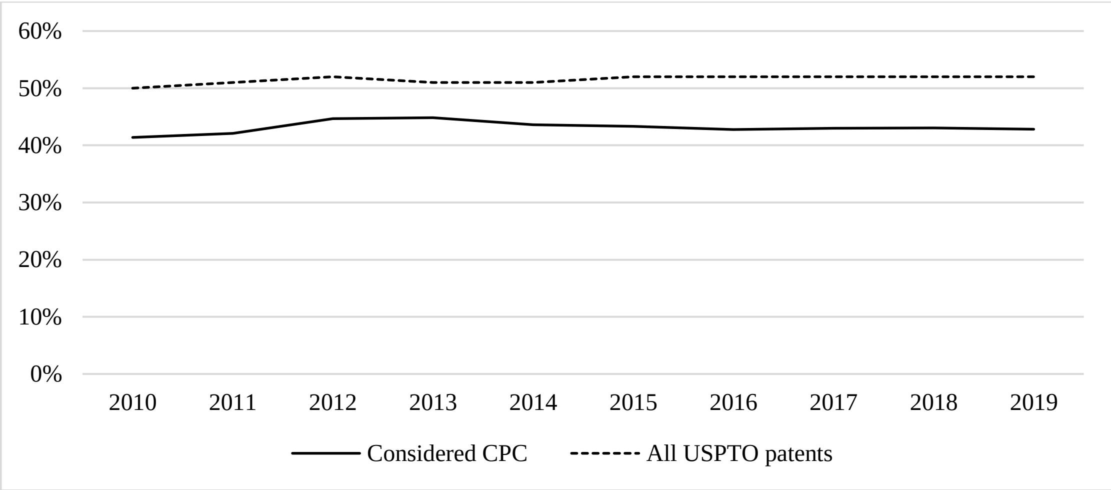
***Graph 1*. Yearly number of patents granted**



Source: our elaborations on the USPTO data.

The information collected in our database gives an interesting first picture regarding the competition surrounding these technologies, which, to a certain extent, may be a first indicator of the capabilities that are needed to enter the 5G race. Graph 2 shows the foreign countries that hold part of the codified knowledge that is related to these technologies. It is possible to notice that the trend in foreign patents in these technologies follows the general trend in relation to all the technologies in the USPTO, but with values lower than 7-8% for the whole period. In these particular technologies, there is a lower presence of patents held by foreign applicants than in all the other technologies.

***Graph 2*. Percentage of patents granted to foreign applicants**



Source: our elaborations on the USPTO data.

Table 3 lists the foreign countries that are present in term of patent assignees in the database. The data show a clear dominance of Asian countries, such as Japan, Korea and China, while European countries follow, in term of patents granted in the CPC considered.

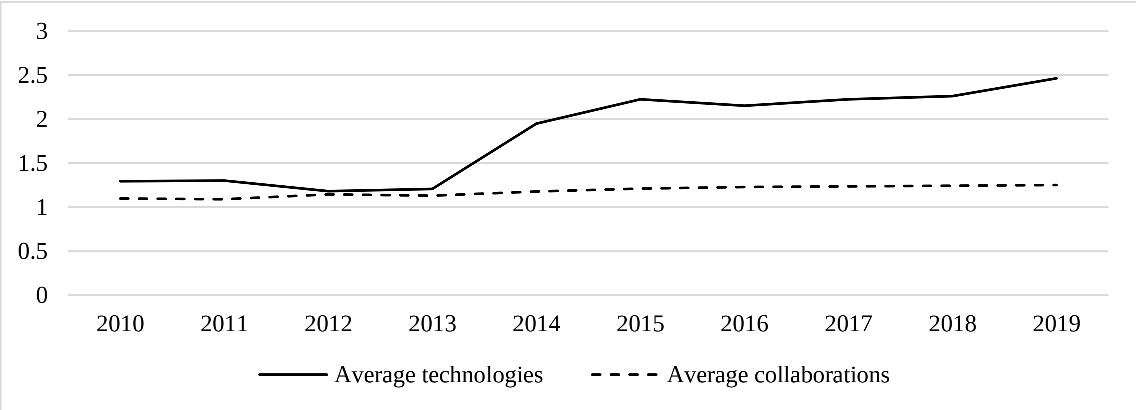
***Table 3.* Most present foreign countries**

Country	% of foreign patents
Japan	32%
Korea	16%
China	8%
Taiwan	7%
Germany	7%
Canada	4%
Sweden	4%
France	4%
Finland	2%
Others	15%

Source: our elaborations on the USPTO data.

After searching the dataset for patents mentioning 5G in their titles and abstracts, we ended up with about 17,000 patents and around 37,000 records. This second number is due to the increase relating to the average number of technological categories to a value of around 2.3 in respect to the value of about 2 in the larger dataset. It is important to observe the evolution, over time, of the number of technological classes involved, and the collaborations among companies in different countries: these data are represented in Graph 3.

***Graph 3*. Yearly average values of technological classes involved in 5G patents co-assignments to different countries**



Source: our elaborations on the USPTO data.

If one considers the average number of technological classes involved in these patents, the results are clear: the number of technological classes involved has strongly increased over time, from a value slightly higher than 1.2 in 2013, to a value of almost 2.5 classes in 2019[6]. This may be due to the evolution of the technology that, in the early years, was developed in separate fields, and that, more recently, has increasingly needed the involvement of different specialisations.

However, it is interesting to note that the companies from different countries appear to develop these new specialisations internally, rather than looking for collaborations outside the country. The values relating to the average number of assignees in different countries who share a patent, do not change much during the period, remaining close to 1, meaning that, in this specific field, it is not common to collaborate beyond the borders of a country. This may be due, as already suggested, to the strong competition between companies in different countries for establishing the supremacy on the technology.

At this stage, following the RCA formulae, which are explained in the methodology section, we computed the specialisation that each country possesses in the technological categories relevant to 5G. Graph 4 shows the values for the diversity and ubiquity of these technological specialisations: it is possible to notice that, as expected, there is a clear negative pattern between diversification and the average ubiquity of specialisations. In fact, countries with a high technological diversification also tend to show a low level of ubiquity, meaning that these countries possess a large basket of technological specialisations, and that they are also specialised in the rarest technologies. This is primarily the case in the US, showing the largest values for specialisations, while South Korea shows the lowest value for the ubiquity of its specialisations. In any case, all the countries in the lower-right quadrant can be considered to be leaders in 5G technology[7].

Those countries appearing in the lower left quadrant are less diversified, if compared to the previous group, but their specialisations remains among the least ubiquitous (rare technologies). This means that, even if their technological basket is not strongly diversified and thus they will probably not be able to

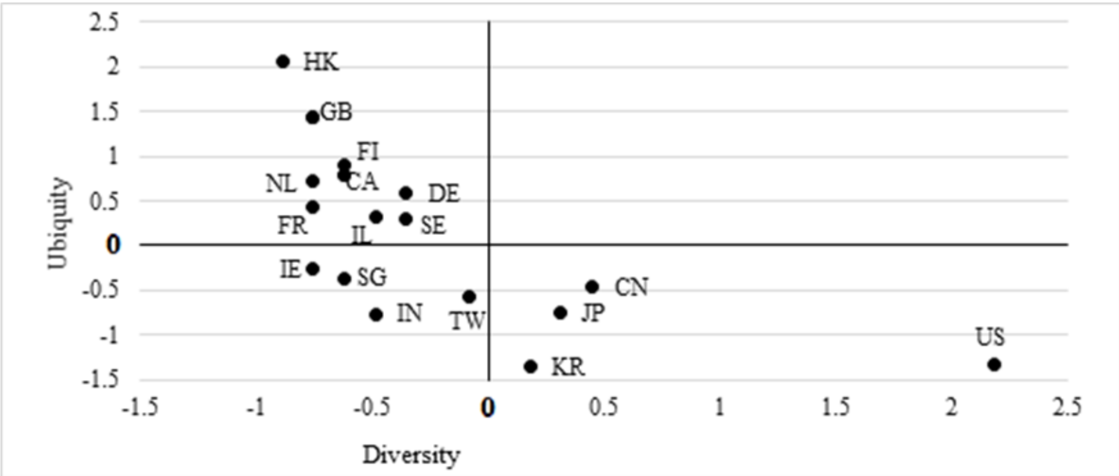
6 In this regard, we refer to the number of technological classes (CPC) to which the patent pertains, and that are reported in each patent initially, by the authors, and that are then screened and validated by the reviewers.

7 To favour the comparisons among different periods, the values of diversity and ubiquity are standardised. The aim of these measures, in fact, is to evaluate the relative position of a country with respect to the others and, thus, after the standardisation, the value of 0 represents the mean of the sample, meaning that if a country has a value higher than 0, it has a number of specialisations that are higher than the average (regarding diversity), or that these specialisations are more common than the average (regarding ubiquity). This also favours the interpretation of the position of the countries in the four quadrants. The countries appearing in the lower right quadrant may be considered to be leaders in both the measures (controlling many and rare specialisations).

compete on the overall development of the technology, they may still contribute to the advancement of rare, and probably essential, technologies that are possesses by only a few other countries. In this group, the extreme position is occupied by India, which shows low values of ubiquity for the relatively few specialisations it possesses.

Finally, the countries appearing in the upper left quadrant, even if listed among innovative countries with respect to 5G, may be considered to be in a less advantageous position. In fact, their specialisations are relatively few and are not among the rarest, meaning that, to be competitive, they have to develop many new technological specialisations and also enter with rarer technologies. Otherwise, they will continue to compete mainly on technologies where the competition is already high. In this group, the extreme positions are occupied by Great Britain and Hong Kong, which show relatively few, and common, specialisations with respect to the other most innovative countries.

***Graph 4*. Diversity and ubiquity 2010-2019 technological specialisations for the most "innovative countries".**



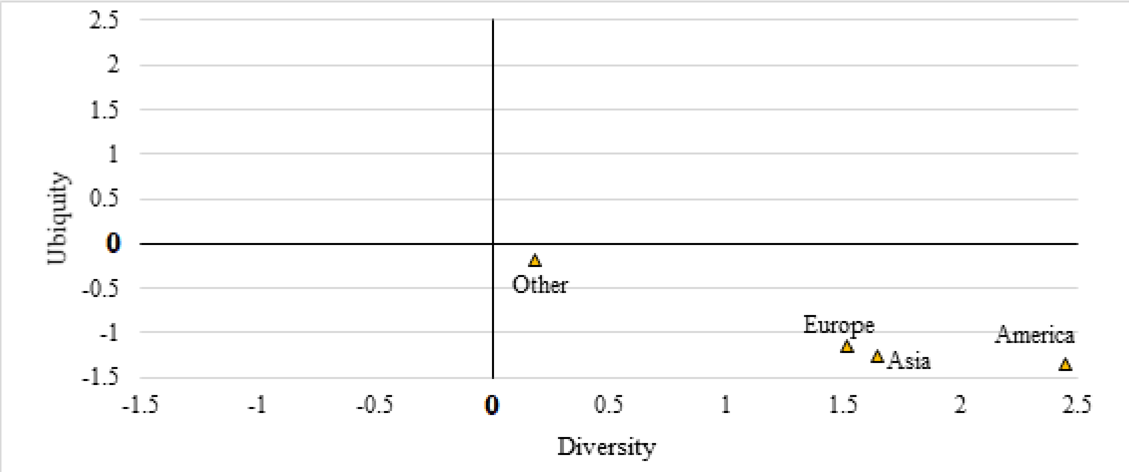
Source: our elaboration

Unfortunately, no European player, not even Finland and Sweden, notwithstanding that they have companies with great innovative traditions in mobile development (Nokia and Ericsson), is present in the leaders' quadrant. Nonetheless, several European players appear in the graph, in fact, beyond Sweden and Finland, Germany, France, Great Britain, the Netherlands, and Ireland are present. Europe is, therefore, present among the innovators in 5G technology, but its capability appears to be strongly fragmented among several different countries.

To give an overview of the specialisations that are present in the different areas of the world for 5G development, we aggregate the values of the specialisations that are present in the four regions considered (America, Asia, Europe, and Others). Interestingly, Graph 5 shows the potentiality for a different story, even if the results need to be considered with caution. In fact, when Europe is considered as a whole, the values of diversity and ubiquity are very close to the values shown for Asia. This clearly points to the industrial opportunity and the effective possibility for an effective EU common strategy in the race to 5G.[8]

[8] In the case of the world's regions, to favour an understanding, the standardisation is applied by also considering the separate countries (Graph 4).

***Graph 5*. Diversity and ubiquity 2010-2019 technological specialisations for world regions. Aggregate values for the period 2010-2019**

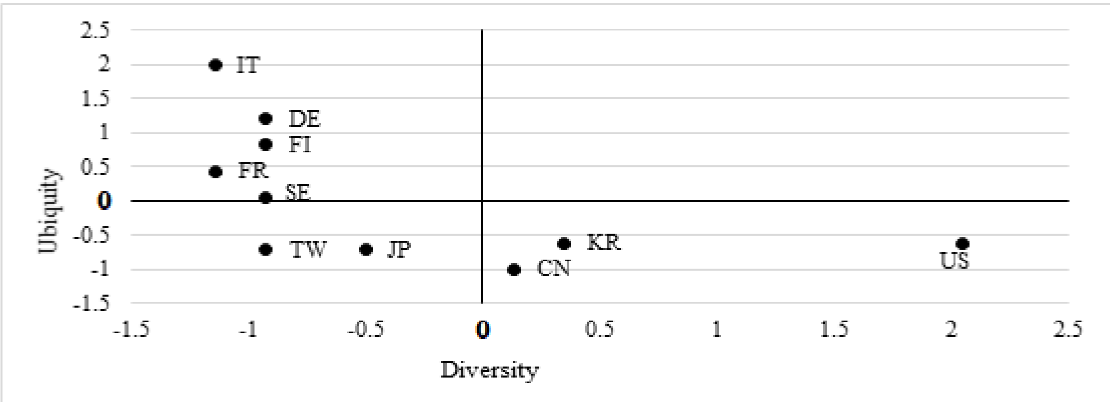


Source: our elaboration

Finally, with Graphs 6 and 7, we split the results of two sub-periods (2010-2014 and 2015-2019) for single countries, and with Graphs 8 and 9, for the same sub-periods, we present the aggregate values for areas of the world, as has already been done in Graph 5.

In these Graphs the evolution of the relationship between diversity and ubiquity in two different phases is depicted: the first roughly corresponding to the beginning of the development of 5G, which is characterised by fewer competing countries (the early adopters) and fewer patents, while the second phase corresponds roughly to the technological implementation phase.

***Graph 6*. Diversity and ubiquity technological specialisations for countries, period 2010-2014.**

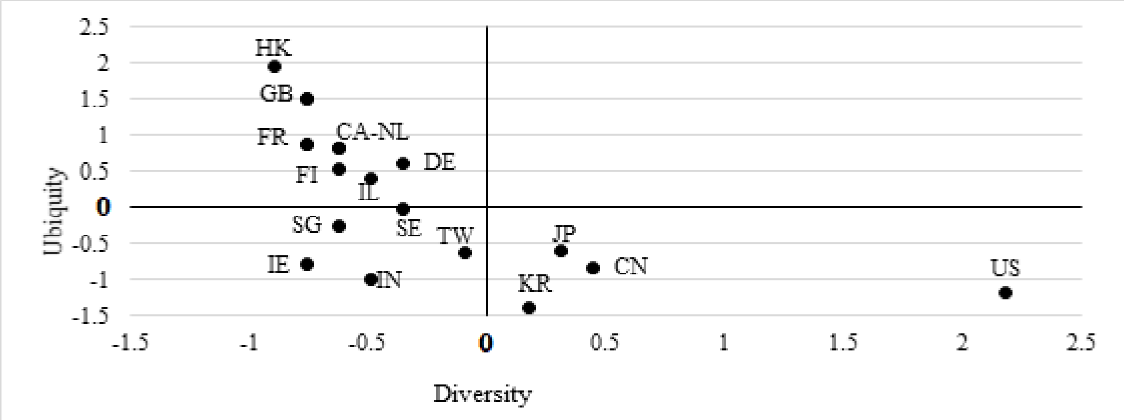


Source: our elaboration

In the first period, the countries that appear in Graph 4 in the lower right quadrant, the leaders of 5G, were already in a good position in term of diversity and ubiquity, primarily the US, China and Korea. European countries appear to be less diversified and, in general, specialised in technologies that are rarer.

It is interesting to notice how a player like Italy, even if with few and relatively common specialisations, was initially able to participate in the innovation race while it no longer appears among the top implementers in the second period. This means that while, at the beginning of the development of 5G, Italian companies were involved in the technological advance of the field, though their innovative capability, during the years of technological consolidation they lost competitiveness with respect to other European and extra-European countries.

***Graph 7*. Diversity and ubiquity: technological specialisations for countries, period 2015-2019**



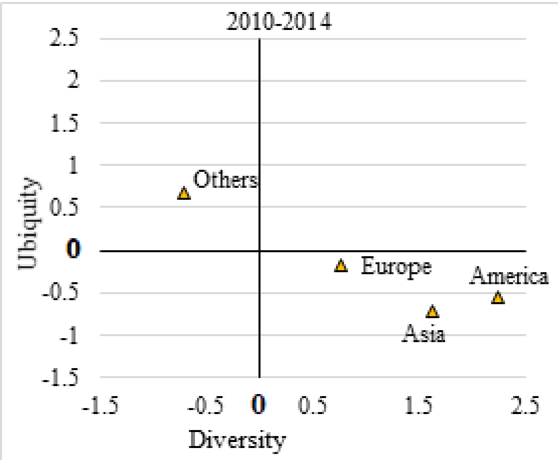
Source: our elaboration

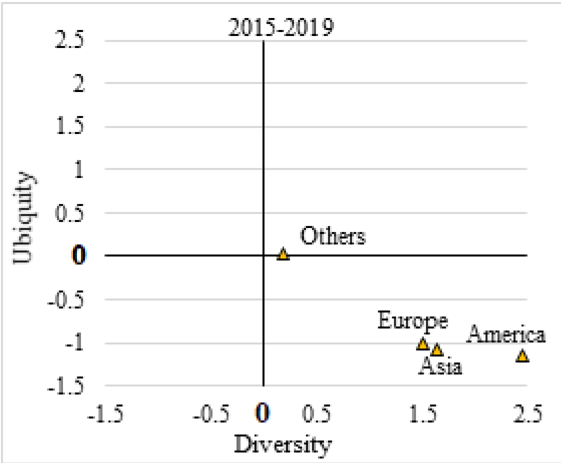
Graph 7 simply confirms the present leadership of the US, and of a few Asian countries, China, South Korea and Japan, already shown in Graph 4. The graph confirms the relatively good position of the countries in the lower left quadrant e.g., India, Taiwan, Ireland and Singapore; in this second period, we also find Sweden, meaning that in the previous period the country specialised in some additional technologies that were characterised by low ubiquity, thus advancing its capacity to effectively compete in 5G development.

From Graphs 8 and 9, the replica of Graph 5 for the sub periods, it is possible to notice that during the first period (2010-2014) Europe, as a region, was clearly lagging behind, but in the second period (2015-2019), it was able to bridge the gap, reaching values practically identical to those of Asia. This confirms the present potentiality for European collaboration.

The leading position of North America that appears in the Graphs was already clearly defined in the first period, even if at the beginning the rarest technological basket was that of Asia.

***Graph 8 and 9*. Diversity and ubiquity technological specialisations 2010-2014 (left side) and 2015-2019 (right side) for regions.**





Source: our elaboration

5. Conclusions

In synthesis, the concept of 'complexity' that is used in this paper to interpret the technological race to 5G builds on the fact that rare technologies are more likely to be produced by countries that possess, and are able to combine, many different specialisations and, conversely, that those countries that are able to introduce rare technologies are solely those countries that hold many different specialisations. We can classify these as "complex countries". This concept of complexity appears to be far superior to any simple counting of patents in understanding the present status of the geo-political competition in 5G.

In fact, what is relevant for global competition is that these complex countries, able to produce the least ubiquitous technologies, face limited competition to sell their products, because other countries are simply not able to replicate them. Holding many different specialisations allows the leading innovators to impose their new complex technologies on the markets. In fact, each new specialisation that may be developed emerges as a combination with the many other specialisations that are already possessed, and this continuously increases the difficulties for countries holding fewer specialisations in accessing the race to the frontier of technological development.

Our analysis suggests that this mechanism of cumulative innovation may severely limit the opportunity of other countries to specialise in 5G. Typically, only a few of the most advanced countries, which specialise in the largest possible number of technologies, will be able to participate in the race to license the entire set of the "complex technology" that leads to 5G.

Certainly, our exploratory analysis of patents is not free of limitations. First, as already explained, the use of a national patent office as the source of the data, even if it is the USPTO, does not fully represent the whole number of patents around the globe, and, unavoidably, gives a more complete picture for the US than for the other countries. Second, our choice to use 'diversity' and 'ubiquity', as the representative measures for technological complexity, is still discussed in the relevant academic community and, anyway, offers only a partial view of the complexity issue.

Notwithstanding these caveats, the study provides the first evidence-based indication that the technologies and the specialisations needed to develop 5G are increasingly in the hands of a few countries around the globe, and that there is a strong and growing divide between these countries and those that follow them.

Two significant preliminary results emerge from our comparison between the measures of complexity of the countries and regions of the world. First, in 5G technology the present leadership of US, China, Japan and Korea is clearly to be acknowledged, as well as the weakness of European countries - with a few notable exceptions. In second place, the aggregate analysis for regions suggests that the position of Europe could significantly change if the countries within the EU were able to develop the right incentives to cooperate more closely.

While the EU's capability today appears weak, being strongly fragmented among its different member states, the competitiveness could be boosted by the joint effort of its countries, and the region as a whole could manage the technological complexity sufficiently to join the leading innovators in 5G technology. Our result, however, probably needs to be further investigated before being considered sufficient evidence of an explicit policy recommendation in this regard.

In general, future steps for this research should explore in more depth the characteristics of the technological complexity of 5G, following an evolutionary approach and adopting a comparative perspective with other technologies, as well as enlarging the study to the data of additional main patent offices in order to get better coverage of Europe and Asia. Moreover, our study can be considered only a first step in the discussion on the quality of the 5G patents and technology in the hands of companies or countries around the globe, and we should go beyond the counting of patents and seriously investigate who is leading the "quality" development of 5G. This type of analysis needs to be further deepened in order to become useful in capturing the fundamental differences in the innovative content and economic value of different portfolios of patents.

In conclusion, this paper suggests a route forward, studying the technological competition in the telecommunications industry, and particularly the development of the fundamental 5G technology. It shows that there are only a few countries at the frontier of the technological development in this field, the US and China, above all, and that the lagging countries will face many difficulties in order to cover a gap that appears to be increasing over time. For most countries, there are simply too many specialisations that will need to be acquired so as to approach the countries that are leading the race. Finally, from this analysis, we may cautiously derive the hypotheses that, if it is able to effectively coordinate the innovation capability of its member states, the EU may still emerge as a credible competitor in the race to 5G.

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