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# The rise of 5G technologies and systems: A quantitative analysis of knowledge production

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ABSTRACT

The advent of a new generation of wireless communications has punctuated the dawn of every decade in recent times. Upgrades to mobile electronic systems represent faster and more robust capabilities of data transfer but bring with it a wide set of complementary changes as they are underpinned by harmonised specific spectrum bands, fresh international technical standards, new network operation requirements, innovative cellular devices as well as new services and a broader array of potential commercial use applications. This paper presents a systematic outline of the development of 5G-related research until 2020 as revealed by over 10,000 science and technology publications. The exercise addresses the emergence, growth, and impact of this body of work and offers insights regarding disciplinary distribution, international performance, and historical dynamics. Findings reveal the progressive growth of the 5G research over the years after original contributions in 2010 and point to a "take-off" around 2014. A set of stylised facts regarding this technology since its infancy are of interest to engineers, regulators and innovation strategists and policy-makers.

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## 1. Introduction

The coming into life of a new technology is both interesting in its own right and instrumental for understanding what happens later. That early evolution is explored here in the case of "5G", the fifth generation of wireless communication devices and systems. The 5G technology is a landmark for new applications and markets supported on denser, deeper and more dynamic access to information. The aim of this paper is to follow the technology over the years and to provide a comprehensive and integrated evidence-driven account of its build-up. We go through the process of technological development with the aid of data analytics methods and text mining techniques that are able to assess a massive set of international peer-reviewed publications on 5G.

We carry a systematic review of over 10,000 scientific papers containing references to 5G in the title, abstracts and keywords by authors affiliated to all types of entities from every country from its origins and up to 2020. This large scale sample resumes nearly two decades of effort by a myriad of knowledge producers pushing forward an infant technology before it was commercially rolled out (around the year 2020). From the perspective of innovation studies and the neo-Schumpeterian economics of technical change in the field of telecommunications, we combine bibliometric and textmetric analytical dimensions to provide a comprehensive and integrated approach that allows us to address several questions, including: When did this technology emerge? What players and geographies led its advance? How do disciplinary perspectives co-exist, and which issues matter the most for its development? The answers, which bring out novel stylised facts about the underlying building process of a breakthrough technology, may hopefully inform the decisions of practitioners and stakeholders shaping this evolving technological system.

The paper is organised as follows. Section 2 outlines a theoretical perspective on tech-economic evolution and the structural changes related to the information and communication technologies (ICT) techno-economic paradigm. Section 3 proceeds with a concise discussion of 5G landscape, while Section 4 articulates the methodological set-up. Section 5 presents and debates the major patterns and key salients having to do with 5G products and ecosystems. Section 6 offers conclusions.

## 2. Knowledge production and the advent of modern connectivity

A neo-Schumpeterian approach to the origins and pathways of new technologies.

The initial stages of a technology are characterised by the interplay of many new learning possibilities. Change is uncertain and leads to a series of reinforcing and expansive complementary developments that are not predictable in advance. Technical progress is a time-consuming and contingent process of discovery, susceptible to the pulls and pressures of context.

The concept of Change is central to the economic system and has in Joseph Schumpeter its most prominent advocate. Today, this view is encapsulated by evolutionary economics: a theory that conceives economic structures in (i) a macro out-of-equilibrium frame, (ii) within which institutional and technologies are endogenous processes co-determining themselves according to complex interactive dynamics, and (iii) with heterogeneous actors and organisations reflecting different beliefs, purposes and capabilities (see Nelson et al., 2018).

A world driven by innovation is about variation, selection and retention (Castellacci, Grodal, Mendonça, & Wibe, 2005). The pace and character of change depend not only on innovators but also on many other agents assuming different roles. In turn, creativity depends on, and is constrained, by existing structures, representing the legacy of prior innovations.

The present study, which deals with a new system in its early stages, draws on such a theoretical perspective. The "neo-Schumpeterian" view, broadly known as "innovation studies", is inherently empirics-friendly and policy-relevant (Fagerberg et al., 2012). This approach has been effectively deployed to address emergent technologies with crosscutting applications and modern ICT capabilities that are distributed across players and sectors (Mendonça, 2003, 2006, 2009, 2012, 2014; Mendonça, Pereira, & Godinho, 2004; Mendonça, Schmoch, & Neuhäusle, 2019). Recently, moreover both wireless networks for the transmission of digital information and artificial intelligence technologies have displayed a degree of "crowding-in", i.e. attracting leading actors like the US and China but also other smaller participants from the "Global South" (Confraria et al., 2021; Righi et al., 2020).

The latest generation of smart mobile communications, 5G, represents the technology where a number of converging trends are currently headed. So far, and in spite of all the policy attention and hype, empirical studies attempting a comprehensive and in-depth empirical appraisal of 5G advances are lacking. Indeed, understanding telecommunications innovation is critical since these technologies have become an increasingly pervasive infrastructure undergoing intense reshaping and are expected to have disruptive impacts on economies and societies. This paper steps in to provide an account of the building process of the latest generation of connectivity technologies.

### 2.1. The techno-economics of telecommunications systems

5G is a data and connectivity technology. It is the latest change of mobile technologies that started to transform the global economy in the last quarter of the 20th century (see Freeman & Louçã, 2001). As it might be expected, its introduction is indicative of new enabling opportunities brought about by general-purpose technologies like ICT (Gambardella et al., 2021; Louçã and Mendonça, 2002).

From 1972 onwards, the successive introduction of semiconductors, electronic personal computers, software, computers linked by telephone lines, the world wide web, mobile phones, and the like, have led to the constant matching, mismatching and re-matching of engineering and governance forms (Geroski, 2003; von Tunzelmann, 2003). From electrical telegraphy in the late 19th century to cloud-managed cyberspace and new platform business models in the early decades of the 21st century, the transition from industrialism to informationalism has accelerated (Castells, 1996; Dutton, 2013; Mansell et al., 2007), and created new types of imbalances and strains (Mansell and Steinmueller, 2020; Wu, 2016; Zuboff, 2019) calling for new societal adjustments and knowledge ecosystem arrangements (Mansell, 2021; Teece, 2021).

Digital devices linked to each other by telecommunications systems increasingly became the modern economy's defining template. Slowly starting with the first prototypes in the 1970s, every new generation wireless access technology brought with it new functionalities and persistently increased degrees of penetration (see Box). For instance, the deployment of 4G access technology around 2010 was particularly impactful: it linked up a new plethora of terminals (smartphones, tablets, smartwatches, etc.) and harnessed a surge in bandwidth consumption (social media, video streaming, etc.). The following "G", still being trialled by many vendors and operators around the year 2020, with commercial operations just rolling out then, is designed to work at higher radiofrequencies: 5G is expected to offer ultra-high throughput at low latencies, supporting a variety of use-case scenarios compatible with heavier industrial data requirements and high-reliability mission-critical services. This technology is expected to remain co-existent with 4G, just as 4G relied upon 3G/2G legacy infrastructures.

However, the successive introduction of upgraded and more capable electronic communications networks is both a matter of technological innovation and governance solutions (Manganelli and Nicita, 2020). Cellular technologies evolve within a set of interdependent institutional environments, such as research systems (universities, public research institutes, corporate laboratories, etc.) and standardisation bodies (like 3GPP, ETSI, etc.). Since telecommunications are "network industries" (providers of general-purpose services of significant socio-economic importance) that rely upon scarce public resources (spectrum), these have been subject to intense public policy attention and debate. From the 1980s onwards, anti-monopolistic concerns led to a liberalisation of national and international markets. This market-oriented framework also led to the establishment or reinforcement of national regulatory authorities entrusted with duties of monitoring and assurance of operator obligations (see Nicita and Belloc, 2016), while governments have designed or overseen the governance for radiofrequency allocation and service deployment (Lemstra, 2018; Oughton et al., 20,121).

History shows that telecoms engineering has gone through secular twists and turns when trying to adapt to shifting demands and regulatory spaces (Martinelli, 2012). The successive technologies have not been simple up-grades, and hopping across different generations has provided moments of discontinuity that have been exploited by different actors (e.g. the Scandinavian equipment manufacturers in 2G/3G, North-American and South Korean smartphone brands in 4G, Chinese vendors in 5G/6G) (Li et al., 2019; Yu et al., 2020). The momentum behind 5G mostly lies in a participated ecology, both symbiotic and competitive, with arguably different strands of work feeding into its ultimate development. Those efforts can be chronicled and mapped with the help of scientometrics.

## 3. The major features and dynamics of 5G

### *3.1. The road to 5G*

Every new mobile generation technology brings new capabilities and requirements in terms of equipment, spectrum, and other complementary assets; it also unleashes a range of systemic changes in terms of applications, market opportunities, and converging industries.

This trend allowed the progressive reduction of transmission costs, the optimization of spectrum assets at increasingly higher bands and the overall improvement of service quality. The sophisticated proposition embedded in 5G brings with it a potential transformation in virtually all dimensions of societal activity and economic sector sthat goes beyond the human-to-human patterns of communication that have characterised the other generations hitherto. It is poised to be an ultra-fast massive always-on/everywhere architecture and to offer the biggest complement so far to fixed-line options.

The key message being spread about 5G throughout its late incubation period and the initial stages of deployment (i.e. late 2010s/early 2020s) is that it fundamentally redefines the nature of digital networking and disrupts mobile-driven markets (Lehr et al., 2021;

**Box**
Counting the "Gs"

Appearing around 1980, "1G" can be understood as a system allowing the transportation of analogue audio over the airwaves from one terminal to another along the cellular network principle. Around 1990 a breakthrough came with 2G: the launch of fully electronic mobile telephony over the GSM standard (the "Global System for Mobile Communications", a radio access set-up ratified at the European Telecommunications Standards Institute - ETSI) was a worldwide success. Whereas 2G brought with the first data services (i.e. Short Message Service - SMS), 3G promised to bring the internet to mobile phones, and it was associated to the UMTS standard (Universal Mobile Telecommunications System - UMTS). However, it was only with 4G that mobile broadband came of age: around 2010, LTE-based networks (Long Term Evolution technology, which defeated the WiMax alternative), which were mostly supplied by Ericsson, Nokia and Huawei, came to support the phenomenally successful smartphone (initially epitomised by Apple's iPhone and Samsung's Galaxy) and the "app-economy" (enabled and driven by new Big Tech giants like Google and Facebook). Rolled out around the year 2020, 5G was heralded to address more than consumer demands: a system able to move industrial and other kinds of big data in massively dense device environments with extremely quick response ratios.

Schneir et al., 2018). The zeitgeist is aptly captured in a *Financial Times* piece:

> "We believe that 5G is a multiyear megatrend that will enable a world where digital computation is increasingly ubiquitous." (C. C. Wei, Taiwan's Semiconductor Manufacturing Company's chief executive; statement reproduced by FT's columnist John Thornhill – "Geopolitical supremacy will depend on computer chips", 16 February 2021, p. 15)

Some of its main drivers have to do with high bandwidth and enhanced lower latency features which underpin large data throughput and immediate response. Industry forecasting and international institutions provide some of the key estimates for data consumption. On the one hand, the McKinsey Global Institute (2020) suggests that by 2030 data consumption will increase 20 times compared to 2020, with much of this growth driven by new users, more time spent watching video, and higher-definition content. On the other hand, The Body of European Regulators for Electronic Communications (BEREC, 2018) predicts that Internet-of-Things (IoT) applications and massive industrial reporting will capitalise on Artificial Intelligence (AI) to drive a number of novel use cases that are currently not envisioned. Meanwhile, parameters such as jitter, inter-channel interference, scalability, coverage, and compatibility with legacy networks must also be taken into consideration when monitoring new trends for mobile use technologies. Thus, the preparations for another generation of connectivity (ever more constant and ubiquitous than the previous) have implicated significant intra and extra-industry concertation (in standard-setting, for instance) as well as enhanced regulatory efforts (in, say, frequency harmonisation) so as to open the way to its practical rollout (Mitra and Agrawal, 2015).

### 3.2. *A participated and coordinated process of innovation*

Critical coordination came along through the 3GPP system in the shape of "Releases" (for instance, Releases 12 of 2015, 15 of 2018, and 16 of 2020). The 3GPP (originally the "3rd Generation Partnership Project") is a forum of technical players and market stakeholders from Asia, Europe and North America, and the acronym still carries the hallmark of its birth context in 1998 (the development of the 3G global initiative).

3GPP provides developers and industry entities with a stable base for the definition and acceptance of technology features, and, by doing so, it covers protocols that ultimately affect the whole innovation supply-chain (from suppliers of equipment and content generators to infrastructure and service providers) worldwide. National and supra-national standard institutions are the central part of this machinery. These bodies, which are in turn composed of policy-making and regulatory institutions, through their binding actions play a crucial role in setting electronic communications templates and trends. In so doing, this institutional set-up provides a "focusing device" for inter-national/inter-sectoral discussions and consensus-building aiming at maximizing the gains to be extracted from spectral resources and to enable global economies of scale and scope.

The need for such an integrated institutional approach is supported in the UN's International Telecommunication Union (ITU) report on the opportunities and challenges of 5G (ITU,2018) and might also play a role in the innovation process (Nikolic and Galli, 2021). A large number of framing contexts contribute to shaping these technologies, some being national or supranational but carrying significant weight; a non-exhaustive list being: CEN, CENELC, CEPT, ENISA, ETSI, GMA, and the WRC.[1] In short, the enhancement of wireless mobile communication technologies has been a collective enterprise.[2] It is an institutionally-based and evolutionary-driven process that tends to be balanced out internationally and also managed as a global common good through which a widely distributed array of actors channel their inputs and interests.

The world of high-tech innovation is thus an institutionally-rich process, and this is demonstrated in the case of electronic communications, which is foundational to the modern informational economy (Steinmueller, 2003; Teubner et al., 2021). The story of 5G, which is a substantial area of contemporary breakthroughs, can further provide insight into the nature and nurture of technical progress. It can, moreover, cast some light into patterns of knowledge specialisation and technological emergence (Rotolo et al., 2015; Taalbi, 2020) and into raging debates regarding the dynamic comparative advantages of "liberal" vs "coordinated" market economies (Akkermans et al., 2009; Wang et al., 2019) and the prospects for creative "catch-up" by developing economies (Godinho and Ferreira, 2012; Lee and Lee, 2021).

Regarding the latest advances in the 5G ecosystem, 2020 was "the year of 5G" with general commercial launches and faster than expected marked subscriber growth (Telecoms.com, 2021). Available references provided by market observers and industry participants point out that by late 2020/early 2021, there were already around 400 service operators investing in 5G worldwide and over 700 announced 5G-compatible devices (GSA, 2021a, 2021b; Telecoms.com, 2021). By this time, above 160 commercial operations had already been launched in more than 130 countries, of which a small proportion (eight operators) were in stand-alone (SA) mode (GSA, 2021a, 2021b). By the end of 2020, China had installed an estimated 700,000 5G base stations (more than the rest of the world combined), South Korea nearly 170,000 (it was the first country to launch commercially, in April 2019) and the United States 50,000 (All About Circuits, 2021; Open Signal, 2021).

[1] CEN (European Committee for Standardization), CENELC (European Committee for Electrotechnical Standardization), CEPT (European Conference of Postal and Telecommunications Administrations), ENISA (European Union Agency for Cybersecurity), ETSI (European Telecommunications Standards Institute), GSA (Global mobile Suppliers Association), WRC (World Radio Congress).

[2] Economic history shows that uninterrupted international cooperation matters critically for frontier knowledge production. Barriers, boycotts, cut-offs and other threats to the free flow of knowledge cause severe potential damage to progress in high-tech areas (Iaria et al., 2018).

## 4. Materials and methods

### 5.1. Research design

In this empirical paper, we assemble a set of observations that allows us to compose a meaningful understanding regarding the 5G phenomenon. The raw observations for the analysis are scientometric data, that is, publication (bibliometric) and content (textmetric) materials on scientific level types of knowledge. The scientometric toolbox is usually deployed to understand the scientific enterprise, but here is used to enlighten engineering progress. We extracted and tabulated all the relevant academic publications that focus on or refer to 5G technologies or 5G telecommunication systems. A supervised machine learning algorithm was developed to enable the textmetric analysis.

Although our sample handles formal output records, it represents the achievements of both researchers (academic scientists) and practitioners (industry engineers) thus revealing advances in science, technology and innovation. In this case, the number and content of publications are taken to be results of purposeful knowledge-seeking efforts that show up in earlier stages of work. However useful we acknowledge they are just a partial indicator since authors or organisations may instead patent rather than publish their research results (Martin, 2019). Limitations are many and well known: publication items tend to be far away from market applications, the propensity to publish and citation dynamics vary along disciplinary lines, etc. Nonetheless, this type of methodology remains highly granular, comparable and adaptable to the evolving landscape of analytical and policy needs (Glänzel et al., 2019).[3] The novelty our integrated bibliometric-textmetric approach brings to the field is how it unveils the actual creative processes driving 5G and the forces organising around it.

*Evidence base*

Bibliographic items are appealing because they span time and space, institutional and thematic categories. They can be examined individually, aggregated or put into a relational perspective. As indicators of creative enterprise, formal publications in scientific peer-reviewed journals provide a controllable and powerful data-pool.[4] To capitalise on this potential, we conducted a thorough computer-assisted literature exploration on the Web of Science (WoS) database.[5] Complementary sources were used. The Scopus database supplies authors' identification since retrieval could be automated through an Application Programming Interface (API). Bibliometrix (an R package) was used since it automatically adds affiliation date to authors' identifications. Descriptors regarding the standing and prestige of periodicals were gleaned from Scimago, the public repository of journal metrics.

Fig. 1 presents the data-collection protocol. A search for academic journal articles only was performed for the complete database with no date restrictions to ensure completeness. Screening took place in which false friend "5G" wordage was identified and expunged to ensure that the final assembled scientific research information contained no false positives.[6]

The final sample includes 10,672 articles that mention "5G" in the title, abstract or keywords. These records were authored by 23,695 individuals (estimated) from 108 countries between 2005 and 2020. Items were published in 697 journals (unique ISSNs) and contain 372,623 references to other documents.

The publication records and their characteristics were primarily processed from a descriptive perspective (count data, averages, proportions, growth rates, ranks, etc.). Summary statistics were computed (namely the conventional concentration index), and network analysis was carried out (graph representations along with the usual network metrics).

Some qualifications are in order from the outset. The search was made for the "5G" string, not to extensive formulations of the same concept such as "fifth generation of mobile communication", "New Radio", or other variations. We import the subject and disciplinary scheme of WoS with no restriction, however, it is well known that it does not necessarily presents an optimised bibliometric categorisation for every study (we advance a compact reclassification in Appendix 1, based on semantic proximity; for a discussion see Milojević, 2020). The identification of individuals is challenging, and their identities are retrieved via Scopus ("rscopus" package). [7] Self-citations were not considered a major problem for the purposes of the research and were included. Several types of robustness-oriented analyses were performed (in order not to hinder the flow of the text they are placed in Appendixes 2 and 3).

[3] Other indicators could have been used, from the most conventional like patents (e.g. Mendonça et al., 2019) to less conventional ones like trademarks (Mendonça et al., 2004, p. 2012; 2014; Castaldi, 2020) and standards (Foucart & Li, 2021; Laer et al., 2021; Teubner et al., 2021).

[4] This perspective brings with it the assumption that the most relevant literature is made available in this way (as an option, book chapters and conference proceedings are sometimes not considered for purposes of analysis).

[5] This source is well known, has extended coverage, and its findings are highly correlated with other databases (Archambault et al., 2009).

[6] Most "false friends" came from a specific field of biology; other errors were weeded out through trial-and-error, (for instance, cases in which "2.5 GHz" could have confounded the search effort, but no instances were found). After stabilising the 5G-related publication set, the data were further filtered out from papers due in 2021, an incomplete year, as our time window ended in 2020.

[7] Authors may have changed affiliation over the course of their career. This implies making decisions: papers were counted for the affiliation at the year of the publication, where change happened all those papers were assigned to the institution and country of the authors' last paper in the database.

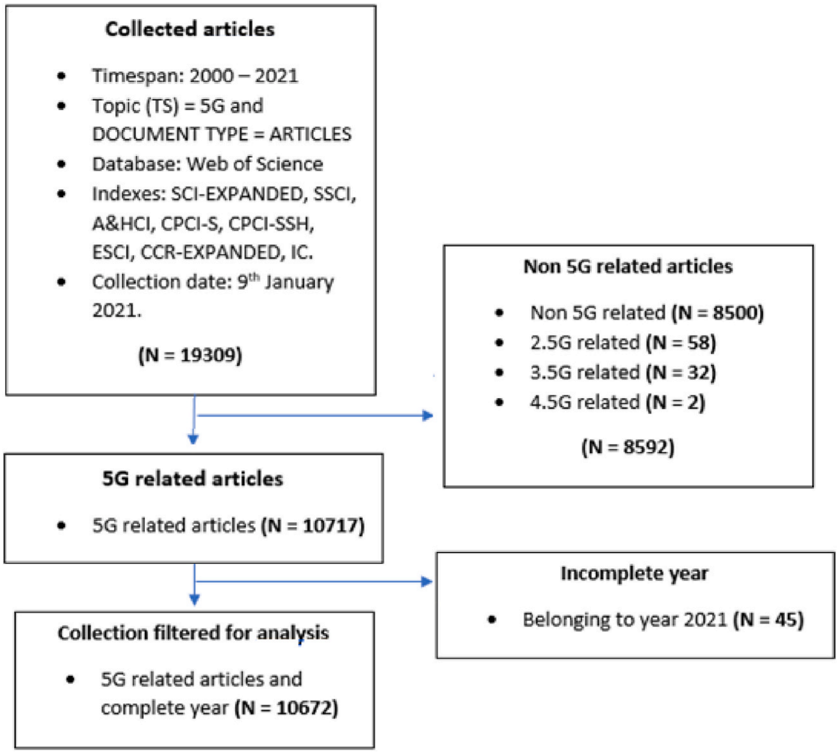



**Fig. 1.** Data collection procedures.

## 5. A bibliometric account of 5G-related research

### *5.1. An overview of the studies published on 5G until 2020*

#### *5.1.1. The rise of the 5G agenda*

The total entries on 5G are shown in Fig. 2. There is a first publication in the year 2005, a single instance in which a glimpse of the forthcoming generation surfaces. It is from 2010 onwards, however, that continuous, persistent and rising production ensues. There is a clear take-off in 2014 when volume sees a step-jump to the level of hundreds; growth is robust thereafter, with no sign of slowing down. That is, when the first major technical standard was set up (3GPP's "Release 14" of 2018) it already stood upon a solid stock of prior research and engineering work. In view of this major stylised fact, other dimensions of 5G development, such as geographical provenience or its technical subdomains, can provide critical complementary insights.

#### *5.1.2. The geography of authorship*

By processing authorship information, it is possible to picture the international distribution of knowledge production. One hundred and eight different countries were detected, spread across the continents. Most authors are established in Asia (13,109 authors), while Europe (6,480) comes next with nearly half of the population of authors, followed by the Americas (3523).

China is the leading country in terms of total publications, followed by the US. Fig. 3 (left-hand graph) conveys a sense of how asymmetric research output really is: China has more publications than the three following countries combined; the US has more publications than the 11 lowest countries in the Top 30. Additionally, there is evidence that 5G knowledge appears to be reasonably distributed. On the one hand, this high-tech field is not a monopoly of high-income countries: almost a third of these countries are upper-middle (China, Malaysia, Turkey, Iran and Russia) and lower-middle income (India, Pakistan, Egypt and Vietnam) countries. On the other hand, 5G research activities come through as relatively globalised: 14 of 30 countries are not from the Anglo-American/ European sphere.[8]

Fig. 3 (right-hand graph) also shows how some (small) countries are (big) contributors relative to their size: that is the case of some "peripheral" European countries, both Scandinavian (Finland, Denmark, Sweden) and Mediterranean (Portugal, Greece, Spain), which

[8] A depiction of aggregate first-authorships (not shown) is even more telling and reveals the extent to which the position of the Anglosphere is eroded in favour of Asia (this finding echoes other analyses using patents, see Godinho and Ferreira, 2012). The top-5 in this first-authorship ranking: #1 China (3448 papers), #2 US (820), #3 South Korea (720), #4 India (548), #5 UK (470). That several other Asian countries ranking higher in this indicator appears to point out to a considerable degree of investment in intellectual leadership in the field.

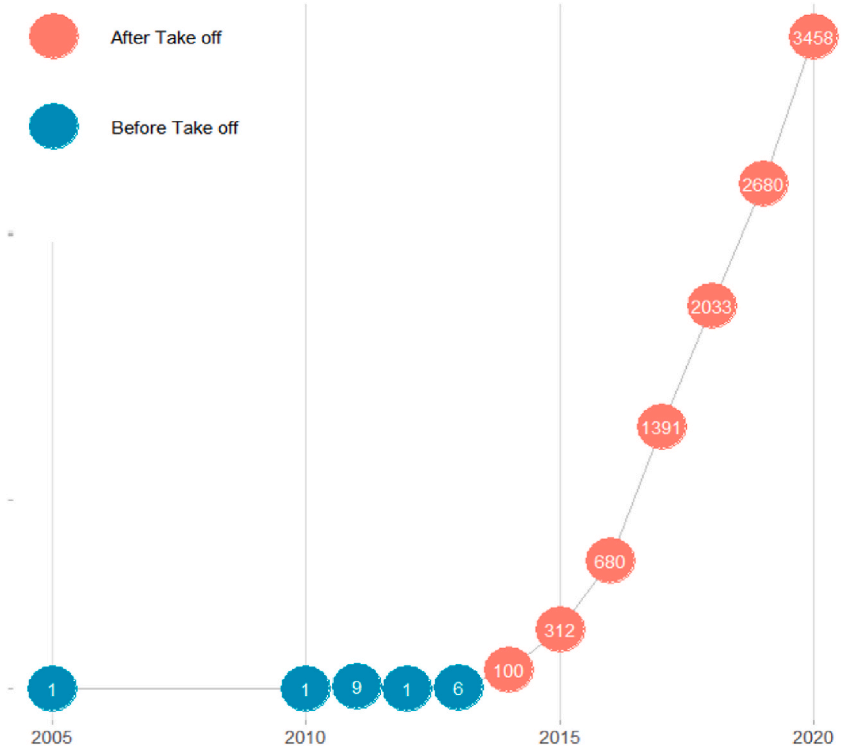



**Fig. 2.** Research items published on 5G, by year, 2005–2020.
Source: this paper, the same for all graphs and tables henceforth.

make it into the Top 10 countries in terms of first authorships per million habitants. The tails of the distributions call attention of the dynamics of entry into this technology, i.e., the diffusion process.

*5.1.2.1. International diffusion of 5G-related research.* Fig. 4 (left-hand graph) accounts for the spread of research on 5G over time. The year in which 5G comes alive as a topic of research is when the number of those involved in publishing also explodes; by the end of the decade, and compared with 2014, three times the number of countries were active in the 5G agenda. A consequence was the steady decline in the country concentration of research in terms of publication shares, as can be gleaned from the Hirschman-Herfindahl index in Fig. 4 (right-hand graph). That is to say, over the years, 5G interest became increasingly distributed, opened-up and more participated.

### *5.2. Institutional set-up, journal platforms and thematic profile*

#### *5.2.1. Major research actors*

The major organisational players in the 5G research scene are university institutions, whether they are universities or university-based research centres (like the multi-university research centre “Instituto de Telecomunicações” from Portugal). In this institutional segment, and in terms of research volume and impact, we see that the top places are occupied by a Chinese and an American university, respectively (Fig. 5).

When it comes to non-academic actors, there is more institutional variety: we see prominent telecom vendors (like Nokia, Ericsson, Huawei, ZTE, Samsung), a few telecom operators (Telefonica, Hutchison, NTT, Orange, Vodafone), ICT manufacturers (Qualcomm, Intel, Samsung, Toshiba), public research entities (VTT, Ministry of Education of China) and all-things-digital private/not-for-profit think tanks (i2cat Foundation, Fondazione Bruno Kessler). A word on dynamics: initially, non-academic organisations were responsible for half of the publication output (around the years 2013 and 2014), nonetheless they have steadily trended downwards since then (25.0% in 2020).

It is worth mentioning that the major private players are the specialist high-tech equipment manufacturers that are household names in the electronic communications industry; the brand name of some of these global giants appears several times, as they have excellence centres in several countries (tending to concentrate in the US and Germany as target territories); we did not consolidate these industrial entities. Topping the non-academic list, we have companies with roots in Finland (number of papers) and South Korea (number of citations).

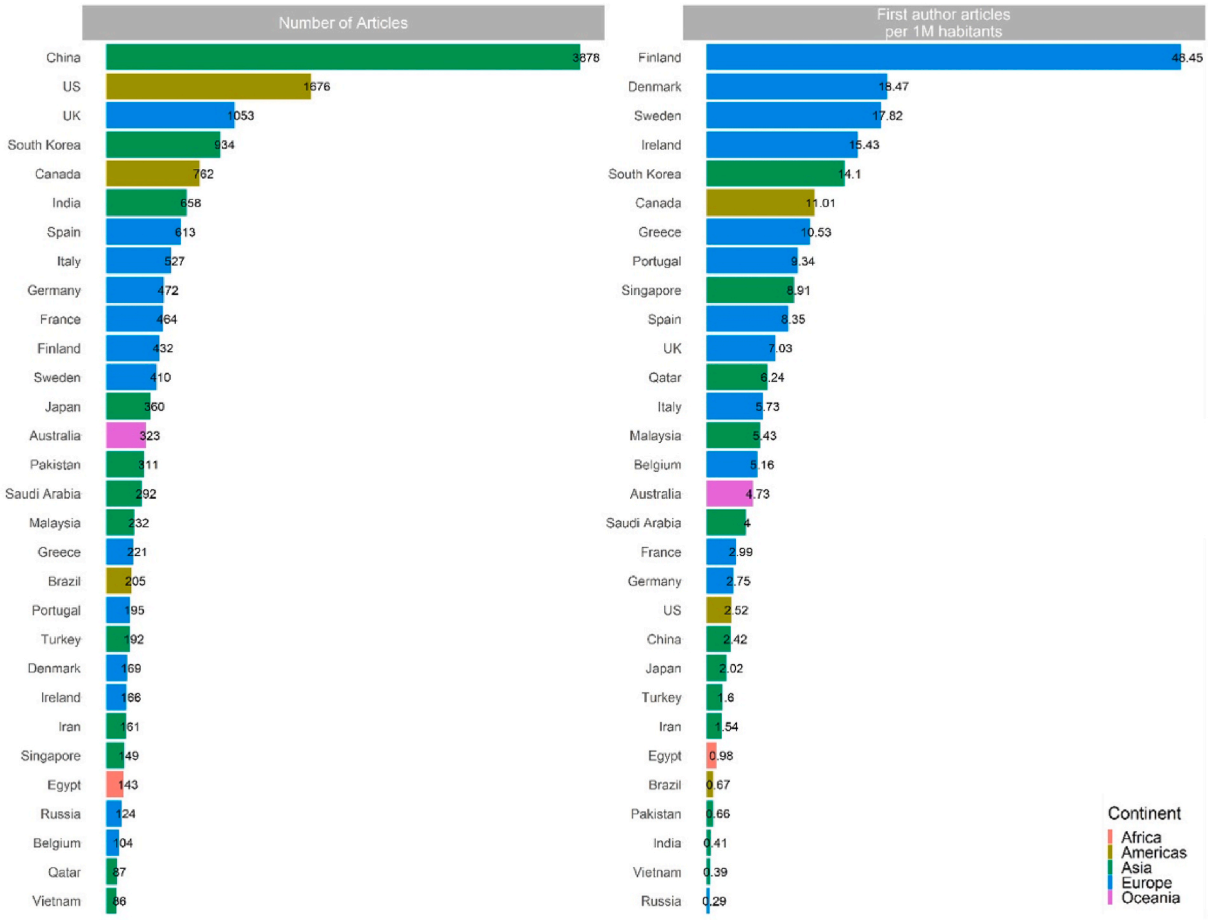



**Fig. 3.** Volume of research papers on 5G, top-30 countries.

### 5.2.2. *Main publishing outlets*

Fig. 6 shows the major journals in which the research appears. The core fields covered have to do with wireless communications, but also with digital, sensors and computer engineering. Among the top venues for 5G-related research, IEEE journals are dominant.[9] The earliest two publications on 5G in our database came out in IEEE outlets.[10]

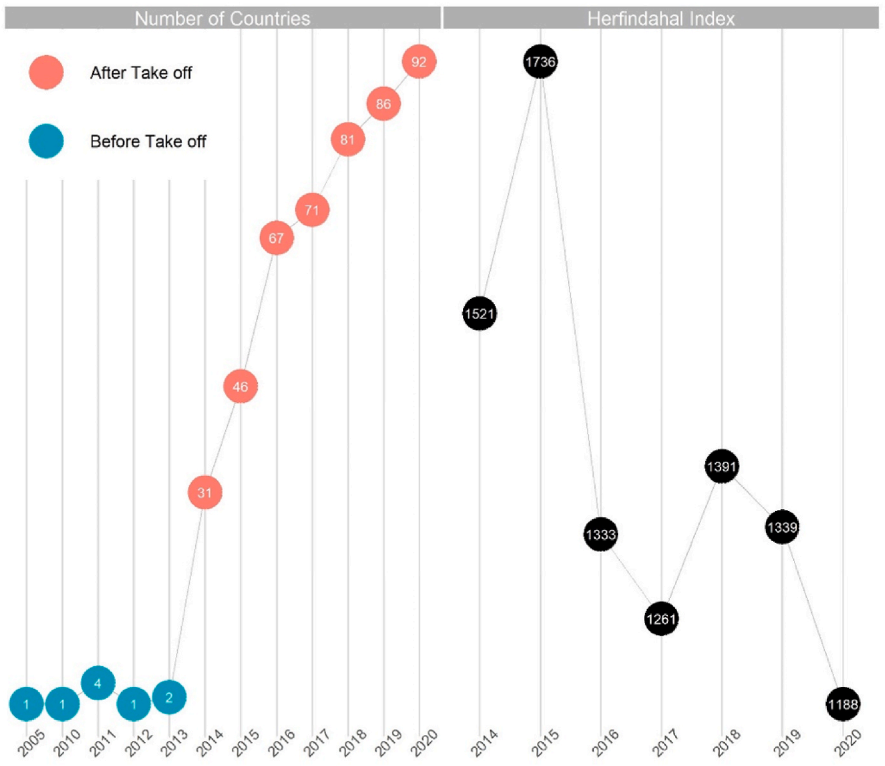
Overall, the number of journals publishing 5G-related research has been remarkably on the rise, from just 6 in 2013 and 26 in 2014 to no less than 444 in 2020. This statistic is not just about growth in the distribution capacity of research; it should also be understood as indicating the increase in the branching out of thematic strands. Different journals position themselves differently tackling different topics, angles of analysis and address distinct audiences.

### 5.2.3. *Key knowledge categories*

Most 5G-related research appears in journals mainly classified as belonging to the knowledge-base of "Electronics and Telecom Engineering". Since journals can be classified into more than one field, there is a large overlap with "Information Technology and Processing". These categories comprise the core (i.e. microelectronics and digital) areas of research. Table 1 shows the result of taking the 42 detected WoS disciplinary categories and developing a new classification scheme that aggregates them into 11 broader fields (Appendix 1). Besides the core areas, we can witness areas of application ("Transport", "Health and Biosciences"), inputs ("Energy", "Materials and Chemistry"), externalities ("Environment, "Health and Biosciences"), as well as reflexivity contexts (a number of

[9] The Institute of Electrical and Electronics Engineers (IEEE) is a non-governmental professional association of global membership. This expert body has its beginning in the US but brings together over 400,000 experts from over 160 countries. While devoted to educational purposes and overall technical advancement, this organisation is influential in setting standards for the roll out of radio, electronics and computer network technologies.

[10] Miao and Niu (2005), then at Tsinghua University, on bandwidth management for multimedia information delivery services with high-data rate and high-mobility, and Han et al. (2010), from Samsung Electro Mechanics Company, on a hybrid conversion mixer architecture for MIMO transceivers.




Note: in colour, the absolute number of unique countries in any given year; in black, the Hirschman-Herfindahl index (H) computed on the basis of first-authorship research shares.

**Fig. 4.** Increasing participation in 5G-related publications per year.
Note: in colour, the absolute number of unique countries in any given year; in black, the Hirschman-Herfindahl index (H) computed on the basis of first-authorship research shares.

behavioural sciences like “Social Sciences and Humanities”, “Business and Economics”, “Public Policy and International Governance”, and “Education”). However useful for descriptive purposes, it must be noted these fields cannot be directly compared since propensities to publish vary widely (see average citations per field as a crude proxy).

The time path of the various research streams is of note; Fig. 7 provides the moving picture. The “core” fields have a robust growth since 5G-related research broke out (2014), while some complementary (“non-core”) areas shot up recently (around 2018), such as Materials, Environment and Energy. Publications having to do with 5G in the behavioural sciences debuted in 2016 (two articles) and just surpassed 1% of the total in 2020 (44 articles).

## *5.3. Evidence on performance and impact*

### *5.3.1. Impact*

Influence can be unpacked by investigating leadership in terms of authorship but also in terms of consequences. Here we look now not only at outputs (publications) but at outcomes (citations). China is the foremost country in terms of total citations, followed by the US (it has comparatively more citations per paper), the UK, South Korea and Canada (Fig. 8).[11]

In Fig. 9 we see a relatively mixed picture in the Top 30 authors list, arranged by "productive" (left-hand side) and "impactful" (right-hand side) contributors. On the one hand, productive authors come from a variety of locations: 11 countries are represented. On the other hand, impactful authors are based in a smaller number of research stations: seven countries, with the US clearly dominating (with half of the authors).

[11] China generates many papers, but with relatively low average citations (14.5 per paper vs 28.1 in the case of the US). Given that in many technological areas the impact of Chinese is mostly internal (see Righi et al., 2020), it may well be that total impact is somewhat underreported here. The same can be true for large non-English speaking countries (say, Brazil or Russia), however, but this effect will arguably not be of the same size as for China.

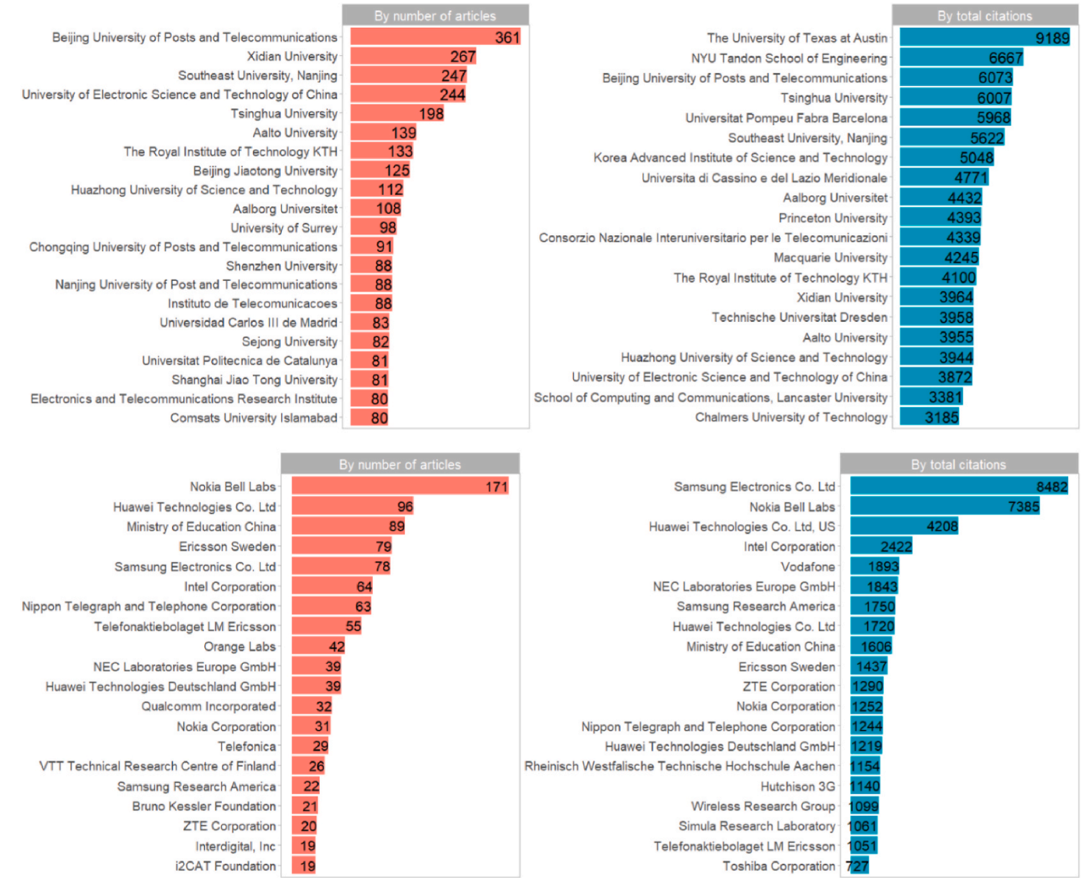



**Fig. 5.** Top 20 most active institutions, academic and non-academic 2005–2020.

### 5.3.2. *Top papers*

Table 2 shows the Top 20 most cited contributions. The geography is heterogeneous: 17 countries are included. Content is variegated: at least half can be described as surveys or review pieces; substantive articles underline some of the defining features of 5G kit, namely the arrays of small antennas known as "MIMO" (multiple-input multiple-output) and "beamforming" capabilities (optimal delivery of radio waves to mobile devices). Articles are all co-authorships. A sizeable proportion (#8) are partnerships between academic and non-academic authors, while two are by non-academics alone.

To gain further insight and highlight the full research and innovation trajectories at play, the top 5G papers that *cite* the top 5G papers in the dataset were also considered (Appendix 2). This sensitivity analysis captures more recent articles and reveals a number of issues that moved to the forefront. As the 2020s were approaching, the trending topics became edge computing, dynamic optimization, and resource allocation, reflecting how telecommunications engineering has been in transition to cellular networks that were ever more convergent with ICT (cloud, virtualisation, network slicing) and smarter in resource management (spectral efficiency, energy savings). This evolution highlights how the challenges tackled in the context of 5G systems had to do with issues that went beyond traditional human-to-human communications and into a variety of high-density multiple-purpose functions, including machine-type and digitally-enabled services demanding new requirements in terms of deployment performance and costs.

### 5.3.3. *Quality improvements in 5G research*

Citations are usual yardsticks of merit in research evaluation. This indicator can be, in turn, mobilised to construe other (more general) indicators, such as the standing of journals. Here each article that goes into a journal is allocated a quartile which shows the average "quality" of publications (the source being Scimago, the science evaluation portal, assigns it based on the influence of the journal). This analysis (not shown) places the average quartile firmly in the first quartile (Q1), while improving consistently over time.[12]

[12] Supplementary evidence is taken from the number of references in each published article, which can be taken as a metric of knowledge complexity and cumulative research progress. In our case, the average article in 2013 contained 22.8 references on average; by 2020, that figure was 38.2.

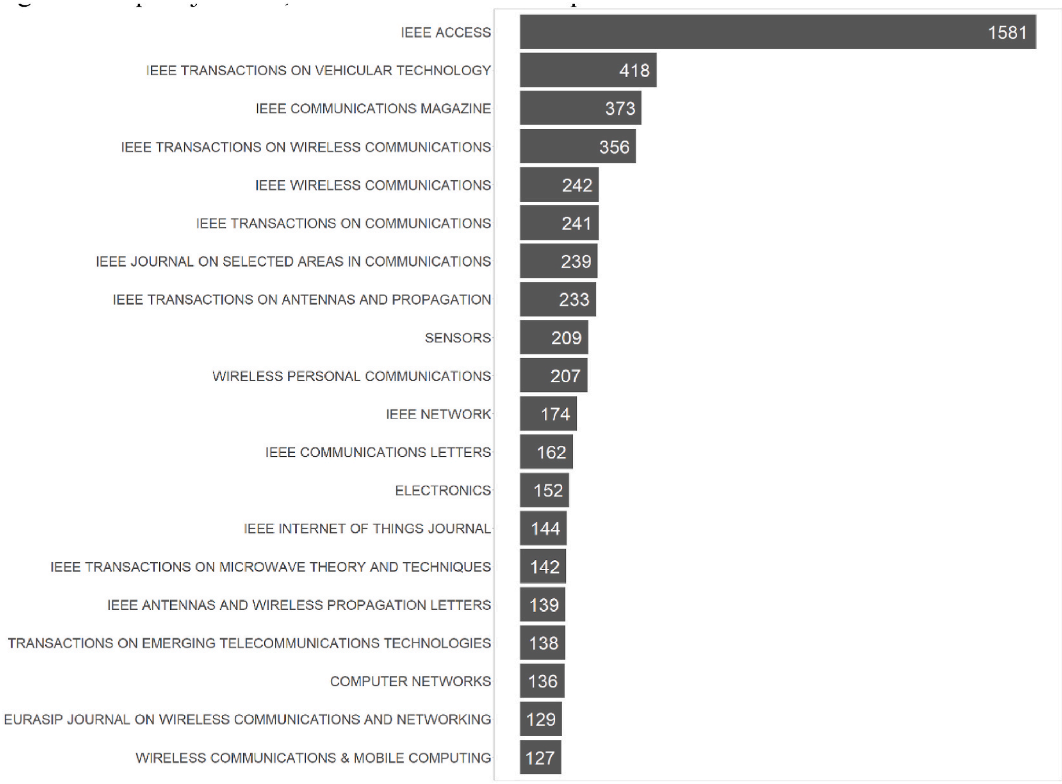



**Fig. 6.** Top 20 journals, number of total articles published.

**Table 1**
Thematic categories, 2005–2020.

| Category group | Articles | Proportion | Average citations | Average citation per year | Total citations | Average growth (YoY) |
|---|---|---|---|---|---|---|
| Electronics and Telecom Engineering | 9895 | 92.72% | 14.36 | 3.88 | 142,106 | 88% |
| Information Technology and Processing | 4638 | 43.46% | 11.22 | 3.5 | 52,053 | 108% |
| Transportation | 502 | 4.70% | 14.27 | 4.16 | 7162 | 105% |
| Materials and Chemistry | 471 | 4.41% | 3.34 | 1.46 | 1572 | 196% |
| Environment | 60 | 0.56% | 2.67 | 1.2 | 160 | 201% |
| Health and Biosciences | 48 | 0.45% | 3.69 | 2.64 | 177 | 249% |
| Social Sciences and Humanities | 34 | 0.32% | 3.76 | 1.25 | 128 | 88% |
| Energy | 27 | 0.25% | 3.3 | 1.36 | 89 | 93% |
| Business and Economics | 25 | 0.23% | 1.48 | 0.76 | 37 | 117% |
| Public Policy and International Governance | 18 | 0.17% | 1.44 | 0.63 | 26 | 150% |
| Education | 10 | 0.09% | 0.9 | 0.47 | 9 | 61% |

In taking the journal quartile approach, Fig. 10 allows for a further assessment of the "quality", or "importance", of the output produced by countries. With this perspective we see the prowess of countries like Canada (stable) and Finland (recently improving), while the US (recently worsening) and China (improving) occupy mid-table positions.

### 5.4. Research networks

#### 5.4.1. International collaboration

If co-authorship patterns can serve as a indicator of research collaboration, 5G appears to be a plural and cooperative venture. A few basic statistics can summarise it: the number of single-author articles (407) is a small proportion of total research output (3.89%); the average number of co-authors in the period was 4.43; the number of single-country papers was 57.92%; the average number of countries involved in a co-authored paper was 1.63 (but declined consistently since 2016).

The findings above already underscore US-China as the most important dyad. Fig. 11 expands the analysis by offering a representation of the authorship network – a graph with 101 nodes. The network has a density of 0.20, that is, the proportion of existing

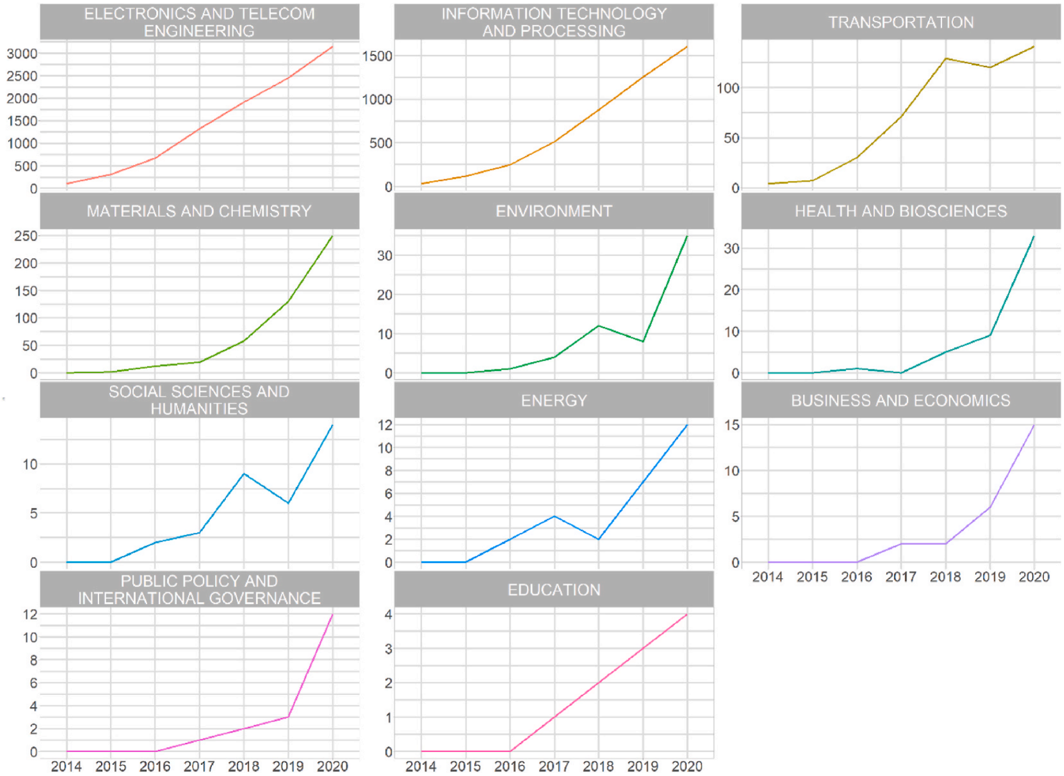



**Fig. 7.** Disciplinary distribution of papers.

links relative to the possible number. The diameter is 4, that is, the shortest distance between the two farthest nodes, and the average path-length is 1.95, suggesting no third actor is too far from two working partners. These set of metrics jointly underscore that the network is not especially sparse (i.e. there is a substantial level of socialisation), indicating that there is diversity and a role for positive effects from the periphery to the centre that cannot be ignored.[13] Additionally, the network is not homogeneous and three groups of countries can be identified: those clustered around super-stars (namely, US and China); Europe and those linked to it (this is the largest group); and the rest (an assorted number of "non-aligned" countries like India, Pakistan, Russia, Saudi Arabia, Turkey, among others). Even though relationship patterns are observed (depicted in colours) it is not clear to what extent they reflect explicit partnership strategies; the dynamics of research collaboration may also be reconfigured as the technology matures.[14]

The most important dyad is China-US, since there are 510 co-authored papers (Appendix 4). China is also the most important partner for the UK, Canada, Australia, Japan and Sweden. Of the Top 30 China leads (#9 times), while the US (#7) comes second.

Table 3 presents measures of the influence and position of countries in the network. The UK is the one with the highest *degree*, i.e., it has the most numerous links to the widest range of different countries. The UK is also, on average, the country with highest *closeness*: in a statistical sense, it is the country having the most direct and indirect connections to other countries. France is the leading "bridge-country", that is, it is most central by the amount of shortest paths that flow through it making an information intermediary (*betweenness*).[15] By observing the top positions for the network metrics (which are highly correlated) a more comprehensive picture of the structure of technological collaboration comes to the fore: along with the UK and France, the US and China (besides being the most important working pair) are the other two most structurally central countries in the 5G technology network (these four countries hold the Top 4 for the different metrics).

### 5.4.2. *Inter-institutional partnering*

There emerges one sizeable global network linking up 1,438 organisations (Fig. 12). Overall, the interconnectedness landscape is punctuated by at least two key features. First, the most influential players are university institutions (from the UK, Finland, Sweden, Portugal and China); the most central corporate players are Nokia Bell, Huawei and Orange Bell (Table 4). These observations are

[13] This structural context points to a potential for novelty as an innovation network (see Gilsing et al., 2008).

[14] Updated knowledge regarding the shape of a technology system can enable the design of policy interventions (Righi et al., 2020).

[15] A standard source like Wasserman and Faust (1994) refer to Degree centrality as based on the number of direct links between nodes, Closeness on the computation of the shortest linkage between all nodes, and Betweenness on the number of times a given node lies on the shortest pathway between other nodes highlights.

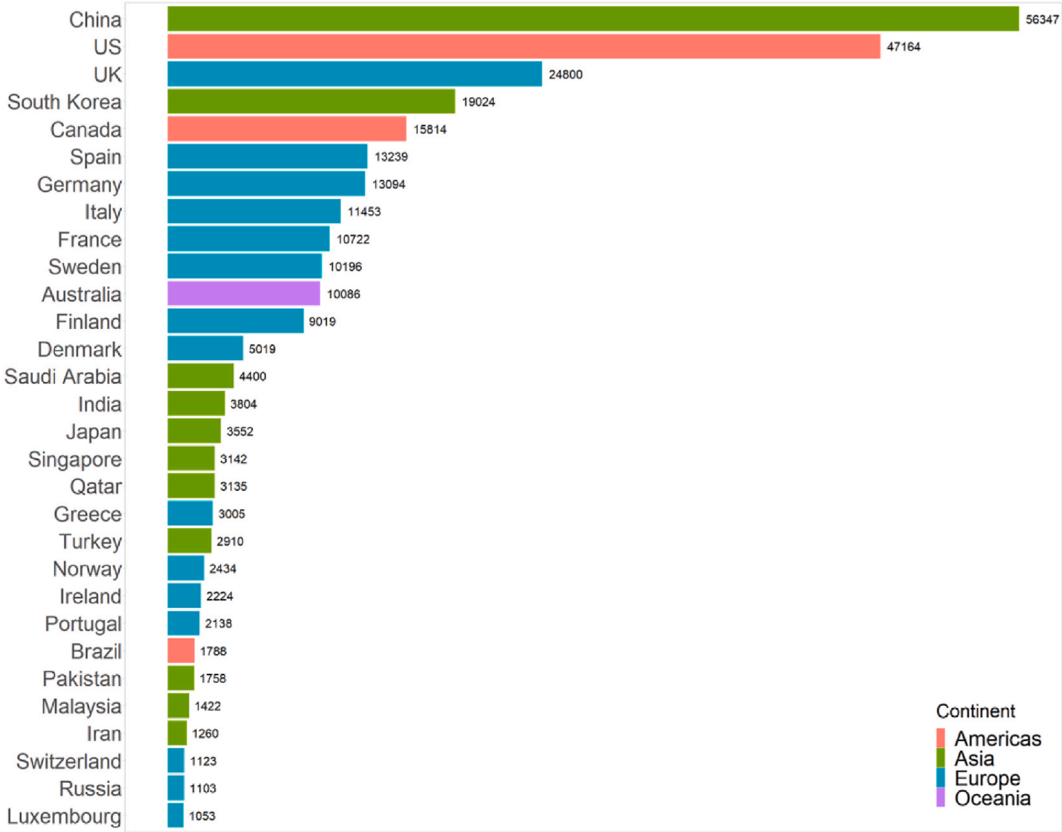



**Fig. 8.** Counts of all citations that accrue to authors established in a given country.

informative, since country data may be to aggregate to pick up the real knowledge bases (competence poles) existing in one given territory. Second, within the overall network, three communities are discernible: the largest community (in orange) is also the most influential) the one with the largest average citations) and is constituted mainly by academic institutions; another community (green) has a dominant corporate sector; and a smaller community (purple), which is the smallest and most academic, seems to differentiate primarily in terms of research profile (more ICT-intensive).

### *5.5. Research directions*

#### *5.5.1. Content mapping*

In interpreting the pre-market incubation of 5G, the concrete character of the actual technological evolution matters. Much of the interesting story that unfolds can perhaps be captured through the constellation of themes that characterises the nature of the technology. Fig. 13 depicts the keywords that appear in the total population of papers, the connections revealing the co-presence key concepts in the literature. This is a compressed snapshot in which the "5G" label is the most central; around it we see large (frequency) and close-by (co-presence) terms that illustrate underpinning concepts: both broad concepts (communication, network, system, design, wireless, architecture, …) and specific implementations (MIMO, NOMA, millimeter wave, cognitive radio, …), which are organised in particular technological dimensions (shades of grey). The revealed structure and dynamics of the 5G technological system can be further explored, with the help of keywords but through different modes of representation.

#### *5.5.2. Content dynamics*

Technological dynamics can be apprehended through publication keyword processing over time.; 5G-related trends are investigated and examined by focusing on term extraction and textmetric analysis: our approach below builds from single-words, or unigrams; a robust analysis, however, needs to consider bigrams and trigrams since more composite terms (multi-words) convey more precise concepts and point to concrete technical solutions (this is provided in Appendix 3).

Fig. 14 shows the presence and the growth of particular themes: dark colours reflect heavy relative presence, the numbers in the

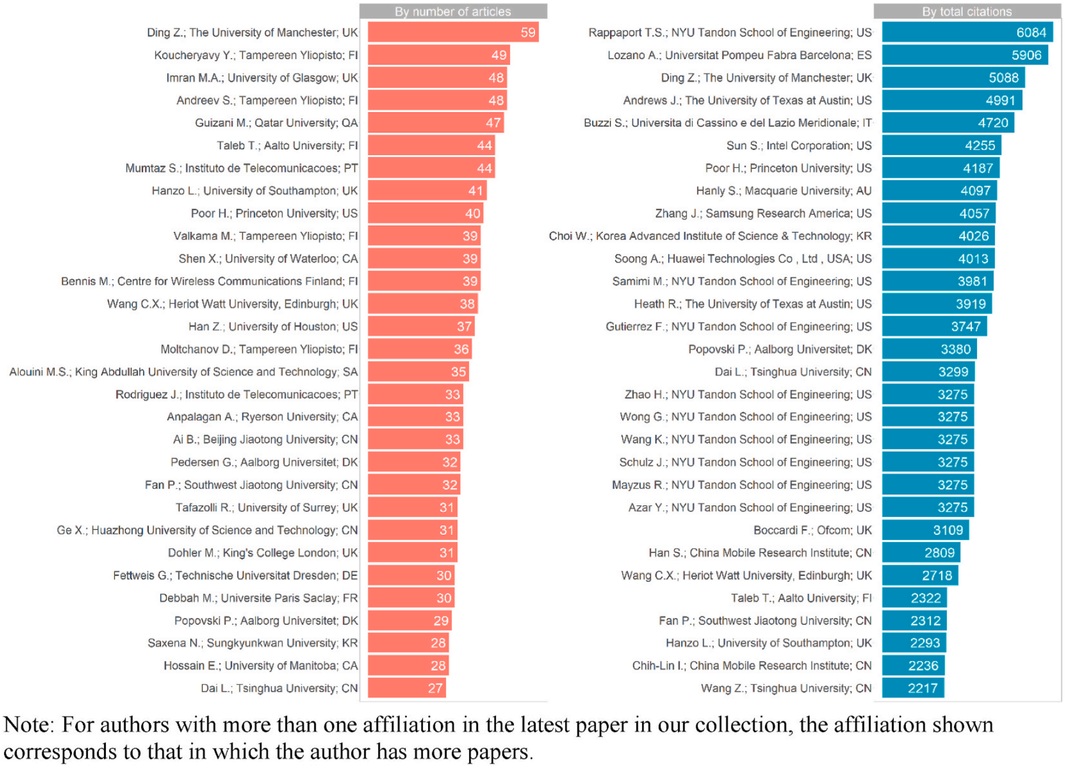



**Fig. 9.** Impactful contributors, Top 30, in number of publications and citations, 2005–2020.
Note: For authors with more than one affiliation in the latest paper in our collection, the affiliation shown corresponds to that in which the author has more papers.

tiles point to the frequencies of presence in abstracts in a given year, the Y-axis shows the terms with the highest growth rates (year-on-year) in descending order. We witness, for instance, the rapid rise of URLLC as a use case (ultra-reliable low latency communication), which appeared in the 3GPP's Release 15 of 2018 (the first full set of 5G standards).[16] As a whole (Fig. 15 and Appendix 3), it is possible to ascertain the distinctive importance of certain features in 5G systems: IOT, resource allocation/management, millimeter waves, software defined networks, etc. Moreover, among recently growing themes we can see new uses (blockchain), applications (unmanned aerial vehicles), features (network slicing), etc. These simple observations show how underlying characteristics and developments of 5G are effectively captured by textmetric approaches to the published material. Indeed, as one might see next, content analysis may also shed some light on the driving forces behind 5G and even on future developments.

## 5.6. Emerging challenges in 5G and beyond

### 5.6.1. Framing factors and rising themes in 5G

5G is a complex equipment system with differentiated subsystems in which the nature and pace of technical advance are modulated by a wide set of coordinated activities. It is of interest to know that a number of framing institutions appeared mentioned in the front-matter of our papers (i.e. title, abstract, keywords): 3GPP (in 411 papers), ETSI (#40), FCC (#22),[17] WRC (#8) and BEREC (#1). That multi-lateral bodies like 3GPP or ETSI surface in the literature underlines their role as leading institutional devices supporting progress in the field of telecom technologies.

In Fig. 15, several well-known challenges related to 5G are singled out: the rising trends highlight their differential dynamics.[18] In

[16] From Appendix 3 we also see the prominence of the non-orthogonal multiple access (NOMA) scheme, which was proposed as a candidate radio access approach in 5G cellular technologies.

[17] Federal Communications Commission, the US agency.

[18] These topics are illustrative, but they can be gleaned from a number of statements from international institutions, an early instance of which is the International Telecommunications Union (ITU) report of 2014 on *Future technology trends of terrestrial IMT systems* (https://www.itu.int/pub/R-REP-M.2320) while a more recent one, also from ITU, is the thematic backgrounder "5G - Fifth generation of mobile technologies" where a number of "challenges and solutions" are pointed out: the increasing complexity of infrastructure, the need for reducing energy consumption, the needed for common standards and stable regulation, the relevance of industrial settings (verticals) for 5G deployment, etc. (https://www.itu.int/en/mediacentre/backgrounders/Pages/5G-fifth-generation-of-mobile-technologies.aspx). See also Freitas et al. (2020a, 2020b).

**Table 2**
Details of the Top 20 contributions, 2000–2020.

| Article | Citations | Year | Authors | Lead Country | Countries | Affiliations | Affiliation type |
|---|---|---|---|---|---|---|---|
| What will 5G be? | 4013 | 2014 | Andrews J.; Buzzi S.; Choi W.; Hanly S.; Lozano A.; Soong A.; Zhang J. | US | US; Italy; South Korea; Australia; Spain | The University of Texas at Austin; Universita di Cassino e del Lazio Meridionale; Consorzio Nazionale Interuniversitario per le Telecomunicazioni; Korea Advanced Institute of Science & Technology; Macquarie University; Universitat Pompeu Fabra Barcelona; Huawei Technologies Co., Ltd., US; Samsung Electronics Co., Ltd. | Academic; Non Academic |
| Millimeter wave mobile communications for 5G cellular: It will work! | 3275 | 2013 | Rappaport T.; Sun S.; Mayzus R.; Zhao H.; Azar Y.; Wang K.; Wong G.; Schulz J.; Samimi M.; Gutierrez F. | US | US | NYU Tandon School of Engineering | Academic |
| Five disruptive technology directions for 5G | 1884 | 2014 | Boccardi F.; Heath R.; Lozano A.; Marzetta T.; Popovski P. | US | United Kingdom; US; Spain; Denmark | Vodafone; The University of Texas at Austin; Universitat Pompeu Fabra Barcelona; Nokia Bell Labs; Aalborg Universitet | Non Academic; Academic |
| Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results | 1321 | 2014 | Roh W.; Seol J.; Park J.; Lee B.; Lee J.; Kim Y.; Cho J.; Cheun K.; Aryanfar F. | South Korea | South Korea; United States | Samsung Electronics Co., Ltd.; Samsung Research America | Non Academic |
| Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends | 1202 | 2015 | Dai L.; Wang B.; Yuan Y.; Han S.; I C.L.; Wang Z. | China | China | Tsinghua University; ZTE Corporation; China Mobile Research Institute | Academic; Non Academic |
| Cellular architecture and key technologies for 5G wireless communication networks | 1140 | 2014 | Wang C.; Haider F.; Gao X.; You X.; Yang Y.; Yuan D.; Aggoune H.; Haas H.; Fletcher S.; Hepsaydir E. | UK | United Kingdom; China | Heriot Watt University, Edinburgh; Southeast University, Nanjing; Shanghaitech University; Shandong University; The University of Edinburgh; NEC Telecom Modus Ltd; Hutchison 3G | Academic; Non Academic |
| Scenarios for 5G mobile and wireless communications: the vision of the METIS project | 1084 | 2014 | Osseiran A.; Boccardi F.; Braun V.; Kusume K.; Marsch P.; Maternia M.; Queseth O.; Schellmann M.; Schotten H.; Taoka H.; Tullberg H.; Uusitalo M.; Timus B.; Fallgren M. | Sweden | Sweden; Italy; US; Germany; Poland; Japan; Finland | The Royal Institute of Technology KTH; Universita Degli Studi di Padova; Nokia Bell Labs; Wireless Research Group; Technische Universitat Dresden; Wroclaw University of Science and Technology; Chalmers University of Technology; Technical University of Munich; Rheinisch Westfalische Technische Hochschule Aachen; Kyoto University; Lunds Universitet; Aalto University | Academic; Non Academic |
| On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users | 952 | 2014 | Ding Z.; Yang Z.; Fan P.; Poor H. | US | US; United Kingdom; China | Princeton University; School of Computing and Communications, Lancaster University; Southwest Jiaotong University | Academic |
| Next generation 5G wireless networks: A comprehensive survey | 932 | 2016 | Agiwal M.; Roy A.; Saxena N. | South Korea | South Korea | Sungkyunkwan University; Samsung Electronics Co., Ltd. | Academic; Non Academic |

(continued on next page)

**Table 2** (*continued*)

| Article | Citations | Year | Authors | Lead Country | Countries | Affiliations | Affiliation type |
|---|---|---|---|---|---|---|---|
| A survey on mobile edge computing: The communication perspective | 874 | 2017 | Mao Y.; You C.; Zhang J.; Huang K.; Letaief K-B. | China | Hong Kong; Qatar | Hong Kong University of Science and Technology; Hamad Bin Khalifa University | Academic |
| A survey of 5G network: architecture and emerging technologies | 851 | 2015 | Gupta A.; Jha R. | India | India | Shri Mata Vaishno Devi University | Academic |
| An overview of signal processing techniques for millimeter wave MIMO systems | 813 | 2016 | Heath R.W.; Gonzalez-Prelcic N.; Rangan S.; Roh W.; Sayeed A.M. | US | US; Spain; South Korea | The University of Texas at Austin; Universidade de Vigo; New York University; Samsung Electronics Co., Ltd.; University of Wisconsin Madison | Academic; Non Academic |
| Network densification: the dominant theme for wireless evolution into 5G | 688 | 2014 | Bhushan N.; Li J.; Malladi D.; Gilmore R.; Brenner D.; Damnjanovic A.; Sukhavasi R.T.; Patel C.; Geirhofer S. | Germany | Germany | Qualcomm Technologies, Incorporated | Non Academic |
| Application of non-orthogonal multiple access in LTE and 5G networks | 686 | 2017 | Ding Z.; Liu Y.; Choi J.; Sun Q.; Elkashlan M.; Chih-Lin I.; Poor H. | US | US; United Kingdom; South Korea; China | Princeton University; Lancaster University; Queen Mary University of London; Gwangju Institute of Science and Technology; China Mobile Research Institute | Academic |
| Cache in the air: exploiting content caching and delivery techniques for 5G systems | 638 | 2014 | Wang X.; Chen M.; Taleb T.; Ksentini A.; Leung V.C. M. | China | China; Germany; France | Huazhong University of Science and Technology; NEC Laboratories Europe GmbH; Universite De Rennes 1 | Academic; Non Academic |
| Power-domain non-orthogonal multiple access (NOMA) in 5G systems: potentials and challenges | 632 | 2017 | Islam S.; Avazov N.; Dobre O.; Kwak K. | South Korea | South Korea; Canada | Inha University, Incheon; Memorial University of Newfoundland | Academic |
| Living on the edge: The role of proactive caching in 5G wireless networks | 626 | 2014 | Bastug E.; Bennis M.; Debbah M. | France | Turkey; Finland; France | Fatih Universitesi; Centre for Wireless Communications Finland; Supelec Campus De Gif | Academic |
| Cooperative non-orthogonal multiple access in 5G systems | 618 | 2015 | Ding Z.; Peng M.; Poor H. | US | US; United Kingdom; China | Princeton University; School of Computing and Communications, Lancaster University; Beijing University Of Posts And Telecommunications | Academic |
| Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions | 595 | 2016 | Ding Z.; Fan P.; Poor H. | US | US; China | Princeton University; Southwest Jiaotong University | Academic |
| Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions | 557 | 2014 | Tehrani M.; Uysal M.; Yanikomeroglu H. | Canada | Canada; Turkey | University Of Waterloo; Ozyegin University; Carleton University | Academic |

particular, we confirm how important for 5G are, or have become, dimensions like infrastructure (physical, logical), security (which includes cybersecurity), sharing (of assets, including spectrum and facilities), verticals (i.e. use-sectors), and (international) standards. Other aspects turn out to surface, although with less frequency, in this type of empirical evidence (e.g. sustainability, patents).

### *5.6.2. The next big thing*

"6G" is putatively the next generation of wireless communications technologies supporting cellular data networks. The technological configuration is still under development, and its full features are yet to be articulated. Table 5 indicates that the early days of 6G

| | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|
| Canada | 1.11 (9) | 1.23 (30) | 1.14 (56) | 1.27 (103) | 1.14 (146) | 1.13 (177) |
| Finland | 1 (5) | 1.5 (20) | 1.38 (40) | 1.5 (66) | 1.45 (84) | 1.14 (80) |
| Australia | 1 (1) | 1.14 (7) | 1.18 (17) | 1.09 (43) | 1.08 (71) | 1.16 (85) |
| Germany | 1 (16) | 1.85 (20) | 1.43 (49) | 1.38 (76) | 1.31 (74) | 1.21 (101) |
| UK | 1.27 (11) | 1.28 (32) | 1.35 (99) | 1.32 (140) | 1.21 (223) | 1.21 (236) |
| Spain | 1 (3) | 1.36 (14) | 1.44 (34) | 1.37 (90) | 1.25 (88) | 1.24 (148) |
| Sweden | 1.38 (8) | 1.65 (17) | 1.16 (50) | 1.18 (71) | 1.13 (75) | 1.24 (91) |
| USA | 1.22 (32) | 1.32 (53) | 1.3 (116) | 1.12 (236) | 1.22 (322) | 1.26 (382) |
| Portugal | 1 (1) | 1.33 (3) | 1.75 (12) | 1.78 (27) | 1.5 (22) | 1.27 (49) |
| France | 1.08 (13) | 1.38 (16) | 1.52 (42) | 1.48 (60) | 1.28 (72) | 1.27 (103) |
| Italy | 1 (7) | 1.33 (12) | 1.22 (32) | 1.55 (64) | 1.33 (94) | 1.29 (126) |
| China | 1.33 (30) | 1.57 (135) | 1.51 (249) | 1.48 (484) | 1.39 (750) | 1.3 (915) |
| Denmark | 2 (2) | 1.83 (6) | 1.53 (17) | 1.62 (29) | 1.43 (44) | 1.31 (26) |
| Greece | 1 (1) | 1.5 (8) | 1.67 (21) | 1.57 (42) | 1.42 (24) | 1.32 (41) |
| Brazil | 1 (2) | 1.2 (5) | 1.3 (10) | 1.72 (18) | 1.5 (28) | 1.36 (53) |
| South Korea | 1.3 (10) | 1.5 (16) | 1.66 (67) | 1.62 (105) | 1.5 (184) | 1.38 (183) |
| Pakistan | | | 1.8 (5) | 1.9 (21) | 1.63 (63) | 1.51 (71) |
| Saudi Arabia | 1.2 (5) | 1.2 (5) | 1.16 (19) | 1.41 (29) | 1.54 (46) | 1.6 (52) |
| India | 1 (1) | 1.86 (7) | 1.47 (17) | 1.81 (43) | 1.88 (94) | 1.84 (156) |
| Malaysia | 1 (1) | 2.67 (3) | 1.56 (9) | 2 (21) | 2 (31) | 1.85 (47) |
| Japan | 1 (1) | 2.44 (16) | 1.67 (18) | 2.05 (59) | 1.66 (44) | 1.95 (86) |

Note: average quartile inserted in each tile (higher numbers mean a smaller quartile; the closer to 1.00 the better); in brackets is the quantity of papers per year

**Fig. 10.** Average journal quartile of publications by country, per year.
Note: average quartile inserted in each tile (higher numbers mean a smaller quartile; the closer to 1.00 the better); in brackets is the quantity of papers per year.

can be traced to the mid-2010s.[19] China entered early and retained its leadership; the US was a laggard but by 2020 was second in terms of papers. Overall, 6G seems to be developing faster than the previous generation, and with a quite diverse array of contributors from the outset.

The search for substitutes and complementors of 5G within the database yields the following results: only two papers address "Open RAN", an alternative to the known 5G set-up (both published in 2020); six papers refer to Wi-Fi 6 (five published in 2020; of the total three are by China-based authors, and the other three are North-American-based). That these mentions occur, albeit at a low frequency, signal that the 5G ecosystem should be understood in a broader canvas and that further research should explore these trajectories in greater detail.

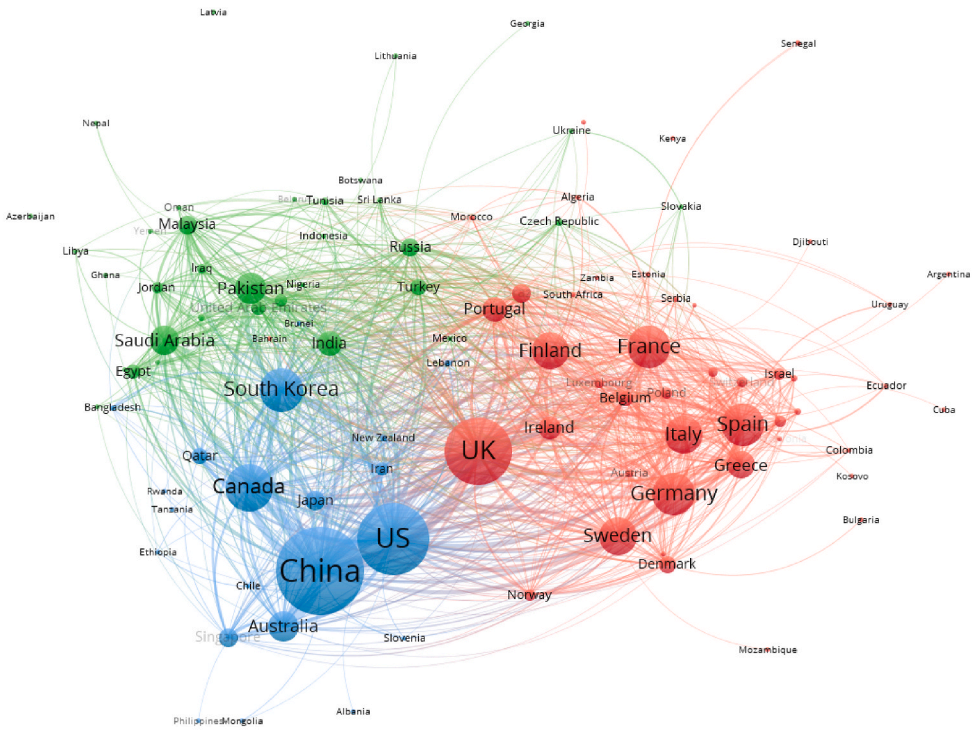
## 6. Conclusions

The origins and growth of ensembles of interlinked electronic computers is a defining feature of the current information revolution (see Freeman & Louçã, 2001). 5G is an important vector of this expansive informational realm, especially as it has been touted as a "revolutionary mobile communication technology" (IDB 2020, p. ix), a "critical and emergent" infrastructure (UK Parliament, 2021; UK Parliament, 2020) associated with the "next production revolution" (OECD 2021, p. 115), and even "a key battleground in a broader struggle for control over the industries of the future" (EIB, 2021).

In this paper, we apply an enhanced bibliometric and text-mining methodological approach to a large dataset from individual journal articles carrying detailed information on authors, institutions, geographies, collaborations, disciplines, impact, and topic dynamics. The first outcome of this underexploited combination of techniques and high-quality sources in the realm of telecommunications economics and policy is a summary panoramic account of advances in 5G systems and the factors behind it. This novel comprehensive and integrative methodology allows us to enhance the understanding of both the quantity and the qualities of the evolution and growth in electronic communications, a fundamental area of cutting-edge research and innovation in the 21st century.

We find that knowledge-creating processes pertaining to 5G follow an inherently evolutionary process (Nelson et al., 2018). 5G

[19] This refers to the presence of 6G within the extracted data, which it should be remembered was narrowly defined to capture 5G; i.e. other papers on 6G are excluded.




Note: Optimal partition is three, according to the algorithm of Blondel et al. (2008)

**Fig. 11.** Country collaboration, 2013–2020.
Note: Optimal partition is three, according to the algorithm of Blondel et al. (2008).

**Table 3**
Country network statistics, ranked.

| Country rank | Degree | Country rank | Betweenness | Country rank | Closeness |
|---|---|---|---|---|---|
| UK | 0.71 | France | 0.110 | UK | 0.0077 |
| China | 0.68 | UK | 0.107 | China | 0.0076 |
| US | 0.66 | China | 0.096 | US | 0.0074 |
| France | 0.65 | US | 0.078 | France | 0.0073 |
| Canada | 0.59 | Spain | 0.043 | Canada | 0.0070 |
| Spain | 0.54 | Kazakhstan | 0.038 | Italy | 0.0068 |
| Italy | 0.53 | Sweden | 0.035 | Spain | 0.0068 |
| South Korea | 0.52 | South Korea | 0.034 | Sweden | 0.0068 |
| Sweden | 0.52 | Canada | 0.033 | South Korea | 0.0067 |
| India | 0.50 | Malaysia | 0.031 | India | 0.0067 |
| Finland | 0.50 | Italy | 0.031 | Finland | 0.0066 |
| Germany | 0.49 | Turkey | 0.030 | Pakistan | 0.0066 |
| Pakistan | 0.49 | Brazil | 0.027 | Germany | 0.0065 |
| Saudi Arabia | 0.48 | Pakistan | 0.027 | Saudi Arabia | 0.0065 |
| Malaysia | 0.46 | South Africa | 0.022 | Malaysia | 0.0064 |
| Greece | 0.43 | India | 0.019 | Greece | 0.0063 |
| Portugal | 0.43 | Saudi Arabia | 0.019 | Portugal | 0.0063 |
| Ireland | 0.43 | Finland | 0.015 | Ireland | 0.0063 |
| Australia | 0.41 | Denmark | 0.015 | Belgium | 0.0062 |
| Belgium | 0.40 | Serbia | 0.011 | Australia | 0.0061 |

publishing emerged from 2010 onwards and proliferated thereafter (a growth rate averaging over 80% per year) and got better over time (increasingly higher-standing science and technology outlets, generated ever-increasing citations). The rise of 5G was driven by a small number of countries, namely China and the US, that made contributions in large amounts and with great impact (as measured by citations). Notwithstanding, this high-tech agenda had a degree of inclusiveness: country composition became more diverse, and other upper-middle (besides China) and lower income (like India or Pakistan) countries asserted themselves as active contributors, that is, peripheral players emerged as a substantive part of the ecosystem and pushed 5G innovation as a whole.

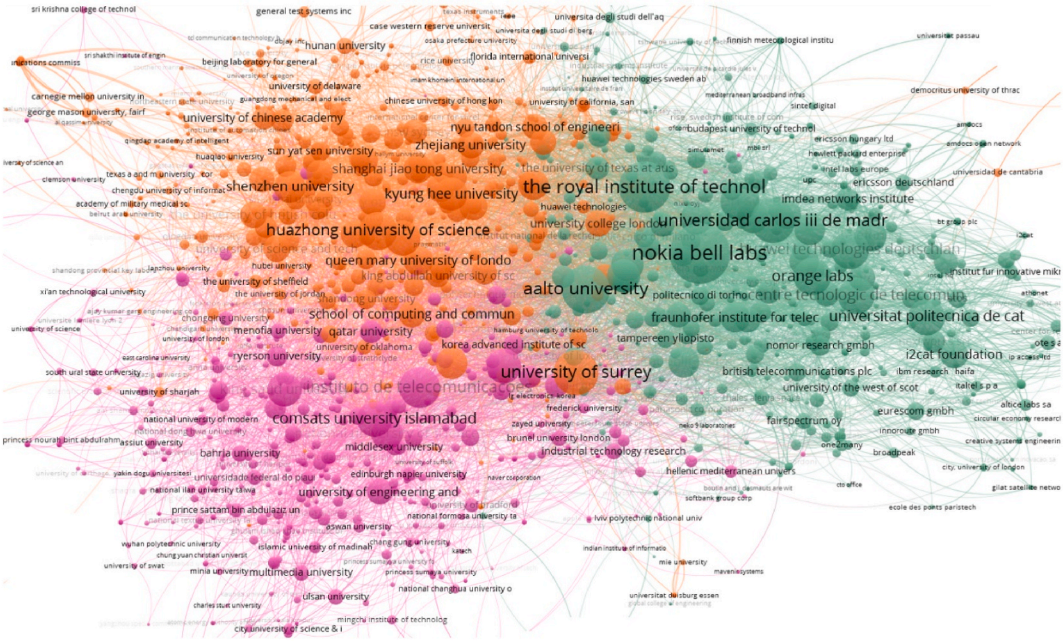
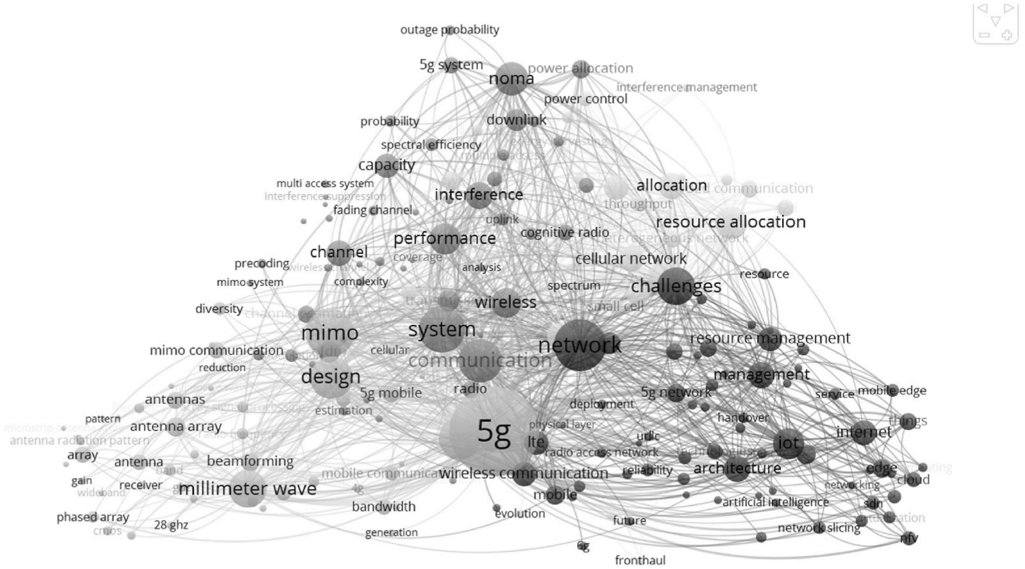



**Fig. 12.** Intra-organisational networks.

**Table 4**
Intra-organisational network statistics (Top 20 performers).

| Affiliation | Degree | Affiliation 2 | Betweenness | Affiliation 3 | Closeness |
|---|---|---|---|---|---|
| Nokia Bell Labs | 0.126 | University of Surrey | 0.053 | Aalto University | 0.000282 |
| The Royal Institute of Technology KTH | 0.103 | Nokia Bell Labs | 0.051 | University of Surrey | 0.000280 |
| University of Surrey | 0.095 | Aalto University | 0.048 | Instituto de Telecomunicações | 0.000278 |
| Aalto University | 0.093 | Instituto de Telecomunicações | 0.048 | Nokia Bell Labs | 0.000277 |
| Instituto de Telecomunicações | 0.083 | The Royal Institute of Technology KTH | 0.038 | Huazhong University of Science and Technology | 0.000277 |
| Universidad Carlos III de Madrid | 0.079 | King Saud University | 0.030 | Huawei Technologies co, LTD | 0.000274 |
| Huazhong University of Science and Technology | 0.075 | Beijing Jiaotong University | 0.029 | King's College London | 0.000271 |
| Universitat Politecnica de Catalunya | 0.070 | Huazhong University of Science and Technology | 0.028 | Beijing Jiaotong University | 0.000270 |
| Orange Labs | 0.070 | Huawei Technologies Co. | 0.028 | University of Southampton | 0.000270 |
| Beijing Jiaotong University | 0.068 | Comsats University Islamabad | 0.028 | The Royal Institute of Technology KTH | 0.000268 |
| Huawei Technologies co, LTD | 0.065 | Universitat Politecnica de Catalunya | 0.024 | Shanghai Jiao Tong University | 0.000268 |
| Comsats University Islamabad | 0.065 | Universidad Carlos III de Madrid | 0.023 | Universidad Carlos III de Madrid | 0.000267 |
| Centre Tecnologic de Telecomunicacions de Catalunya | 0.062 | King's College London | 0.021 | Comsats University Islamabad | 0.000267 |
| King Saud University | 0.061 | Zhejiang University | 0.019 | Qatar University | 0.000265 |
| Ericsson Sweden | 0.059 | Oulun Yliopisto | 0.019 | Universitat Politecnica de Valencia | 0.000264 |
| King's College London | 0.059 | Technische Universitat Dresden | 0.019 | King Abdullah University of Science and Technology | 0.000264 |
| Technische Universitat Dresden | 0.058 | Ton Duc Thang University | 0.018 | Zhejiang University | 0.000264 |
| University of Southampton | 0.055 | University of Southampton | 0.018 | Fraunhofer Institute for Telecommunications, Heinrich Hertz Institut, HHI | 0.000264 |
| Shanghai Jiao Tong University | 0.054 | Orange Labs | 0.018 | University of Toronto | 0.000262 |
| Huawei Technologies Deutschland GMBH | 0.054 | Universitat Politecnica de Valencia | 0.017 | Beijing Institute of Technology | 0.000262 |

By 2014, published 5G research took a sharp and sustained increase, which mostly took the form of an electronics engineering trajectory with an increasing digital component; by 2020, the degree of fusion between telecommunications and computing was clear. Also, by the turn of the new decade, when the first commercial experiments became live, a number of other issues were unfolding,




Note: Preference was given to the free display of the authors' own labelling making this is an informationally cost-efficient (raw) representation, derived directly from the original paper keywords as they were found in the sample material; no join-up of terms or construct build-up was attempted, only duplicates were collapsed together (e.g. singular/plural variations for the same term)

**Fig. 13.** A map of 5G keywords, all papers.
Note: Preference was given to the free display of the authors' own labelling making this is an informationally cost-efficient (raw) representation, derived directly from the original paper keywords as they were found in the sample material; no join-up of terms or construct build-up was attempted, only duplicates were collapsed together (e.g. singular/plural variations for the same term).

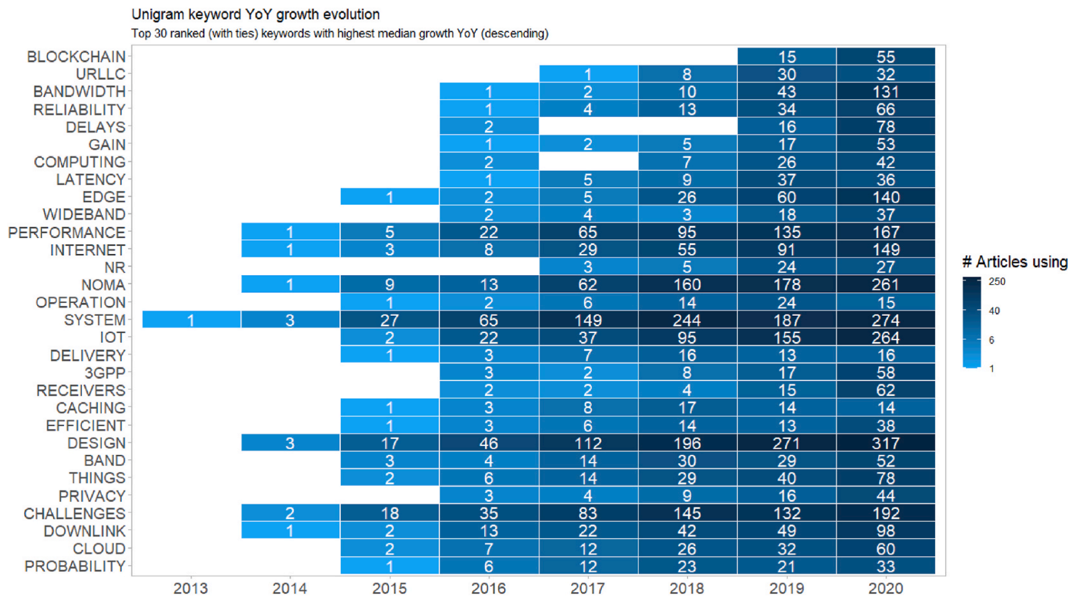



**Fig. 14.** Growing technologies, single keywords (unigrams).

namely areas of application (transport, healthcare), inputs (energy, materials), externalities (environment, health), and governance challenges (expressed in many economics, social sciences, and international relations publications). As far as institutional sectors are concerned universities are the most dynamic, but global firms (especially telecom equipment manufacturers) and non-governmental organisations (namely, private research foundations) have also been top actors.

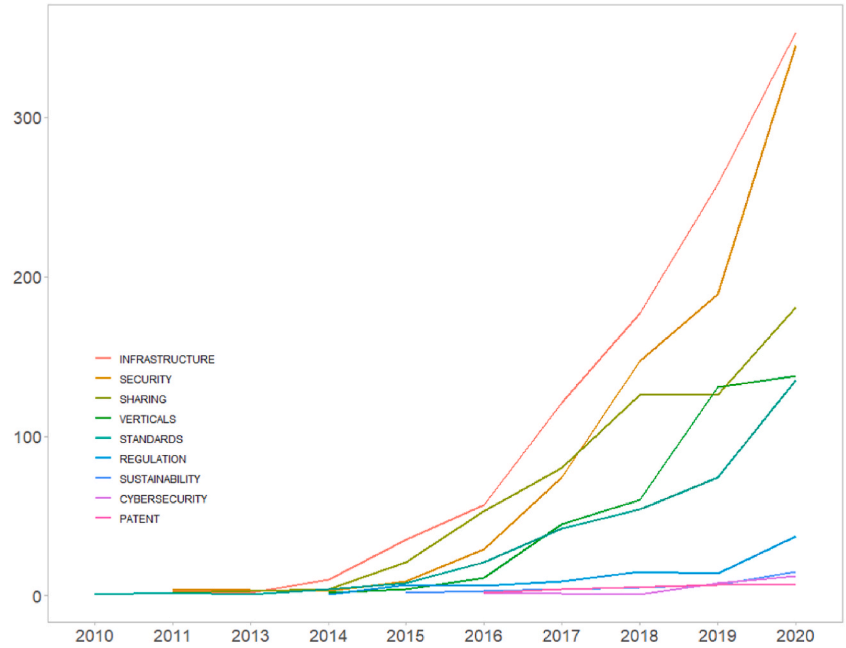



**Fig. 15.** Major 5G challenges.

**Table 5**
The beginnings of 6G.

| Year | Articles | Countries |
|---|---|---|
| 2015 | 1 | China (1) |
| 2016 | 4 | UK (2); France (2); Germany (2); Spain (2); Saudi Arabia (1); Malasya (1); Poland (1); Sweden (1); Denmark (1); Greece (1); Italy (1) |
| 2017 | 7 | China (4); US (1); Turkey (1); Malasia (1); UK (1); Pakistan (1); Saudi Arabia (1); Spain (1) |
| 2018 | 14 | China (6); UK (4); South Korea (2); Pakistan (2); Canada (1); Greece (1); Japan (1); Serbia (1); Russia (1); India (1) |
| 2019 | 39 | China (22); UK (7); US (5); Canada (4); South Korea (3); India (3); Australia (2); France (2); Finland (2); Singapore (1); Japan (1); Iran (1); Qatar (1); Iraq (1); Pakistan (1); Luxembourg (1); Spain (1); Sweden (1); Ireland (1); Brazil (1); Russia (1); Serbia (1); Ukraine (1) |
| 2020 | 121 | China (50); US (30); UK (14); Japan (10); Finland (9); India (8); Canada (8); Saudi Arabia (6); South Korea (6); Italy (6); Turkey (6); Spain (5); Australia (5); France (5); Germany (5); Malasya (3); Greece (3); Portugal (2); Poland (2); Denmark (2); Brazil (2); Singapore (2); Sweden (2); Egypt (1); Colombia (1); Czech Republic (1); Israel (1); Sri Lanka (1); Belgium (1); United Arab Emirates (1); Cyprus (1); Netherlands (1); Ukraine (1); Slovakia (1); Chile (1); Austria (1); Russia (1); Bangladesh (1); Pakistan (1); Croatia (1) |

Some methodological limitations constrain the reach of our findings. Indeed, these limitations also flag future ways to improve our empirical paper. First, we relied on *codified contributions* of a high level of sophistication; for reasons of database reliability, we did not consider proceedings and grey literature that, arguably, are faster to appear and closer to *tacit expertise* and *industrial application*. Second, *technology-based* indicators like patents of invention and product-announcements were not considered. Clearly, not all workable ideas filter through our science-based indicator, and hence results have to be qualified accordingly. Third, other sources (standards, trademarks) could provide ways to check the robustness of our stylised facts, but future studies should also benefit from the opportunity of relying on *market diffusion* data, such as equipment deployment and final user data, as 5G rolls out in the 2020s. Finally, an explanatory agenda regarding differential performance over time, across geographies, and regarding players and the communities around them, and likewise for the governance tools and standards deployed, is needed (e.g. Curado et al., 2021; Damásio et al., 2018; Lyra et al., 2021; Paredes et al., 2022; Wiegmann et al., 2022).

The trends and turns in the emergence of the 5G technical system show how plural and collegial innovation has been. The nexus of national and international institutions, both formal and informal, seems to have been efficient and coordinated enough for fostering robust, open and cumulative change. Along these lines, public policy, regulatory strategy and technological diplomacy orientations that contribute to such global commons are expected to enhance socio-economic development at large. Initiatives that assure that the free flow of knowledge remains uninterrupted, that sustain cooperation around complex innovation agendas, and that facilitate access to frontier research have the potential to decisively contribute to advances not only in science and technology but also in terms in human and ecological progress as a whole.

## Classification codes

L5 Regulation and Industrial Policy; L63 Microelectronics, Computers, Communications Equipment; O31 Innovation and Invention: Processes and Incentives.

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## Appendices

**Appendix 1**
Re-classification of WoS thematic categories.

| Scopus Categories | Category Group |
|---|---|
| Engineering | Electronics and Telecom Engineering |
| Telecommunications | Electronics and Telecom Engineering |
| Computer Science | Information Technology and Processing |
| Optics | Electronics and Telecom Engineering |
| Transportation | Transportation |
| Physics | Electronics and Telecom Engineering |
| Chemistry | Materials and Chemistry |
| Instruments & Instrumentation | Information Technology and Processing |
| Materials Science | Materials and Chemistry |
| Science & Technology - Other Topics | Electronics and Telecom Engineering |
| Automation & Control Systems | Information Technology and Processing |
| Operations Research & Management Science | Information Technology and Processing |
| Environmental Sciences & Ecology | Environment |
| Information Science & Library Science | Information Technology and Processing |
| Mathematics | Information Technology and Processing |
| Communication | Social Sciences and Humanities |
| Energy & Fuels | Energy |
| Business & Economics | Business and Economics |
| Remote Sensing | Information Technology and Processing |
| Public, Environmental & Occupational Health | Health and BioSciences |
| Meteorology & Atmospheric Sciences | Environment |
| Education & Educational Research | Education |
| Astronomy & Astrophysics | Electronics and Telecom Engineering |
| Medical Informatics | Health and BioSciences |
| Geochemistry & Geophysics | Electronics and Telecom Engineering |
| Government & Law | Public Policy and International Governance |
| Biophysics | Health and BioSciences |
| Metallurgy & Metallurgical Engineering | Electronics and Telecom Engineering |
| International Relations | Public Policy and International Governance |
| Radiology, Nuclear Medicine & Medical Imaging | Health and BioSciences |
| Polymer Science | Materials and Chemistry |
| Life Sciences & Biomedicine - Other Topics | Health and BioSciences |
| Health Care Sciences & Services | Health and BioSciences |
| Robotics | Information Technology and Processing |
| Public Administration | Public Policy and International Governance |
| Physical Geography | Electronics and Telecom Engineering |
| Nuclear Science & Technology | Information Technology and Processing |
| Imaging Science & Photographic Technology | Electronics and Telecom Engineering |
| Construction & Building Technology | Electronics and Telecom Engineering |
| Mechanics | Electronics and Telecom Engineering |
| General & Internal Medicine | Health and BioSciences |
| Geography | Information Technology and Processing |
| Geology | Environment |

(*continued on next page*)

**Appendix 1** (*continued*)

| Scopus Categories | Category Group |
|---|---|
| Neurosciences & Neurology | Health and BioSciences |
| Surgery | Health and BioSciences |
| Social Sciences - Other Topics | Social Sciences and Humanities |
| Acoustics | Electronics and Telecom Engineering |
| Psychology | Health and BioSciences |
| Oncology | Health and BioSciences |
| Research & Experimental Medicine | Health and BioSciences |
| Oceanography | Environment |
| Biotechnology & Applied Microbiology | Materials and Chemistry |
| Social Issues | Social Sciences and Humanities |
| Rehabilitation | Health and BioSciences |
| Physiology | Materials and Chemistry |
| Electrochemistry | Materials and Chemistry |
| Mineralogy | Materials and Chemistry |
| Mining & Mineral Processing | Materials and Chemistry |
| Toxicology | Health and BioSciences |
| Thermodynamics | Electronics and Telecom Engineering |
| Pharmacology & Pharmacy | Health and BioSciences |
| Crystallography | Electronics and Telecom Engineering |
| Spectroscopy | Electronics and Telecom Engineering |
| History | Social Sciences and Humanities |

**Appendix 2**
Most cited papers citing the most cited 5G-related papers, key characteristics.

| Original paper | Present in collection | Median year of citation | Common keywords | Common countries | Common affiliations | Common categories |
|---|---|---|---|---|---|---|
| A survey on mobile edge computing: The communication perspective | 17% | 2019 | Optimization (24); Mobile Edge Computing (23); Resource Allocation (22); Cloud (17); Resource-Allocation (17) | China (73); US (30); United Kingdom (19); Canada (12); Korea (8) | Beijing Univ Posts and Telecommun (11); Xidian Univ (10); Univ Elect Sci and Technol China (7); Tsinghua Univ (6); Sun Yat Sen Univ (6) | Telecommunications (86); Engineering (84); Computer Science (62); Transportation (9); Automation & Control Systems (3) |
| A survey of 5G network: architecture and emerging technologies | 52% | 2018 | Architecture (16); Massive MIMO (16); Cellular Networks (12); Systems (12); Internet (11) | China (36); United Kingdom (15); Canada (12); US (10); India (9) | Beijing Univ Posts and Telecommun (6); Shri Mata Vaishno Devi Univ (6); Univ Elect Sci and Technol China (5); Tsinghua Univ (3); Linkoping Univ (3) | Telecommunications (82); Computer Science (67); Engineering (62); Transportation (5); Optics (3) |
| An overview of signal processing techniques for millimeter wave MIMO systems | 41% | 2018 | Channel Estimation (34); Massive MIMO (23); Design (19); Systems (16); MIMO (14) | China (49); US (46); Sweden (12); Australia (10); Spain (10) | Southeast Univ (20); Univ Texas Austin (16); Tsinghua Univ (11); Sch Elect and Comp Engn (7); Univ Vigo (7) | Engineering (94); Telecommunications (80); Computer Science (20); Transportation (6); Materials Science (1) |
| Application of non-orthogonal multiple access in LTE and 5G networks | 39% | 2018 | Nonorthogonal Multiple-Access (39); Power Allocation (21); Noma (19); Systems (18); Performance (17) | China (72); United Kingdom (42); US (25); Australia (19); Canada (16) | Queen Mary Univ London (19); Univ Lancaster (17); Xidian Univ (13); Princeton Univ (10); Univ Manchester (9) | Telecommunications (94); Engineering (87); Computer Science (22); Transportation (5); Chemistry (2) |
| Next generation 5G wireless networks: A comprehensive survey | 65% | 2018 | Wireless Networks (25); Massive MIMO (13); Internet (11); Software-Defined Networking (10); Architecture (9) | China (52); US (26); UK (22); Korea (12); Canada (11) | Southeast Univ (7); Beijing Univ Posts and Telecommun (6); Tsinghua Univ (5); Univ Oulu (5); Xidian Univ (4) | Telecommunications (90); Computer Science (71); Engineering (63); Transportation (3); Health Care Sciences & Services (1) |
| Power-domain non-orthogonal multiple access (NOMA) in 5G systems: potentials and challenges | 63% | 2018 | Nonorthogonal Multiple-Access (57); Noma (23); Challenges (23); Power Allocation (22); Systems (20) | China (55); UK (29); Canada (25); South Korea (17); US (15) | Mem Univ (9); Univ Manchester (8); Zhejiang Univ (7); Xidian Univ (7); Princeton Univ (7) | Telecommunications (93); Engineering (89); Computer Science (45); Transportation (9); Chemistry (2) |
| Cache in the air: exploiting content caching and delivery | 51% | 2017 | Delivery (16); Stochastic Geometry (13); Wireless (12); Content Delivery (11); Optimization (9) | China (62); US (41); Canada (20); | Beijing Univ Posts and Telecommun (14); Shanghai Jiao Tong Univ (11); Carleton Univ (8); | Telecommunications (96); Engineering (82); Computer Science (48); Transportation (5); Communication (1) |

(continued on next page)

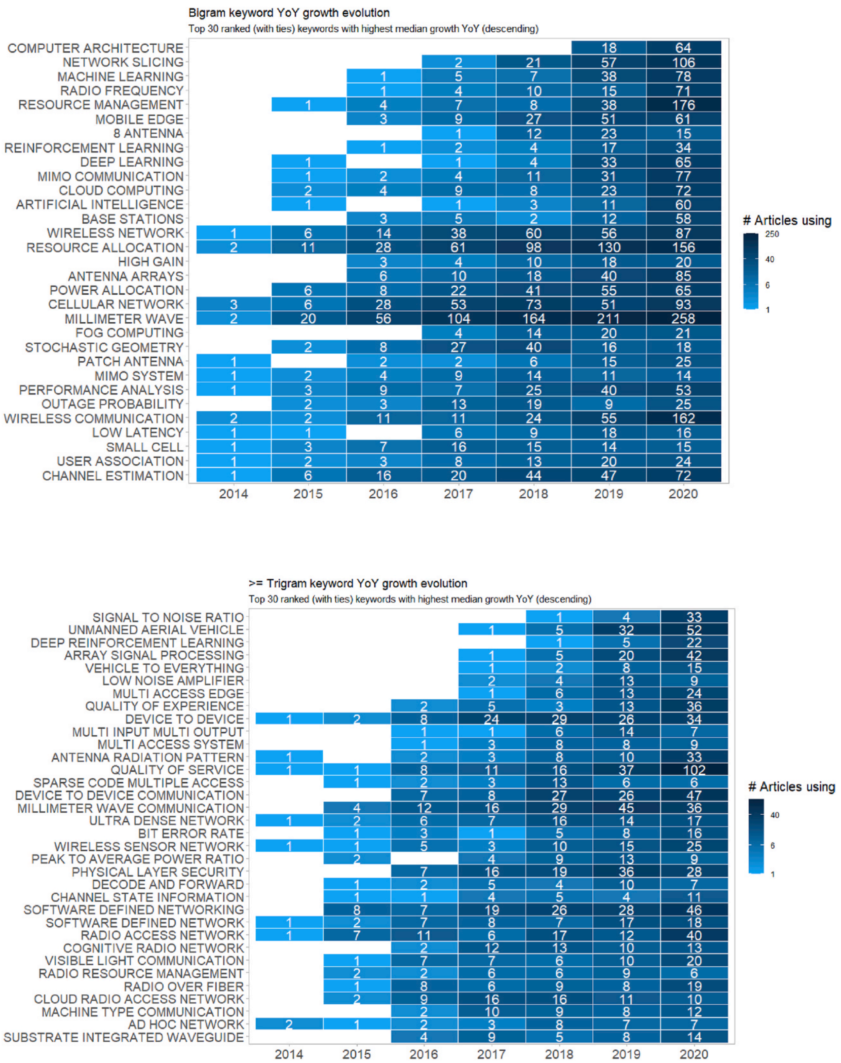
**Appendix 2** (*continued*)

| Original paper | Present in collection | Median year of citation | Common keywords | Common countries | Common affiliations | Common categories |
|---|---|---|---|---|---|---|
| techniques for 5G systems | | | | France (13); Finland (12) | Univ British Columbia (7); Huazhong Univ Sci and Technol (5) | |
| Cooperative non-orthogonal multiple access in 5G systems | 52% | 2017 | Nonorthogonal Multiple-Access (37); Power Allocation (22); Systems (20); Non-Orthogonal Multiple Access (19); Outage Probability (17) | China (71); UK (41); US (23); South Korea (16); Canada (14) | Univ Lancaster (26); Xidian Univ (15); Princeton Univ (12); Queen Mary Univ London (10); Southwest Jiaotong Univ (10) | Telecommunications (93); Engineering (80); Computer Science (21); Transportation (11); Chemistry (1) |
| Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions | 43% | 2017 | To-Device Communication (28); Cellular Networks (22); Challenges (21); Massive Mimo (18); Resource-Allocation (17) | China (37); USA (27); UK (15); Canada (15); India (9) | Tsinghua Univ (6); Univ Lancaster (5); Muroran Inst Technol (4); Queens Univ Belfast (3); Beijing Univ Posts and Telecommun (3) | Telecommunications (86); Engineering (76); Computer Science (51); Transportation (14); Instruments & Instrumentation (1) |
| Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions | 45% | 2017 | Nonorthogonal Multiple-Access (33); Power Allocation (19); Noma (18); Performance (18); Systems (17) | China (63); UK (38); USA (26); Australia (14); Canada (14) | Univ Lancaster (18); Queen Mary Univ London (14); Princeton Univ (10); Xidian Univ (10); Southeast Univ (8) | Engineering (89); Telecommunications (86); Computer Science (24); Transportation (8) |
| Living on the edge: The role of proactive caching in 5G wireless networks | 46% | 2017 | Wireless Networks (15); Wireless (11); Content Delivery (10); Internet (9); Cellular Networks (9) | China (54); USA (43); France (15); UK (13); Canada (13) | Beijing Univ Posts and Telecommun (10); Southeast Univ (9); Math and Algorithm Sci Lab (9); Princeton Univ (8); Shanghai Jiao Tong Univ (8) | Telecommunications (88); Engineering (75); Computer Science (42); Transportation (2); Automation & Control Systems (1) |
| Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends | 50% | 2017 | Nonorthogonal Multiple-Access (37); Power Allocation (21); Challenges (19); Noma (18); Performance (14) | China (69); UK (45); USA (23); Canada (16); Australia (11) | Univ Lancaster (15); Queen Mary Univ London (11); Xidian Univ (10); Tsinghua Univ (10); Southeast Univ (9) | Telecommunications (93); Engineering (84); Computer Science (29); Transportation (7); Optics (2) |
| On the Performance of Non-Orthogonal Multiple Access in 5G Systems with Randomly Deployed Users | 43% | 2017 | Power Allocation (25); Nonorthogonal Multiple-Access (24); Non-Orthogonal Multiple Access (Noma) (20); Noma (16); Performance (16) | China (64); UK (50); USA (31); Australia (13); Greece (11) | Univ Lancaster (35); Princeton Univ (17); Queen Mary Univ London (11); Southwest Jiaotong Univ (10); Xidian Univ (9) | Telecommunications (87); Engineering (86); Computer Science (19); Transportation (13); Optics (2) |
| Cellular architecture and key technologies for 5G wireless communication networks | 59% | 2016 | Massive Mimo (23); Wireless (16); Communication (13); Architecture (12); Networks (11) | China (52); UK (31); USA (22); Canada (10); South Korea (7) | Heriot Watt Univ (13); Southeast Univ (10); Huazhong Univ Sci and Technol (9); Shandong Univ (8); Queen Mary Univ London (5) | Telecommunications (77); Engineering (73); Computer Science (41); Physics (6); Transportation (6) |
| Five disruptive technology directions for 5G | 62% | 2016 | Massive Mimo (28); Channel Estimation (17); Cellular Networks (14); Technology (13); Systems (12) | USA (44); China (29); UK (20); Sweden (11); Canada (9) | Univ Texas Austin (11); Tsinghua Univ (9); Univ Southampton (8); Southeast Univ (7); Aalborg Univ (7) | Telecommunications (82); Engineering (75); Computer Science (39); Transportation (4); Optics (3) |
| Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results | 63% | 2016 | Massive Mimo (31); Channel Estimation (22); Mimo (17); Technology (17); Beamforming (16) | US (58); China (35); South Korea (14); UK (12); Canada (7) | Univ Texas Austin (18); Southeast Univ (8); Tsinghua Univ (7); Beihang Univ (5); Tongji Univ (5) | Engineering (86); Telecommunications (82); Computer Science (29); Transportation (7); Optics (1) |
| Millimeter wave mobile communications for 5G cellular: It wll work! | 63% | 2016 | Massive Mimo (34); Channel Estimation (16); Mimo (15); Networks (11); 28 Ghz (11) | US (56); China (21); UK (17); South Korea (10); Canada (8) | Univ Texas Austin (19); Polytech Sch Engn (8); Tandon Sch Engn (6); Southeast Univ (6); Univ Southampton (4) | Engineering (83); Telecommunications (82); Computer Science (31); Transportation (4); Acoustics (1) |
| Network densification: the dominant theme | 67% | 2016 | Massive Mimo (21); Resource-Allocation | China (37); Usa (27); | Xidian Univ (6); Tampere Univ Technol (6); | Telecommunications (94); Engineering (80); Computer |

(*continued on next page*)

**Appendix 2** (*continued*)

| Original paper | Present in collection | Median year of citation | Common keywords | Common countries | Common affiliations | Common categories |
|---|---|---|---|---|---|---|
| for wireless evolution into 5G | | | (14); Optimization (12); Cellular Networks (12); Wireless Networks (10) | Canada (18); United Kingdom (12); Korea (10) | Sungkyunkwan Univ (5); Beihang Univ (4); Univ Manitoba (4) | Science (43); Transportation (3); Communication (1) |
| Scenarios for 5G mobile and wireless communications: the vision of the METIS project | 65% | 2016 | Mobile (37); Massive Mimo (20); Cellular Networks (14); Challenges (12); Wireless (12) | China (35); United Kingdom (17); Usa (17); Sweden (17); Canada (15) | Ericsson Res (6); Aalborg Univ (6); Nokia Bell Labs (5); Tsinghua Univ (5); Aalto Univ (5) | Telecommunications (86); Engineering (70); Computer Science (42); Transportation (7); Materials Science (1) |
| What will 5G be? | 64% | 2016 | Massive Mimo (25); Resource-Allocation (13); Wireless (13); Systems (13); Channel Estimation (11) | China (40); Usa (32); United Kingdom (21); Canada (14); Sweden (13) | Southeast Univ (8); Univ Texas Austin (6); Tsinghua Univ (5); Univ Southampton (5); Kings Coll London (5) | Telecommunications (90); Engineering (81); Computer Science (31); Transportation (6); Optics (1) |




**Appendix 3.** Growing technologies, composite keywords of two words (bigrams and trigrams).

**Appendix 4**
Country collaborations, Top 30 co-authorships, 2005–2020.

| Country | Country | Articles together |
|---|---|---|
| US | China | 510 |
| China | UK | 359 |
| China | Canada | 249 |
| China | Australia | 149 |
| USA | South Korea | 129 |
| China | South Korea | 119 |
| US | UK | 110 |
| US | Canada | 107 |
| UK | Spain | 95 |
| Spain | Germany | 87 |
| China | Singapore | 87 |
| UK | Germany | 82 |
| China | Sweden | 73 |
| Spain | Italy | 72 |
| China | Japan | 71 |
| Finland | South Korea | 70 |
| Canada | UK | 69 |
| France | Germany | 69 |
| Pakistan | South Korea | 68 |
| US | Germany | 66 |
| France | Italy | 66 |
| Pakistan | UK | 63 |
| UK | France | 62 |
| Germany | Italy | 60 |
| France | Spain | 59 |
| US | Finland | 58 |
| China | Saudi Arabia | 58 |
| US | Italy | 58 |
| Finland | France | 56 |
| UK | Italy | 56 |

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