Technical research innovations of the US national security system

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Abstract

Since the Second World War the US defense has been a major participant in the development of radical innovations in information and communication technologies (ICT's), most famously probably the digital computer and the internet. A regularly present, but less known creator of R&D innovations is the intelligence community. To understand the role and impact of defense and intelligence-related research for driving ICT innovations, we analyzed which technological paradigms were promoted by US defense and intelligence agencies and the development of these research trajectories over time. Using bibliographic analysis, we clustered 82239 scientific papers funded by the US National Security System, published between 2009-2017, in research fronts, and after that aggregated the research fronts into technological paradigms. Our analysis identified main technological paradigms promoted by the US defense's sectoral system of innovation, such as quantum science and graphene as fields that could generate high impact in the new generation of radical technologies. The efforts of intelligence agencies was highly concentrated on quantum science, social forecasting, computer cognition and signal processing. Our research highlights the role of US security players in shaping research fields.

Keywords: Innovation; technological paradigm; technological trajectory; defense; intelligence; national security; bibliographic analysis

Word count: 7833

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Introduction

Since World War II, the United States has mobilized a considerable amount of resources for national security issues, including a related R&D strategy, focused both on the development of complex weapons systems and new means of collecting, processing and analyzing information. The terrorist attacks of 09/11 provoked further changes in the US national security system (US NSS). Less restrictive surveillance laws were approved giving more powers for intelligence agencies to collect and analyze information. Furthermore, the national security apparatus became involved in two wars in Afghanistan and Iraq. These events had a considerable impact on the defense and intelligence budget (Daugherty Miles, 2016), while a new set of agencies for the promotion of technological innovations were created; e.g., emulating DARPA located in the DoD, HSARPA (DHS), IARPA (ODNI) and ARPA-E (Department of Energy) were formed. These agencies together with the already existing security and intelligence agencies emerged as one of the largest financiers of technological research, shaping the landscape of scientific innovations and outputs.

Notwithstanding the importance of the US NSS for R&D innovations there has been a dearth in systematic, in-depth views into the type and degree of scientific outputs directed by US defense and intelligence agencies over time. Our objective is to understand and outline, through a perspective of technological paradigms (TP) and bibliometric methodology, the landscape of the scientific output of the US NSS as the driver of technological research innovations.

US national security funding for research innovations

The role of the US defense sector in promoting innovations has been sparsely studied. From the investment side, Mowery (2012) noted that despite the considerable literature about innovation systems there are few that approach defense-related investments in innovation. This contrasts sharply with the fact that defense-related R&D and procurement programs have exercised enormous influence over innovations in the ICT sector since WWII. The overall indications are that defense-spending affects scientific research in multiple ways. Malik (2017) measured the impact of defense expenditure on high-technology exploitation, demonstrating that defense-spending increased scientific output in publications and patents. Libaers (2009) further showed that DoD grants are linked to higher involvement of academics resulting in a higher number of industrial partners and more consultancy work, indicating that DoD-funding leads to a shift in the focus of research conducted. Plummer and Gilbert (2015) associated defense activity with “closed science”, when analyzing the role of defense agencies’ funding of entrepreneurship. They concluded that funding defensed-based research for universities decreases regional entrepreneurship activities in the short-term, however is positively related to entrepreneurship in the long-term. Together with other studies about spill-over effects from military to civilian innovations and research (Acosta, Coronado, Marín, & Prats, 2013; Kas et al., 2012; Olijnyk, 2018), these findings indicate that defense-related funding impacts the way scientific research is conducted and the development of technological innovations.

The national security apparatus also comprises organizations with the aim to collect, process and analyze information about threats against the US. This role is covered by the term *intelligence*. There are numerous intersections between intelligence activities and the field of information science (IS), to the extent “that is indeed difficult to find any topic in information science and technology not relevant to intelligence, information warfare, and national security, or conversely” (Davies, 2005, p. 313). The trend in the specialized literature concerning intelligence and technology is divided along two main branches: On the one hand, there is interest in understanding how technology could affect the intelligence systems, either concerning new means of collection, processing and analysis of information by the intelligence practitioners or the generation of new threats (Vogel & Knight, 2015; Warner, 2012). On the other hand, there are case studies about economic and technological espionage (Cochran, 2003; Macrakis, 2004). The role of national intelligence agencies in academic innovations and research has received much less attention (Cronin, 2011) in line with the role of US defense funding more generally.

Research as sectoral system of innovations

To understand the impact of the US national security system on technical research innovations, we consider it as a sectoral system of innovations (SSI) (Malerba, 2002). This implies the analysis of the patterns of technical innovations within the US NSS, acknowledging the fact that different sectors may follow disparate logics in their development and experience shifts in activities over time. Such shifts can be captured in the form of technology trajectories which can be understood as "the pattern of 'normal' problem solving activity (i.e. of 'progress') on the ground of a technological paradigm" (Dosi, 1982, p. 152). In a similar way to scientific paradigms (Kuhn, 1970), the "normal route" of a technological paradigm (TP) is often marked by discontinuities but is also selective, since the next set of problems that have to be solved leaves other questions unresolved.

Technological trajectories are often marked by shifts in the knowledge accumulation, which point to changes inside a TP. These shifts lead to disparate, although inter-connected research fronts (RF's), which are "discontinuous, starting and ending abruptly as scientists move from one puzzle to the next" (Morris, Yen, Wu, & Asnake, 2003, p. 414). Figure 1 illustrates this process in the evolution of technological trajectories. Morris et al. (2003) argued that research fronts are the unsolved puzzles of interest inside a scientific paradigm; raising the question what drives such shifts. Furthermore, the interdependencies and complementarities of technological paradigms define the boundaries of a sectoral system of innovation (Malerba, 2002).

To understand the foci and developments of research innovations funded by the US NSS, we therefore aim to answer the following research questions:

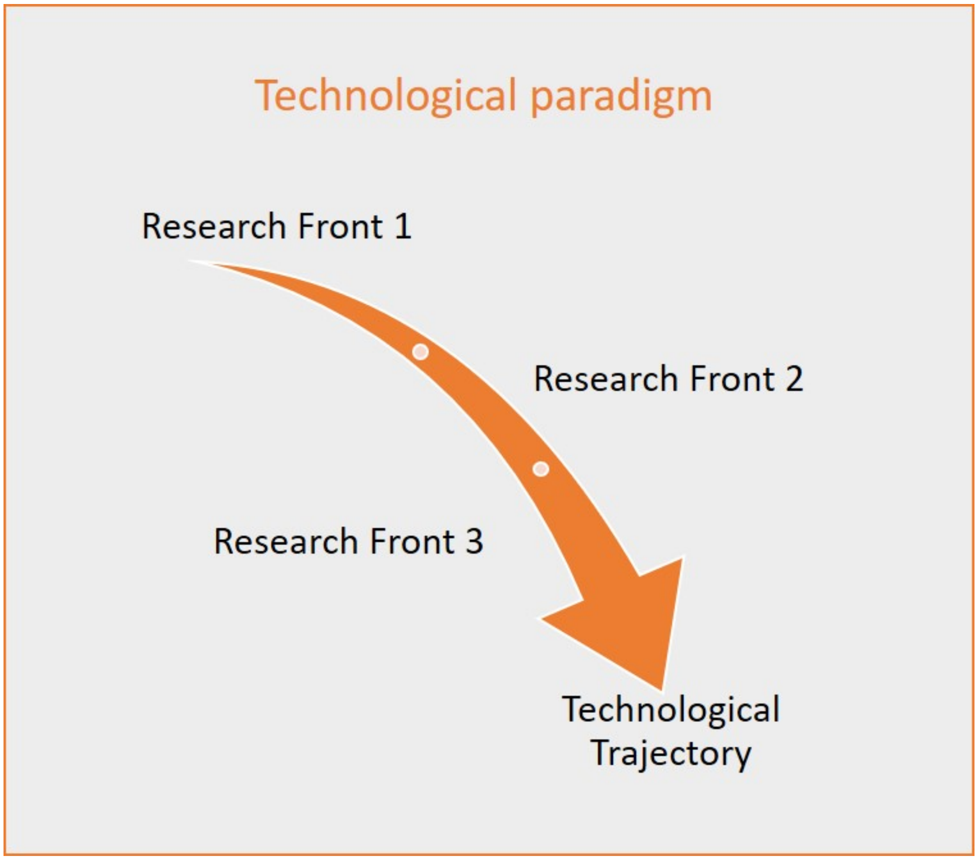

Figure 1. Shifts in trajectories within technological paradigms

RQ1: What are the technological paradigms promoted by the US NSS?

RQ2: In which way are technological trajectories changing over time?

The US defense system is not a homogeneous field; rather a multitude of actors are active at the same time, either working together or in parallel. It would therefore be problematic to treat defense-funding as one undifferentiated unity. To obtain a comprehensive understanding of the US defense sector as SSI, a differentiated view on the various agents is required, investigating the type of the various funding agencies involved in the system. We specifically focus on intelligence-related funding, as intelligence can be considered a subsystem of national security agencies, leading to our third research question:

RQ3: Inside the national security system, are there technological paradigms specific to *the intelligence subsystem?*

Overall, our study is focused on mapping the technological content promoted by the US National Security System (US NSS), in the form of TP's, with special attention to the intelligence subsystem. Our results provide the technological portfolio of US national security related innovation activities that could be used in future studies to understand the impact of US national security related R&D inputs on specific technological fields nationally as well as globally.

Methods

Study approach

Our study employs bibliometric analysis with a bottom-up approach, where the results of the lower levels work as input for the higher levels of analysis (Waltman & Van Eck, 2012). The first and lowest level is the corpus of scientific papers funded, partially or totally, by components of the US NSS. These documents can be grouped into a mid-level of analysis composed of RF's, which are obtained by applying a clustering algorithm on first-level documents. The highest level is composed of the TP's, which are identified by textual clustering of RF's. In this way nested levels of analysis can be established that represent the technological content of sectoral systems of innovation: documents, RF's and TP's. Investigating documents and RF's over time further allows the mapping of the technological trajectories within specific TP's. These steps are summarized in figure 2.

Data and data collection

To answer our question about the type of technical innovations promoted by the US NSS, we retrieved and investigated publications partially or totally funded by components of the US NSS. As it was only in 2008 that data about funding agencies became available we decided to retrieve data from the Web of Science (WoS) database starting from 2009 up until 2017 (the last complete year before our data collection). The US NSS was defined as the set

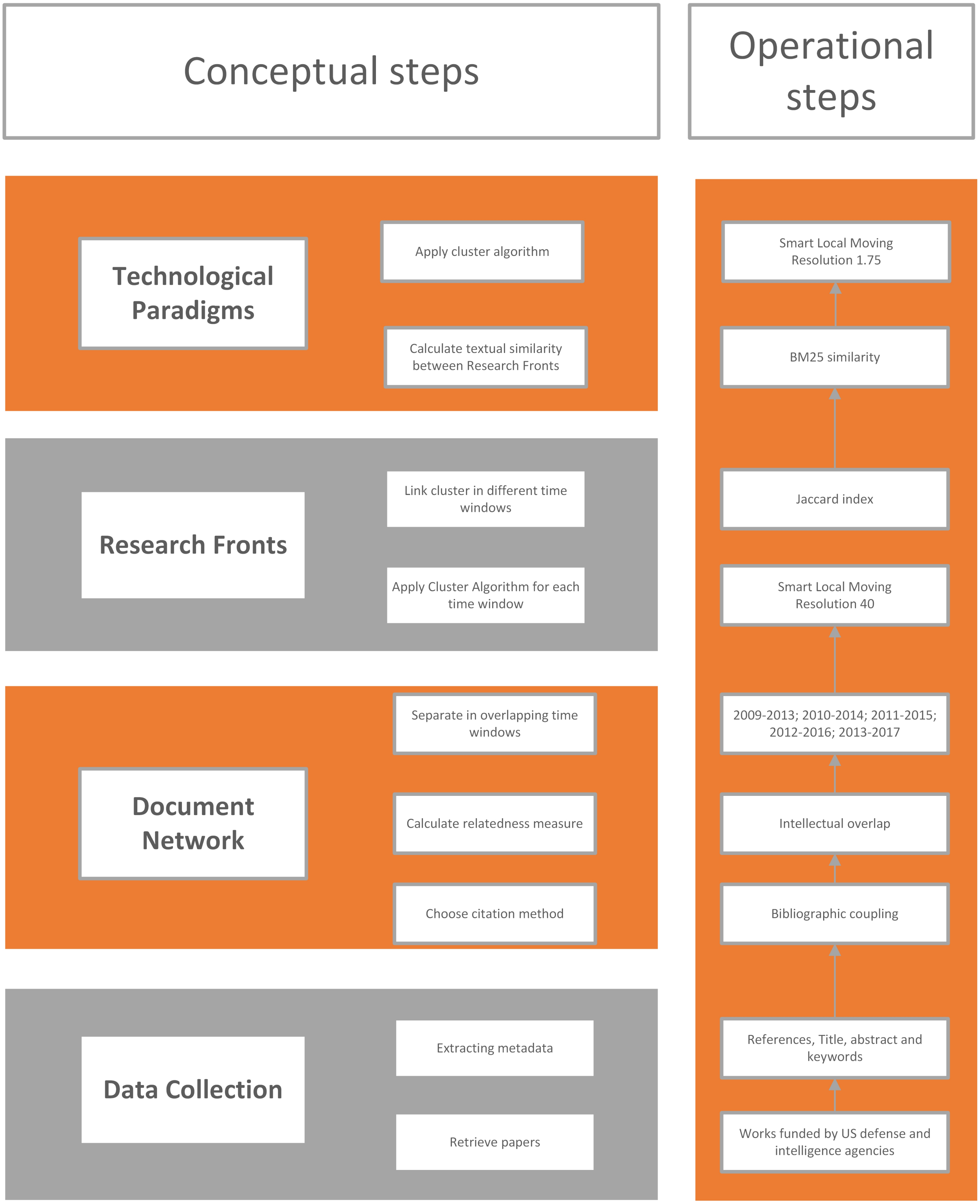

Figure 2. Methodological procedures

of organizations with a role in national security affairs. We considered the following criteria: The organization is subordinated to one of the regular attendees of the US National Security Council (United States President, 2017) and participant of the US intelligence community (The United States Intelligence Community, 2018). This includes military organizations, such as the US Army, Navy and Air Force, intelligence-related agencies such as the NSA and CIA, civil agencies such as the Department of State, and organizations related to law enforcement, such as the FBI and the DEA.[1] Table 1 shows the list of organizations included and a sample of the queries used. We selected research articles as well as review and proceeding papers, as they constitute the most prevalent type of academic outputs. For each entry, we collected the fields title, abstract, keywords and cited references. Following Boyack and Klavans (2010) we included only documents with at least five references in order to avoid a high number of strong links based on small overlaps. Also, in order to avoid over-aggregation around highly cited references, those cited more than 400-times were excluded. The references were processed in a simple way: When existing, the Digital Object Identifier (DOI) was extracted for each reference and this number was used as a reference number. Otherwise, the reference was used as it appeared in the data retrieved from the WoS. This led to a total of 82239 documents.

[1] Even though the US Department of Energy fits our criteria, we decided to not include it in the analysis. The US Department of Energy alone has around hundred of thousands of documents. This high volume denotes that energy issues could be a system by itself; thus, its relationship with the US NSS deserves a closer consideration in a future research.

Table 1

Agency classification and query for data retrieval

Classification	Agency	Query sample
Defense	Drug Enforcement Agency (DEA)	Drug Enforcment Agency
	Federal Bureau of Investigation (FBI)	Federal Bureau of Investigation OR FBI
	Homeland Security Advanced Research Projects Agency (HSARPA)	Homeland Security Advanced Research Projects Agency OR HSARPA
	US Air Force and laboratories	US Air Force OR U.S. Air Force OR Air Force of Scientific Research
	US Army and laboratories	US Army OR U.S. Army OR Army Research Lab*
	US Coast Guard	US COAST GUARD OR U.S. COAST GUARD
	US Department of Defense (DOD)	US Department OF Defense OR US DEPARTMENT OF DEFENSE OR U.S Department of Defense
	US Department of Homeland Security (DHS)	Department of Homeland Security
	US Department of State (US DOS)	US Department of State OR U.S. Department of State
	US Department of the Treasury (TRE)	Department of the Treasury
	US Marine Corps	Marine Corps
	US Navy and laboratories	US Navy OR U.S. Navy OR Naval Research Lab*
Intelligence	Defense Advanced Research Projects Agency (DARPA)	Defense Advanced Research Projects Agency OR DARPA
	Intelligence Advanced Research Projects Activity (IARPA)	Intelligence Advanced Research Projects Activity OR IARPA
	National Geospatial Intelligence Agency (NGA)	National Geospatial Intelligence Agency
	National Reconnaissance Office (NRO)	National Reconnaissance Office
	National Security Agency (NSA)	National Security Agency
	Office of Director of National Intelligence (ODNI)	ODNI OR Director of National Intelligence

Note:

The asterisk (*) represents any group of characters, including no character.

Identifying RF's and TP's

To be able to identify RF's in our corpus, thematic linkages between documents needed to be established. We used the bibliographic coupling method (Kessler, 1963) as this method avoids pitfalls present in the direct citation approach. The direct citation approach creates a cluster solution by consulting direct citations between documents. As citations can refer to documents that are not part of the corpus itself, this analysis might lead to the inclusion of documents that were not funded by the US NSS, therefore diluting our dataset. Besides, Eck and Waltman (2017) noted that a lack of direct citation relations between publications in a corpus can lead to faulty clustering classifications between documents. Furthermore, since it does not rely on direct citations, the bibliographic coupling method allows to cluster papers that are close together in time and thus offers more precise results for emerging RF's, where papers may be published in rapid succession or high numbers without yet referring to each other (Boyack & Klavans, 2010).

In order to create the network of documents, links between documents were weighted using the intellectual overlap equation (Colavizza, Boyack, Eck, & Waltman, 2017), and selecting the Top-15 similarities with procedures proposed by Boyack and Klavans (2010). After these steps, the general bibliographic coupling network was composed of 763,052 links between the 80234 remaining documents.

We separated the overall bibliographic coupling file into five sub-corpora according to the following time windows: 2009-2013, 2010-2014, 2011-2015, 2012-2016 and 2013-2017. The overlapping windows were already used in previous works for detecting RF's (Huang & Chang, 2014; Upham & Small, 2010). As noted by Morris et al. (2003, 2003, p. 414), "when moving from past to present, bibliographic coupling between two documents is static, because bibliographic coupling is based on the fixed reference lists of the two documents". With the use of overlapping time windows we transformed the static network in a dynamic one based on link exclusion, in order to achieve RF's with a more limited time duration.

Table 2 summarizes the data for each time window.

Table 2

Summary of data at document level

Period	# links	# documents
2009-2013	200,923	42630
2010-2014	202,810	44886
2011-2015	194,682	45451
2012-2016	192,988	45883
2013-2017	188,909	45177

For each file, we applied the smart local moving algorithm (Waltman & Van Eck, 2013). We executed the algorithm 1000-times with a resolution of 40 and minimum cluster size of 25, which corresponds to level 3 of the classification system of Waltman and Van Eck (2012).

To link temporal networks along the time windows, as proposed by Lancichinetti and Fortunato (2012), we calculated the Jaccard index, given by the equation $J(A,B) = \frac{|A \cap B|}{|A \cup B|}$, where A is the number of documents of a specific cluster at time t, and B is the number of documents of a specific cluster at time $t+1$. The calculation was executed between each time window and the subsequent window. Thematic clusters within different time windows are linked to the same RF if and only if two conditions are satisfied: First, the cluster at time t has at least one Jaccard Index value $\geqslant 0.4$ in a subsequent time window. Second, the maximum value for the cluster A at time t is with the cluster B at time $t+1$, and conversely, the maximum value for the cluster B is also with the cluster A. If these conditions are satisfied, the cluster B is a continuation of cluster A. If not, they are different RF's. The result of this procedure is the sum of RF's in the total corpus. To be considered a relevant RF, we followed Boyack and Klavans (2010) and selected only clusters with a minimum of 25 documents.

TP's were identified using the clustering of the RF's as input, considering their textual similarity. The BM25 similarity between each pair of clusters was calculated following equations given by Boyack and Klavans (2014). The RF's were considered as documents, and their contents were indexed from the title and abstracts of the papers included in the RF. The pairs were filtered using Top-15 similarity (Boyack & Klavans, 2010). We ran the smart local moving algorithm 100 times with a resolution of 1.75.

We tested several resolutions to find a result that allowed clearly identifiable groupings of technologies. For this end, we analyzed mainly intelligence related technologies comparing them with the IARPA projects[2] such as network analysis, quantum computation, brain cognition, and image and sound recognition. We considered that a minimum resolution, which kept these technologies separate was "ideal" and could also give a sensible solution for other paradigms. To be considered a relevant TP of the US NSS, we selected only clusters with a minimum of 1,000 documents.

After all the procedures, from 82239 retrieved documents, 76582 documents were classified in RF's and TP's (93.12% coverage).

Intelligence-related TP's. As intelligence-related we listed those paradigms that had at least one of the US intelligence agencies as a funding organization. We called *intelligence intensity* the ratio between the observed likelihood of intelligence documents, either at RF or TP level, and the probability of possessing an intelligence sponsor across the whole corpus. Thus, we considered as *intelligence-related* RF's and TP's whose ratio was significantly higher than 1.0.

Labeling and science classification. Each document was associated with at least one of the general fields of science following the CWTS schema (CWTS - Centre for Science and Technology Studies - Leiden University, 2018). Publications belonging to multiple science fields were counted fractionally, and the science fields were summed up either at the

[2] available at https://www.iarpa.gov/index.php/research-programs

RF or TP level. The RF and TP received a science classification according to the field that occurred most frequently. The labeling of RF's was realized using the author keywords and WoS provided keywords. The words passed separately through a stemming process and were unified afterwards. The RF was labeled with the keyword that presented the highest term frequency–inverse document frequency (TF-IDF) value. The TP's were labeled manually based on the analysis of the most frequent keywords and the titles of the most cited works.

Results

In this section, we report on the results of the main TP's and RF's funded by the US NSS. We start with a general overview concerning TP's related to the science fields involved and differences in intelligence agencies' participation. The next section brings detailed information about the technical content of the TP's, together with the composition of RF's of the intelligence related paradigms. The last sub-section provides a more detailed discussion considering the technological trajectories of intelligence-related paradigms.

General overview

On average, since 2009 the US NSS has sponsored 8,509 documents per year with the peak of publications in 2013 (figure 3a). *Physical sciences and engineering* is the field with the most publications, accounting for around 52.02% of the works published. On the another extreme, *Social sciences and humanities* is the field with the least publications (figure 3b).

The documents were classified in 2592 RF's and 33 TP's. Figure 4 shows the map of TP's concerning the science classifications. Approximately mirroring the proportion of documents, *Physical sciences and engineering* is the most prominent field in 18 paradigms. Conversely, *Social sciences and humanities* does not appear as the most prominent field in any TP.

Most of the work conducted in the context of the US NSS is funded through military organizations. Only 3.64% of the documents had at least one of the intelligence organization

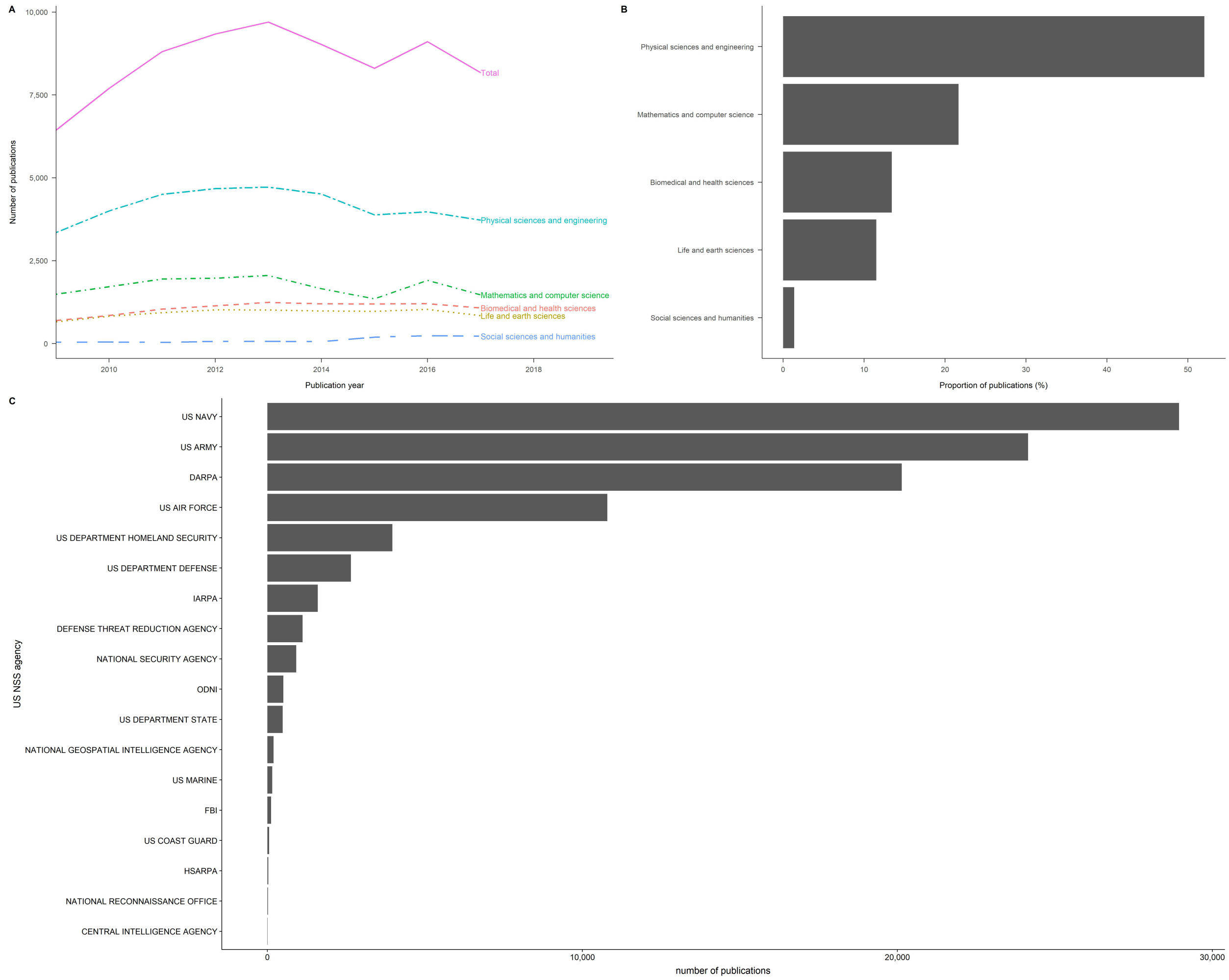

Figure 3. Overview of science fields and funding agencies in publications promoted by the US NSS

as funding agency indicating that the visible output in terms of scientific publications for this funding stream is low (figure 3c).

A Chi-square test of homogeneity was performed to test whether the distribution of intelligence-funded documents differs across the 33 TP´s. Results are significant with $\chi^2(32) = 9{,}318$, $p < .001$. 31 TP's showed higher or lower levels of intelligence-related outputs than expected, i.e., significantly higher or lower participation than the average amount of intelligence-related documents in the overall corpus. As shown in figure 5, the intelligence agencies show a high level of participation only in the following TP's: *Quantum information*,

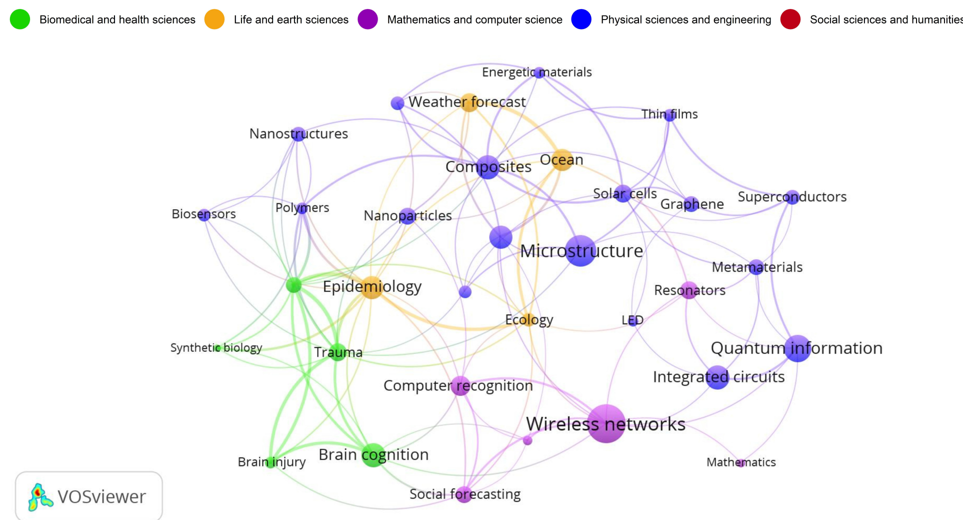

Figure 4. Science map of TP´s. The size of each circle represents the number of documents, while the distance represents the textual similarity

Computer recognition, *Social forecasting*, *Signal processing*, *Superconductors*, and *Mathematics*. The paradigm of *Brain cognition* presents a proportion both of intelligence and defense documents around the corpus that differs not significantly ($p > 0.05$); the rest presents a level of participation of intelligence agencies below the expectation. For instance, the paradigms *Energetic materials*, *Polymers*, and *Solar cells* presented the three lowest values of intelligence intensity.

Technical research content

In this section we present more detailed information about the TP's grouped according to their science classification. We also present the science classification at the RF level of the intelligence-related paradigms.

Physical sciences and engineering. This science field comprised 44154 documents (57.66% of the corpus), distributed across 18 TP's. Table 3 presents information about the technological and research content of the TP's, the diversity index and the

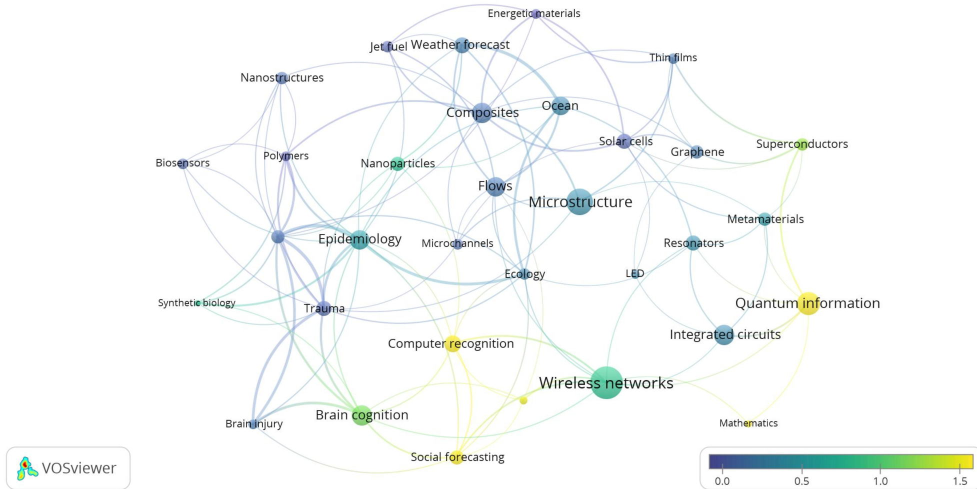

Figure 5. Intelligence intensity of TP´s

intelligence intensity.[3]

The research in this science field spans a variety of subjects. For instance, considering energy research there are the TP's of *Energetic materials* and *Solar cells*. Concerning materials there are *Graphene*, *Microstructure*, and *Composites*. Related to computers, there are *Quantum information*, *Superconductors* and *Integrated circuits*.

There are two highly intelligence-related paradigms classified as Physical sciences and engineering: *Quantum information* and *Superconductors*. Both paradigms are related to the development of supercomputers, the former to research on quantum mechanics phenomena which need to be solved for the development of a quantum computer, and the latter to research about semiconductors and superconductor materials. The basic research nature of these two paradigms is shown by their low diversity index (respectively 0.6 and 0.52).

[3] The diversity index calculations (Porter & Rafols, 2009) were executed through the R package *Robustrao* (Calatrava Moreno, Auzinger, & Werthner, 2016) considering the scientific fields existent at the RF level. The index ranges between 0 and 1. The higher the index the more interdisciplinary is the RF.

Table 3

TP´s concerning the field of Physical and engineering

Technological paradigm	# documents	Keywords	Diversity index	Intelligence intensity
Microstructure	4951	behavior ; mechanical properties ; microstructure ; deformation ; composites	0.71 (0.11)	0.37
Quantum information	4341	entanglement ; computation ; light ; qubits ; cavities ; spin	0.6 (0.09)	6.02
Composites	3894	performance ; composites ; mechanical properties ; polymer ; carbon nanotubes	0.69 (0.07)	0.19
Integrated circuits	3746	generation ; laser ; wave guides ; silicon ; pulses	0.55 (0.13)	0.34
Flows	3661	flow ; dynamics ; simulation ; large eddies simulation ; stability	0.77 (0.08)	0.21
Solar cells	2769	efficiency ; solar cells ; performance ; field effect transistors ; films	0.69 (0.06)	0.09
Nanoparticles	2600	image ; design ; crystals ; scintillator ; nanoparticles	0.77 (0.1)	0.80
Graphene	2543	graphene ; films ; transistors ; chemical vapor deposition ; transport	0.63 (0.05)	0.23
Metamaterials	2497	metamaterials ; light ; plasmonics ; films	0.67 (0.08)	0.47
Superconductors	2426	topological insulator ; insulator ; transition ; phase ; atoms ; superconductors	0.52 (0.09)	1.20
Nanostructures	2300	nanoparticles ; spectroscopic ; explosives ; sers ; nanostructures	0.75 (0.09)	0.15
Jet fuel	2232	performance ; oxidation ; stability ; design ; combustion	0.74 (0.08)	0.09
Biosensors	2073	microfluidics ; biosensors ; dna ; devices ; chip	0.77 (0.06)	0.13
Microchannels	2053	surfaces ; films ; fabrication ; microchannels	0.72 (0.1)	0.15
Thin films	2047	thin films ; augmented wave method ; metals ; total energies calculations ; ferroelectric	0.6 (0.1)	0.20
Polymers	1895	protein ; surface ; self assembled monolayers ; polymers ; adhesion	0.78 (0.07)	0.04
Energetic materials	1873	energetic materials ; crystal structure ; densities functional theories ; explosives ; salts	0.66 (0.09)	0.01
LED	1754	gan ; molecular beam epitaxial ; light emitting diodes ; growth ; hemts	0.56 (0.1)	0.31

Thus, all the RF's of *Quantum information* were classified in the field of *Physical sciences and engineering* (figure 6). This includes RF's *Cryptographics* and *Security* (in the left corner of the map), which indicate some of the technical applications of the paradigm. In turn, *Superconductors* presents only one RF, *Magnetic tunnel junctions*, in the field of mathematics and computer science (figure 7). The three lowest intelligence-related paradigms are in this science field (*Energetic materials*, *Polymers*, and *Solar cells*).

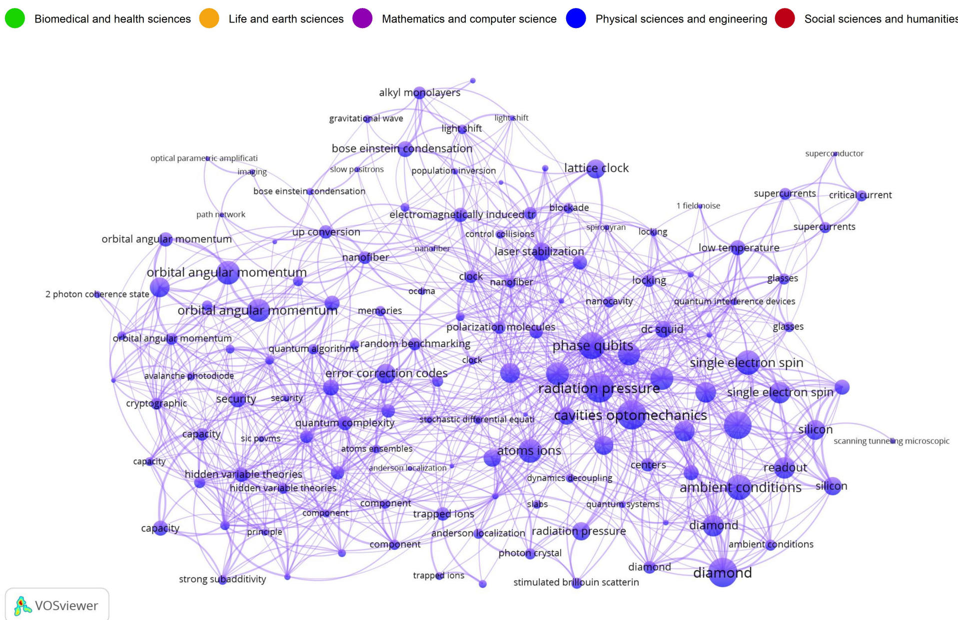

Figure 6. Science classification of RF's with respect to *Quantum information*

Mathematics and computer science. This science field comprised 16059 documents (20.97% of the corpus) distributed across 6 TP's. Table 4 shows detailed information about these TP's. The bulk of research presented is related to information collection and processing (*Signal processing* and *Wireless networks*), as well as information analysis (*Social forecasting* and *Computer recognition*). This science field presents a high participation of the intelligence agencies. Of the 6 TP´s, 4 showed higher levels of intelligence-related documents than expected in the overall corpus: *Computer recognition*, *Social Forecasting*, *Signal processing*, and *Mathematics*. The other two TP's, *Resonators* and *Wireless networks*, were lower than expected.

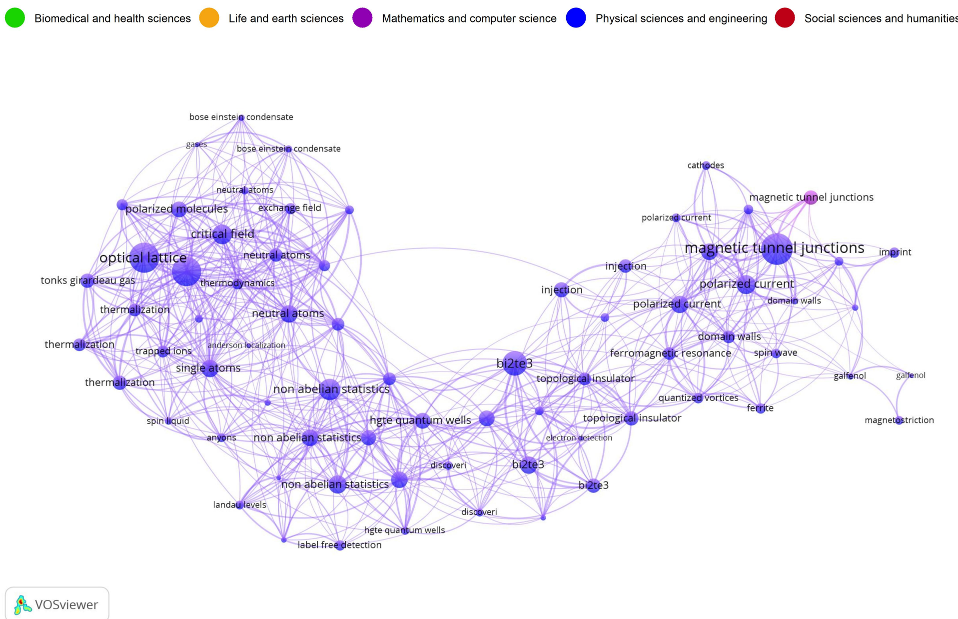

Figure 7. Science classification of RF's with respect to *Superconductors*

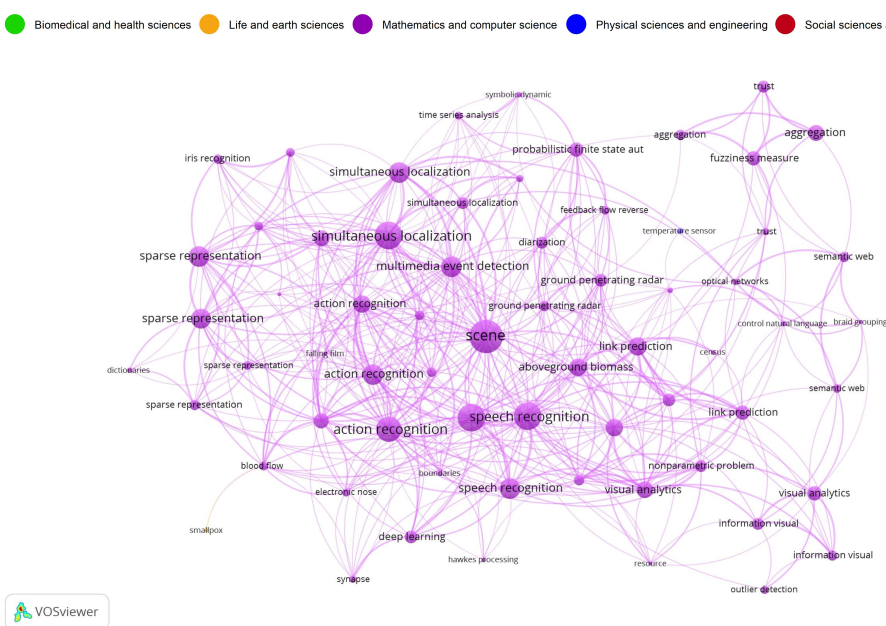

Figure 8. Science classification of RF's with respect to *Computer recognition*

Computer recognition (figure 8) presents a high diversity index (0.74), although most of the RF's were classified in the field of Mathematics and computer science. *Social forecasting* (figure 9) presented an even higher diversity index (0.83), since it is composed of RF's also

Table 4

TP's concerning the field of mathematics and computer science

Technological paradigm	# documents	Keywords	Diversity index	Intelligence intensity
Wireless networks	6071	optimization ; design ; performance ; capacity ; wireless networks	0.66 (0.12)	0.82
Computer recognition	3105	recognition ; classification ; features ; face recognition ; image	0.74 (0.09)	2.84
Resonators	2804	design ; cmos ; resonators ; silicon ; oscillator	0.62 (0.19)	0.38
Social forecasting	2688	social networks ; complex networks ; performance ; dynamics ; decision make	0.83 (0.06)	1.63
Signal processing	1569	compressed sensing ; reconstruction ; signal recovering ; regression ; recovering	0.76 (0.07)	1.43
Mathematics	1440	graphs ; dynamics ; space ; uncertainties ; shallow water	0.6 (0.2)	7.09

classified in Physics, related to network analysis (e.g. *Interdependent networks* and *Financial Markets*) and social sciences (e.g. *Terrorism* and *Judgment*). *Signal processing* (figure 10) also shows a high diversity index (0.76) with RF's classified in biomedical sciences, such as *Olfactory* and physics. In turn, *Mathematics* (figure 11) showed a low diversity index (0.6) even though it has mobilized some RF's in Physics.

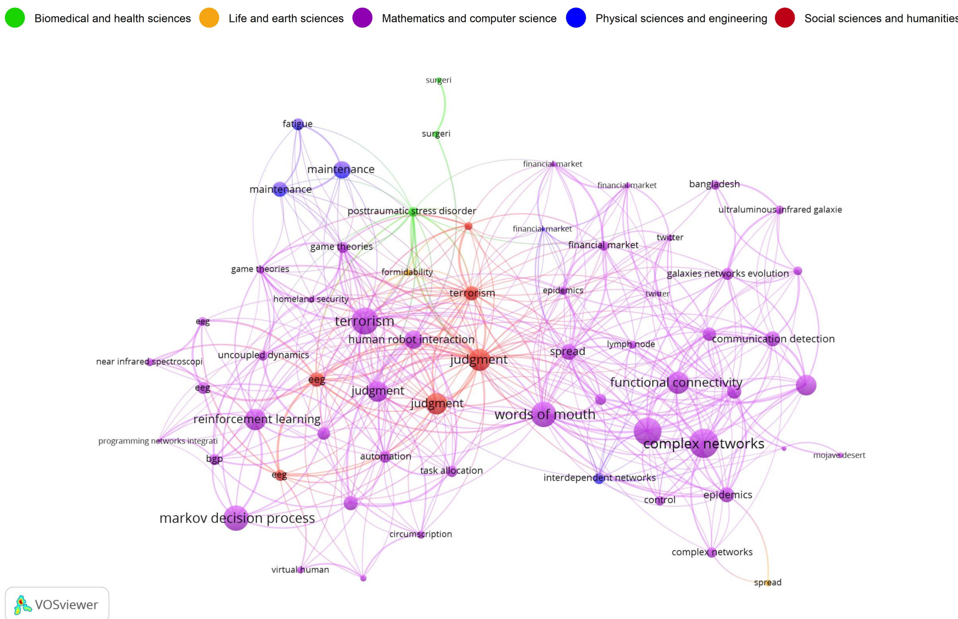

Figure 9. Science classification of RF's with respect to *Social forecasting*

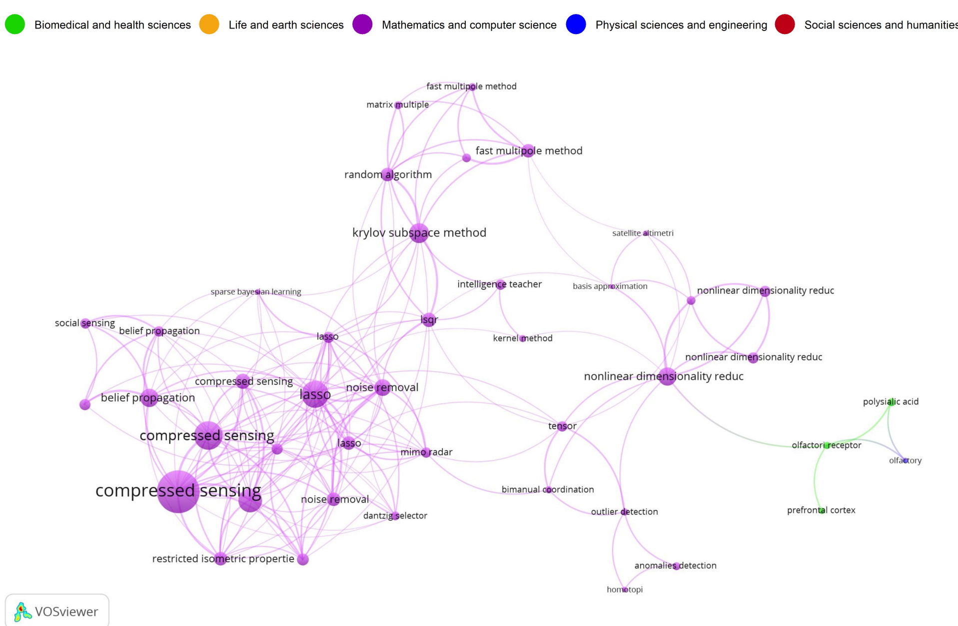

Figure 10. Science classification of RF's with respect to *Signal processing*

Biomedical and health sciences. This science field system comprised 11256 documents (14.70% of the corpus), distributed across 5 TP's. Table 5 shows detailed information about the TP´s. The research spans several areas, such as *Neuroscience*, with

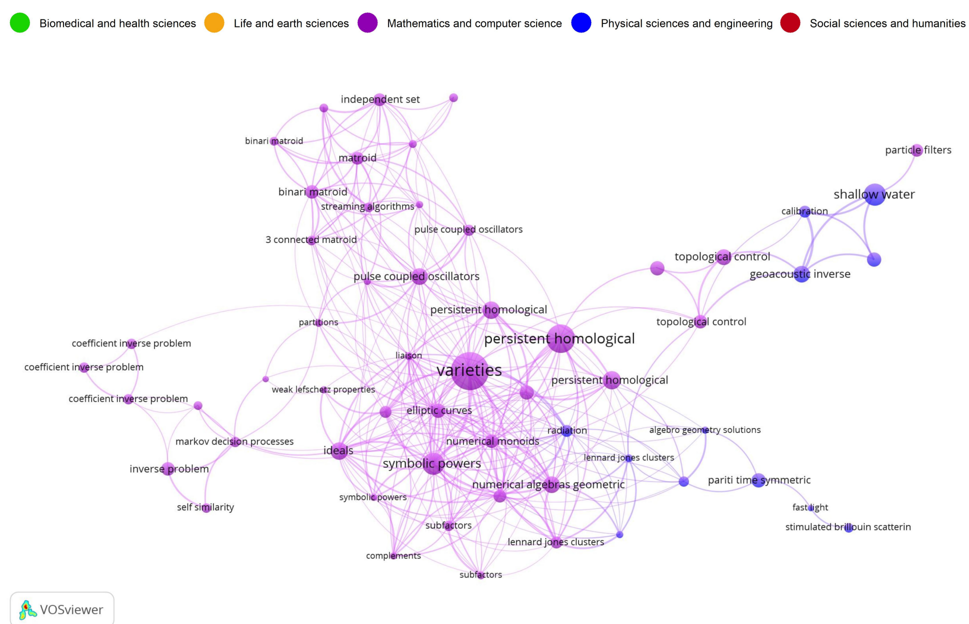

Figure 11. Science classification of RF's with respect to *Mathematics*

the paradigms of *Brain cognition* and *Brain injury*, *Trauma* and *Synthetic biology*. *Brain cognition* is the paradigm with the highest intelligence intensity, however the proportion of intelligence documents does not differ significantly from the expected value in the corpus ($p > 0.05$), whilst all others have intelligence intensities that rank below the expected.

However, given its stated importance to intelligence-related research, we considered *Brain cognition* as an intelligence-related paradigm.[4] *Brain cognition* presents high interdisciplinarity (0.76) with RF's classified in all other big fields of science with exception of Life and earth sciences (figure 12). Thus, for instance, there are RF's in Social sciences (*Fluid intelligence*) and Computer science (*Markov decision processing*).

[4] The current director of IARPA gives an account of the role of the agency in promoting research in neuromorphic computing, in order to understand how the brain processes information so efficiently and with less energy compared to that needed by supercomputers. According to him, the objective, more than the development of a new computer, is to discover "a new approach to measuring neural structure and activity. In many cases, the most successful scientific leaps come from the development of new approaches to measurement that enable multiple discoveries" (Matheny, 2016, p. 37).

Table 5

TP's concerning the field of Biomedical and health sciences

Technological paradigm	# documents	Keywords	Diversity index	Intelligence intensity
Brain cognition	3804	brain ; attention ; prefrontal cortex ; cortex ; neurons	0.76 (0.09)	1.10
Trauma	2785	in vitro ; scaffolds ; trauma ; cells ; differentiation	0.82 (0.07)	0.11
Gene expression	2556	expression ; gene expression ; breast cancer ; bone marrow transplantation ; survival	0.75 (0.08)	0.17
Brain injury	1808	traumatic brain injuries ; posttraumatic stress disorder ; performance ; depression	0.84 (0.04)	0.21
Synthetic biology	1169	escherichia coli ; synthetic biological ; expression ; gene expression ; protein	0.72 (0.11)	0.75

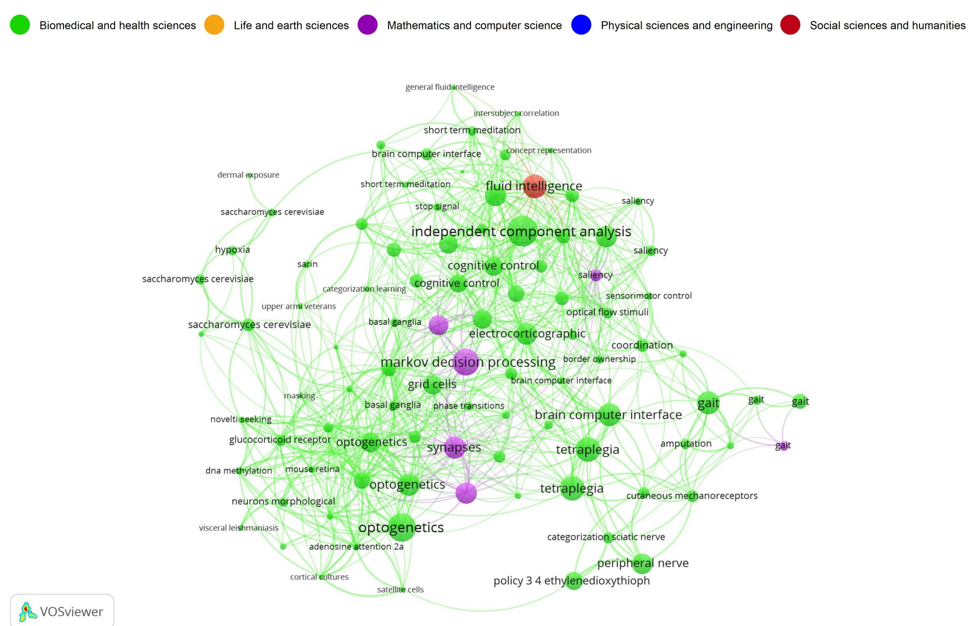

Figure 12. Science classification of RF's of *Brain Cognition*

Life and earth sciences. This science field comprises 11772 documents (15.37% of the corpus), distributed across 4 TP´s. Table 6 shows detailed information about these TP's. The research is mainly about natural phenomena, such as *Ocean* and *Ecology*, and this science field does not show any highly intelligence-related TP's.

Table 6

TP's concerning the field of life and earth sciences

Technological paradigm	# documents	Keywords	Diversity index	Intelligence intensity
Epidemiology	3619	transmission ; infection ; evolution ; dynamics ; vaccine	0.8 (0.05)	0.51
Ocean	3472	ocean ; waves ; variable ; circulation ; propagation	0.7 (0.12)	0.32
Weather forecast	2993	part i ; dynamics ; boundaries layer ; simulation ; prediction	0.52 (0.22)	0.25
Ecology	2218	behavior ; population ; tursiops truncatus ; fish ; marine mammals	0.77 (0.08)	0.30

Technological trajectories of intelligence-related paradigms

In order to understand the technological trajectories of the intelligence-related paradigms, we show two main characteristics over time. First, we compared the global scientific output promoted by the US NSS over time together with the US Defense spending on R&D. Second, we considered the time evolution of the intelligence-related TP's with respect to their fastest growing research fronts (FGRF).

Defense funding and scientific output. Following other bodies of literature which provides an account of the correlation between R&D spending and scientific output (Wagner & Jonkers, 2017), we noted that, considering a lag of five years, the US Defense spending on R&D is strongly related to the US NSS scientific output ($r = .84$, 95% CI [.40, .97], $t(7) = 4.11$, $p = .005$).[5] The defense R&D budget shows a striking and continuous increase until 2008, a slight increase from 2008 to 2010, and a decline afterwards (figure 13a). Similarly, the US NSS total scientific output reached its peak in 2013 showing a declining trend afterwards.

[5] We ran other time lags and 5 years resulted in the highest correlation. Furthermore, it is important to highlight that the intelligence budget is only publicly available as topline figures, i.e., the global spending without any detailed information concerning the budget of individual agencies' R&D. Thus, we used the information about defense R&D provided by OECD (2018) as a proxy.

The total R&D defense spending is a sensible proxy for the analysis of specific TP´s, since 24 of 33 TP´s also showed a peak of documents in 2013. The intelligence-related paradigms (figure 13b) show the same trend. Six of the 7 reached the peak in 2013. The exception is *Social forecasting* which reached the peak in 2015. After 2013, *Brain cognition* and *Social Forecasting* present a stable scientific output, and *Computer recognition* a less stable output. However, in 2017, all the intelligence related TP´s presented fewer documents than in 2013. This suggests that publication rates seem to follow a general logic of growth and decline independent of paradigms, although with some exceptions (e.g. *Computer recognition* in 2016). Yet, without more precise funding information related to the spending related to each article, which could give an account of funding per TP, it is not possible to know if the differences after 2013 are related to the redistribution of funding between research areas or different cycles of output production which are dependent on changes in the scientific field.

Fastest growing RF's. In order to understand in which way the intelligence-related technological trajectories changed over time concerning intelligence intensity and technological content, we analyzed the growth rate of intelligence related RF's.[6] Results are presented in figure 14.

Most of the FGRF's in *Mathematics*, *Computer recognition* and *Quantum information* are intelligence related. Other paradigms presented a mixed trend. *Social forecasting* included both low intelligence intensity FGRF's (*Complex networks*), and intelligence-related FGRF's (*Judgment*). *Brain cognition*, presented two FGRF's with low intelligence intensity (*Brain Computer interface* and *Independent component analysis*), and two intelligence related ones with the same label (*Optogenetics*). *Superconductors* presented the same mixed trend, but with an important difference.

[6] The growth rate was calculated dividing the year range by number of documents in the RF. After that, the growth rate was normalized using the Z-score grouping the RF's according to the TP. We considered as fast growing only the RF's with Z-score higher than 2.0.

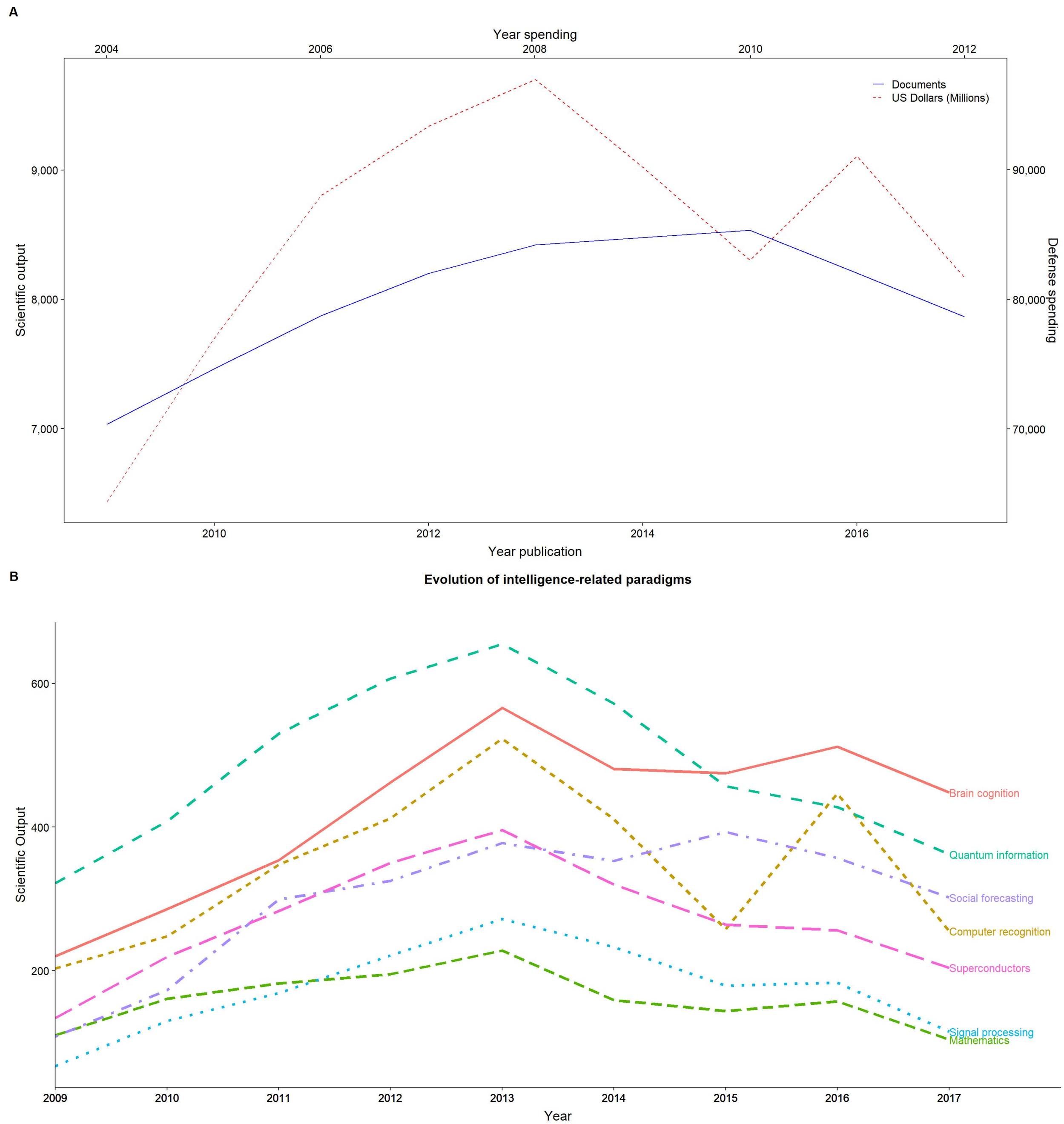

Figure 13. Scientific output evolution over time. (A) overall US NSS; (B) intelligence-related paradigms

The oldest FGRF *Optical lattice* showed high intelligence intensity, while the most recent one presented a low intelligence intensity, denoting that a similar technological content had suffered a change in the involved organizations. The same can be observed for

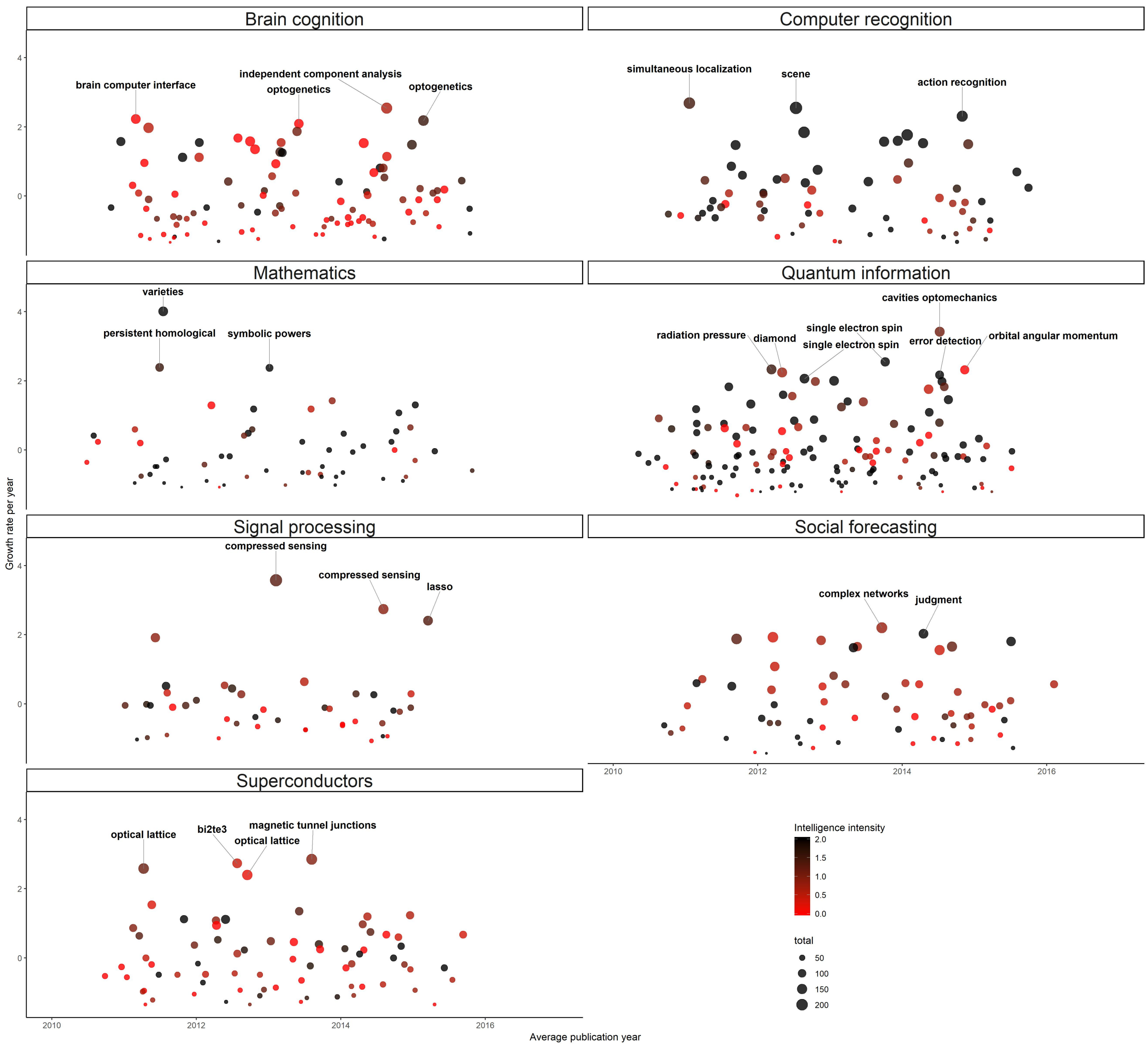

Figure 14. Evolution of intelligence-related TP's for FGRF's. For visualization purposes, the limit of intelligence intensity was set to 2.0

Signal processing, where the FGRF's related to *Compressed sensing* decreased their intelligence intensity over time.

Discussion

The availability of funding data from WoS opens a new opportunity to understand the evolution of a sectoral system of innovation from bibliometric data. With this in mind, we presented empirically grounded mapping of the scientific and technical output of the US NSS. The relevance of this system on the innovative landscape has been felt since World War II with massive funding in R&D which generated ICT with high societal impact, such as the internet and the digital computer.

Science fields

The results show that the US NSS has been promoting research in a variety of scientific fields. With the exception of social sciences, we identified technological paradigms classified in all major science fields. Social sciences presented a low proportion both at the document and paradigm level, although there are research fronts classified in this field in highly interdisciplinary paradigms. From the bibliometric perspective, this result is in accordance with findings of Grassano, Rotolo, Hutton, Lang, and Hopkins (2017), who found that the reporting of funding in social sciences is limited, and Boyack and Klavans (2014) who detected that the primary output of the social sciences is through books and other kind of publications not indexed by the WoS or Scopus.

However, the low proportion of social science can also be explained as a result of the alternative ways of communication inside the US NSS like specialized think thanks, such as the Rand Corporation. We also consider the intelligence community as "in-house" producer of social sciences. There are for example the National Intelligence Estimates, that are analytic products of the intelligence community aiming to understand or predict threats to US interests. Usually these documents are classified, but in the FOIA repository[7] we found complete reports about issues related to social sciences such as the political movements of the world and reports of economic production. More recently, we found the set of predictive reports about global trends (National Intelligence Council, 2012) which is elaborated with participation of specialists all around the world and coordinated by the ODNI.

[7] available at https://www.cia.gov/library/readingroom/nic-product-type/national-intelligence-estimates

In terms of overall academic output, the US NSS has a clear interdisciplinary nature, although with a strong focus on Physical sciences and engineering.

Technological paradigms

The technological paradigms denote several areas of research of relevant current subjects, such as climate change (*Ocean* and *Ecology*), energy issues (e.g. *Solar Cells*) and communication (*Wireless networks*). Concerning the technological content, we focus our discussion on two technological paradigms, *Graphene* and *Quantum information*, since their technological importance concerns the development of a new science foundation.

Graphene is the thinnest and strongest material ever measured, know for its thermal and electrical conductivity (Geim, 2009). Given its importance in defense issues, on December of 2017 the European Defense Agency hosted a meeting in order to carry out a new study about the future applications of graphene in the military domain and its impact on the European defense industry (European Defense Agency, 2017). Report commissioned by the US Army Research Laboratory indicated that research on graphene could generate benefits for the American soldier, offering “more efficient power electronics and communication systems, transparent and flexible electronics, and wearable electronics” (Dubey et al., 2012, p. ii). From a commercial perspective, the carbon nano tubes, that are seamless cylinders of one or more layers of graphene, have the potential to impact industries which produces composites, coatings and films, microelectronics, energy storage, and biotechnology (De Volder, Tawfick, Baughman, & Hart, 2013).

Concerning the *Quantum information*, the report to the White House from the US National Science and Technology Council (2016) discussed the importance of the development of the Quantum Information Sciences, emphasizing that QIS “is far more than a new approach to computing or a collection of technological applications: it is a scientific paradigm in its own right.” The report discussed various applications such as: sensing and metrology, communication, simulation and computing. In a similar manner, an analysis by the intelligence community stated that "quantum computing is a technology wild card that could begin to have an impact by 2030, with implications for basic scientific discovery, search, and cryptography" (National Intelligence Council, 2012, p. 85). Reporting about the technology priorities for investment, the Office of the Director of National Intelligence stated that research in quantum computing and quantum key management technologies is a hard target to accomplish (2014). The high intelligence involvement observed in our data is an expression of these strategic decisions and the importance give to these new fields.

Considering these two technological paradigms we can infer that the US NSS is trying to overcome basic physics limits in order to achieve radical innovations.[8] The rapid buildup of graphene (represented in TP's *Composites* and *Graphene*) make this technology figure as a relevant research field inside the US NSS. We consider this a striking factor considering that this material was isolated for the first time only in 2004 (Geim, 2009). Likewise, *Quantum information* is a trajectory departing from the current paradigm of digital computers, since it relies on a different phenomenon for information processing based on quantum mechanics. Thus, besides the direct effect of this research for defense issues, the new science foci by the US NSS through these two TP's could generate innovations with great societal impacts.

Intelligence-related technologies

Of the 6 intelligence-related TP´s, four of them were positioned in the Mathematics and computer science field, which confirms the informational nature of the intelligence activities. These results show that the efforts of the intelligence agencies are mainly targeted towards the development of new computer capacities and structured analytic methods for the identification and prediction of world events. Our data suggests that this is sought

[8] As stated by Ruttan (2006), it was primarily military and defense-related demand that drove down rapidly the learning curves of general-purpose ICT technologies, however, concerning computers, there would be some constraints imposed by basic physical principles which could interrupt the trajectory development.

through a number of different approaches.

The paradigm *Social forecasting* showcases publications which could be classified in two main categories: a) Network analysis, represented by FGRF *Complex networks* and b) *Human judgment*, which encompasses research about ways to understand the human decision-making and identify which personal features define a good judgment from a bad one. Furthermore, the paradigm *Computer recognition* is mainly related to computer algorithms aimed to action recognition. In conclusion, what is pursued in this area is the object recognition contextualized in a set of concatenated actions of human or artificial targets on the field, according to the current intelligence doctrine of activity-based intelligence (Atwood, 2015). The analysis of the FGRF's denoted this kind of research within the RF's *Simultaneous localization* and *Action recognition*.

Besides the immediate applications of this kind of research for intelligence activities, it is important to highlight the potential impact on the innovative landscape, since the intelligence-related paradigms point to the creation of new computer capabilities in different ways.

As explained above, especially *Quantum information* presents the possibility of radical innovation with a new science basis. Otherwise, the paradigm of *Computer recognition* brings incremental innovation with the same current basic science, however re-framing a new set of problems to be solved and redirecting the current trajectory development of the computers. That is why, as stated by Trajtenberg (2003, p. 22), computer technology has been developed in a very "asymmetric, skewed way vis-à-vis human capabilities", with improvement of the brain (central processor) to the detriment of the sensory capabilities. As a result, we have computers "virtually deaf, dumb, blind but highly intelligence, being capable of performing enormous amounts of routine computation."

Overall, our findings show that the intelligence-related research activities are concentrated around a small number of areas within the broader US NSS. Using a bibliometric approach our research was able to isolate innovation areas of the intelligence-related actors in the overall US NSS, including their development over time.

Conclusion

In this article, we considered the US National Security System as a sectoral system of innovation. Our goal was to identify and understand the evolution of the technological trajectories promoted by the system with special attention to the intelligence-related sub-system. We found that borders of the US NSS as sectoral system of innovation are very broad, with interdependencies and complementarities between and within the technological paradigms.

Specifically, the intelligence related research is very focused towards providing new recognition capabilities for the current computers or even the development of a new computer based on quantum mechanics. We further illustrated that the scientometric approach offers the possibility to understand the dynamics and evolution of technological paradigms and SSI.

Despite our meaningful findings about the technological content of the US NSS, this study is not without limitations. Since complete information about funding agencies is only available from 2009, this time range hindered the identification of longer-term changes inside technological paradigms. Furthermore, the funding information only denoted the presence of the funding agencies, without information about the amount of funding made available per paper. This hindered a more precise analysis of the evolution of the technological paradigms over time and their relative importance inside the system.

Concerning the methodology, it would have been fruitful to be able to combine the bibliometric techniques utilized here with expert advice to be able to understand the evolution of the presented technological trajectories. Furthermore, sentiment analysis could be used and combined with the analysis of research fronts over time to check if the technological paradigms are composed by technological limitations or possibilities.

Besides that, the results are limited because they do not put into perspective the scientific output generated by other actors in the US National innovation system as well as non-defense actors such as companies and civil agencies. In addition, the data analyzed does not offer an explanation about the weight of the National Security agencies vis-a-vis other organizations. Based on the technological paradigms identified, future research is suggested to compare the role of additional public and private agencies within and outside the national security system on scientific output. Only by comparing the magnitude of other sectoral systems we will be able to understand the full impact of the US NSS on the research and innovative landscape.

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