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THE DEVELOPMENT OF RADIO-FREQUENCY IDENTIFICATION (RFID) RESEARCH: 1990-2017



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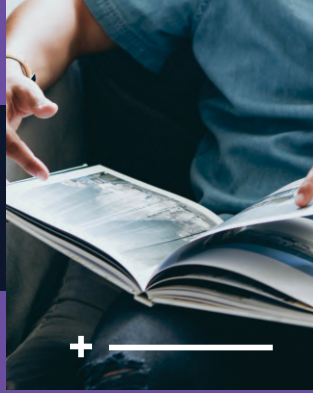
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➔ INTRODUCTION

Radio-Frequency Identification (RFID) is a wireless short-range radio technology that uses electromagnetic signals to detect and communicate information between objects [1], [2]. RFID technology consists of three main components. The first one is a transceiver. A transceiver is responsible for managing the entire system of the technology by acquiring and filtering data and communicating with other RFID systems [3]. A transceiver usually consists of a host computer or middleware with decoder to translate the signals.

The second component is an antenna. The antenna works as a mediator in the system. It is responsible for communication between the transceiver and the third component of the system, the tag. It emits radio signals to activate the tag and to read and write the data into the system. The antenna and the transceiver can be combined into one unit to become a reader. The reader can be set as a fixed mount or handheld device, where it would detect the presence of RFID tag in the electromagnetic zone [4]. The reader will then decode the encoded data from the tag so that the data can be transferred into the computer for further processing.



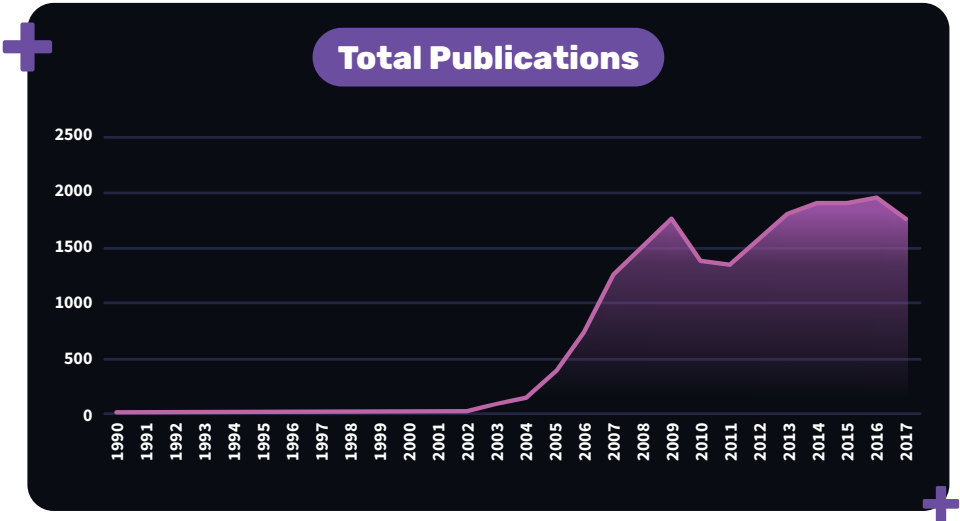


As previously mentioned, the last component of RFID is the tag. The tag is arguably the most vital component of RFID. Tags can be attached to mobile or immobile objects for tracking and tracing. Each tag may have either read-only or rewritten internal memory, depending on the type and application of the RFID system [5]. The function of this internal memory is to store unique information of the objects that will be communicated to the antenna and the transceiver for identification purposes. The reader will locate the object by conducting this electromagnetic communication with the tag once it is in the range, resulting in data generation [6].

The use of RFID in the industry has been rapidly increasing over the years. RFID is currently being used for many purposes, such as to prevent theft, to manage entrance into a property, to track both living and inanimate objects, to help monitor people with disability [7], and many other uses. The technology is also identical to the concept of Internet of Things (IoT). RFID technology builds the directory of data in an IoT system by supplying information on the trackable objects into the digital database that select users can access and manage [8]. RFID is becoming popular due to its affordable price, which makes it possible for an organization to apply the technology to many objects and inventories [9]. The use of the technology also increases due to its benefits for various industries, from supply chain management to other public sector organizations, in increasing efficiency and providing better service for the stakeholders [6].

With the increasing adoption of the technology across sectors, one cannot help but wonder about the dynamics and development of RFID research over the years. As shown in Figure 1, the total number of scientific publications related to RFID technology has been steadily increasing. Based on the data from Web of Science, the number of publications has increased more than 1700 times from 1991 to 2017. There was no result of RFID publication in 1990, while only one scientific publication specifically focused on RFID technology in 1991. Fast forward to 16 years later, the total number of RFID publications in 2017 reached 1766. We can also see how the number of publications started to pick up in the early 2000s, which is parallel with the rise of digitalization and Internet of Things in the manufacturing sector [10].

Figure 1. Total Number of RFID Publications from 1991 - 2017



Those being said, this paper will analyze the development of the technology over the period of 1990 to 2017 by covering several parameters, such as the most productive scientific fields in the research, the most prominent authors and their affiliations, collaborative patterns between research organizations and between nations, and the citation characteristics of the publications. This paper will divide the years into three periods, each covering a decade: 1) 1990-1999, 2) 1999- 2008, and 3) 2008-2017. This paper will analyze the development of RFID research by comparing these three periods.

The next part of this paper will explain the research methodology, which covers explanations on the data collection process and analysis of the paper. The third part of the paper will cover the research field classification of the publications based on Web of Science categories. Furthermore, the fourth part will elaborate on the authors by looking into the most prominent authors in the field and the affiliations of the authors, which include organization and country of origin. In the fifth part, the paper will assess the pattern of collaborations between organizations and countries over the three periods. Lastly, the paper will be concluded by highlighting important findings from the analysis.





➔ RESEARCH METHODOLOGY

➔ DATA COLLECTION

For the purpose of conducting this research, I use data on scientific journals provided by Web of Science. In collecting the data, I use two search terms in this study: “RFID” and “radio-frequency identification”. The search was limited to the topics covering these search terms, which include the occurrences of these terms in the title, abstract, or keywords. In the search, I specifically exclude the term “residual feed” as some agricultural research gets included in the search result when I only look up for “RFID”. Residual feed intake (RFI) is a concept related to resource allocation in cattle breeding and only one letter different compared to “RFID”, which leads to the inclusion of some publications on RFI in the search result. I only collect data from 1990 to 2017, and I include publications indexed in Science Citation Index Expanded (SCI- EXPANDED), Conference Proceedings Citation Index- Science (CPCI-S), Book Citation Index- Science (BKCI-S), and Emerging Sources Citation Index (ESCI). I exclude social science and chemical indexes as I want to focus on STEM publications and chemical indexes are irrelevant to RFID technology. The complete search term is as follows:

TS: ((rfid OR "radio-frequency identification") NOT (residual feed*))

Timespan: 1990-2017. Indexes: SCI-EXPANDED, CPCI-S, BKCI-S, ESCI.



➔ DATA CLEANING AND ANALYSIS

The search using those two terms and the criteria resulted in 20,335 publications. However, there are multiple publications with repeated entries in the result. This is primarily due to the same publication being presented at several conferences or being published in multiple journals or books. Therefore, I cleaned the data by eliminating multiple duplicates based on the title. I clean up the data by importing the data to Vantage Point and running the “remove duplicate” function by exact title. I also filtered out publications based on the document type. I only include articles, proceeding papers, and reviews as other document types, such as news items, often do not have enough citations. The clean-up resulted in a total of 19,658 publications from 1990 to 2017.

The next thing to do is to clean up the “Author Affiliations (Organization Only)” field. Some organizations are listed multiple times due to different spellings and/or variations in their names (e.g., abbreviation and long form). There are also some instances where an organization's divisions are listed separately from the parent organization. I ran the “List Clean-up” function in Vantage Point using the “Organization Names” fuzzy matching file to group these different variations and divisions into one unity. I also did manual clean-up by combining and verifying different departments and variations of these organizations.

After cleaning up the data in Vantage Point, I analyzed and visualized the clean data by using Vantage Point, Excel, and Gephi. I divide the data into three periods of year as I want to look into the dynamics of RFID research over the years. The first period covers 64 records from 1990 to 1999. The second period includes 4,236 records from 1999 to 2008. In the last period from 2008 to 2017, the dataset covers 16,888 records. In part 3, I use Web of Science categories to look at the productivity of each academic field over the periods. For part 4 of the paper, I generate insight on the top 10 list of most productive authors in each period based on full counting. I also take a look at the list of first authors to see if the result will be different compared to the list of full-counting authorship. I analyze author affiliations to see which organizations and countries produce the most publications in each period. I also take a look at which organization type produces the most publications based on the three categories I mentioned in the previous paragraph.

Lastly in part 5, I visualize the network of collaborations between organizations and nationalities by exporting the data from Vantage Point to Gephi. I use the “Export to Gephi” script from Vantage Point to create a static, one-mode symmetric type of network chart. I filter out the nodes to less than 20 organizations and countries with most publications in each period to avoid overcrowding and keep the network chart's clarity. I use Fruchterman Reingold for the layout of the chart, and I adjust the size of each node accordingly to the number of publications and the shade of the node to the degree centrality score. When it comes to the lines, I adjust the thickness and the shade of the color based on the quantity of collaborations between two nodes.



➔ MOST PRODUCTIVE ACADEMIC FIELDS

Research publications on RFID mostly come from the fields of engineering and computer science. This is reflected in the findings from each period. I use Web of Science categories instead of Research Area to represent different groups of academic fields as the Web of Science categories offer more specific groupings compared to Research Area, which is more general. I also limit the ranking to the top 10 of the most productive categories and group the subsequent categories into “others” due to overcrowding, as it could reach over 180 fields in total. It should be noted that there are some publications that are categorized into multiple Web of Science categories. Therefore, the total number of publications in each period is inflated.

Figure 2. Total Number of Publications per Web of Science Category from 1990 to 1999



From 1990 to 1999, the field of electrical and electronic engineering has the most publications with 32 records, or 50% of total publications. Telecommunications and interdisciplinary computer sciences follow behind with 13 and 8 records, or around 20% and 12.5% of the total records, respectively. Other engineering and computer science categories round up the top 10 except for one, which is agriculture. All publications under the agriculture category talk about the use of RFID for animal identification, which is a common practice in farms and cattle industry. Other fields outside the top 10 include 38 categories. Most of these other categories are variations of engineering and computer science, with some subdivisions of natural sciences such as ecology and fisheries. These other categories have no more than two publications each.

Figure 3. Total Number of Publications per Web of Science Category from 1999 to 2008



The fields of electrical and electronic engineering and telecommunications also dominate academic publications from 1999 to 2008. Electrical and electronic engineering has the most publications with 2,204 records, or more than 52% of total publications. Telecommunications follows behind with 1,543 records, or around 36% of the total records. Six computer science categories follow behind the top two, along with automation and control systems and physics to round up the top 10. The rise of computer science in RFID publications marks the shift of research from the physical infrastructure of RFID to its integration with the internet. This is in line with the rapid proliferation of internet of things and digital technology in general during the 2000s. This finding also shows the close relationship between RFID and internet of things as these two technologies are highly intertwined [8], [10]. Other fields outside the top 10 include 133 other categories, a significant increase from the previous period. The list includes a more varied list of academic fields, ranging from healthcare sciences to construction and building technology. Therefore, it shows a more diverse research and application of the technology in other scientific fields and industries.

Figure4. Total Number of Publications per Web of Science Category from 2008 to 2017



From 2008 to 2017, the top two most productive fields are still occupied by electrical and electronic engineering and telecommunications. Electrical and electronic engineering still has the most publications with 8,963 records, or more than 53% of total publications—a slight increase from the previous period. Telecommunications follows behind with 4,784 records, or around 28.3% of the total publications. This marks an almost 10 percentage points decrease from the previous period. Five computer science categories follow behind the top two, along with physics and automation, and control systems. However, a new category—Operations Research and Management—emerges into the top 10 with 668 records, or nearly 4% of the total publications. The rise of operations research and management confirms the research trend within supply chain operations. Some scholars hail RFID technology as “the next revolution in supply chain” [11]. The technology is expected to help transform supply chain operations by improving inter- and intra-organizational business activities by minimizing human interventions—which would lead to a more efficient practice [12].





➔ AUTHORSHIPS

➔ MOST PRODUCTIVE AUTHORS

I am using full counting measure to count the authorship. Each author in a paper will get one full credit, no matter how many author(s) are involved in a paper. I did not use weighted counting as RFID research is multidisciplinary in nature. It covers different academic fields with varying rules on giving credit to the authors. Measuring authorship through the number of publications with first authorship, for example, will not be able to be implemented in this paper as authors in a computer science publication is often being ordered alphabetically [13]. This defeats the purpose of using first authorship as a measure of author's contribution. Therefore, first authorship will not be included in this paper.

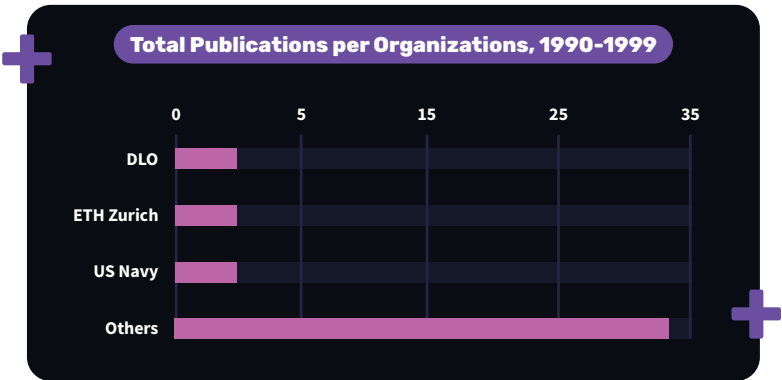
Table 1. List of Top Authors in RFID Research.

1990-1999		1999-2008		2008-2017	
Authors	#Publication	Authors	#Publication	Authors	#Publication
Benedickter	3	Kim, H	24	Ukkonen, L	137
Hchamtac	3	Park J-S	21	Tentzeris, M	105
Ipetrioli	3	Tentzeris M	21	Sydanheimo, L	94
CRedi, J	3	Yang, Li	19	Bjorninen, T	66
A tie between 13 other authors	2	Rida, A. and Ukkonen, L. (a tie)	16	Tedjini, S.	64

From table 1 we can see how the list of top authors in RFID research keeps changing from one period to another. During the years of 1990 to 1999, not many papers on RFID were published. There were four authors who shared the top spot with three publications each. From 1999 to 2008, the previous top names in RFID research had been replaced with new researchers. We can see how Korean authors—H. Kim and J-S. Park—became the top authors in the field with 24 and 21 publications, respectively. Other authors follow closely behind with more than 15 publications each. In 2008 to 2017, we can see how there are two authors from the previous period that came out on top in the list. L. Ukkonen became the top author in RFID research with 137 publications. Previously, Ukkonen was the fifth most productive author in 1999-2008 with 16 publications. The second most productive author in 2008-2017, M. Tentzeris, was the third most productive authors in 1999-2008 with 105 and 21 publications, respectively. Overall, we can see how the productivity of each author has increased multiple times over the years, along with the rapid growth of RFID as a research field.

➔ **ORGANIZATIONS WITH MOST PUBLICATIONS**

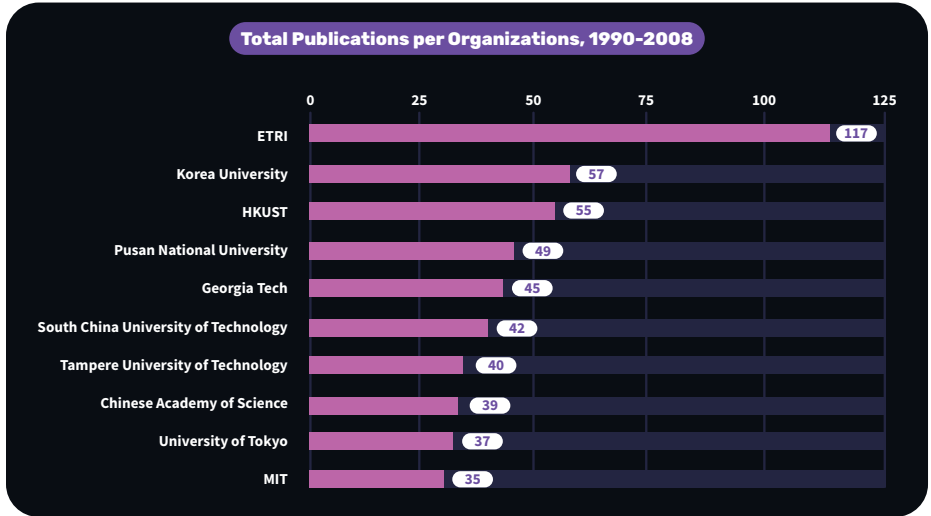
Figure 5. Total Number of Publications per Organization from 1990 to 1999



From 1990 to 1999, there were only three organizations that produced more than one paper in the 10- year period. DLO (Dienst Landbouwkundig Onderzoek/Plant Research International), ETH Zurich, and the US Navy contributed two publications each. The other 34 organizations contribute one paper each.



Figure 6. Top 10 Organizations Based on Total Number of Publications from 1999 to 2008



From 1999 to 2008, the top 10 most productive organizations in RFID research are mostly universities. Electronics and Telecommunications Research Institute (ETRI) became the most productive organization by far, with 117 publications. Three Asian universities—Korea University, Hong Kong University of Science and Technology (HKUST), and Pusan National University—follow behind with 57, 55, and 49 publications, respectively. Georgia Tech became the most productive organization in the Western hemisphere with 45 publications. Overall, we can see how Asian organizations dominate the field with 7 out of 10 organizations in the top 10. North America was represented by Georgia Tech and MIT, while Europe was only represented by Tampere University of Technology.



Figure 7. Top 10 Organizations Based on Total Number of Publications from 2008 to 2017

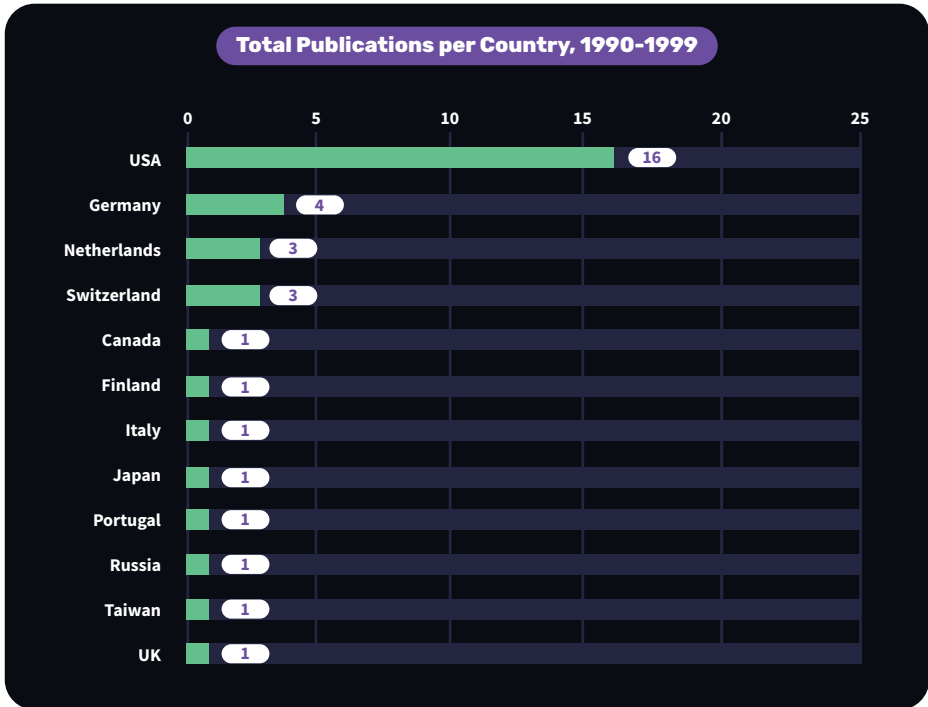


From 2008 to 2017, Georgia Tech rose up to become the top organization in RFID research with 227 publications. Chinese Academy of Sciences placed second with 188 publications, while Tampere University of Technology followed closely behind with 182 publications. Similar to the previous period, Asian organizations dominate the top 10 list with 6 organizations. Although this time, all of the Asian organizations came from China and Taiwan. In addition to Georgia Tech and Tampere University of Technology, two other non-Asian universities join in the top 10 with University of Florida (fifth place, 158 publications) and Monash University (ninth place, 122 publications). This once again shows the domination of Asian organizations and academic organizations in RFID research.



→ COUNTRIES

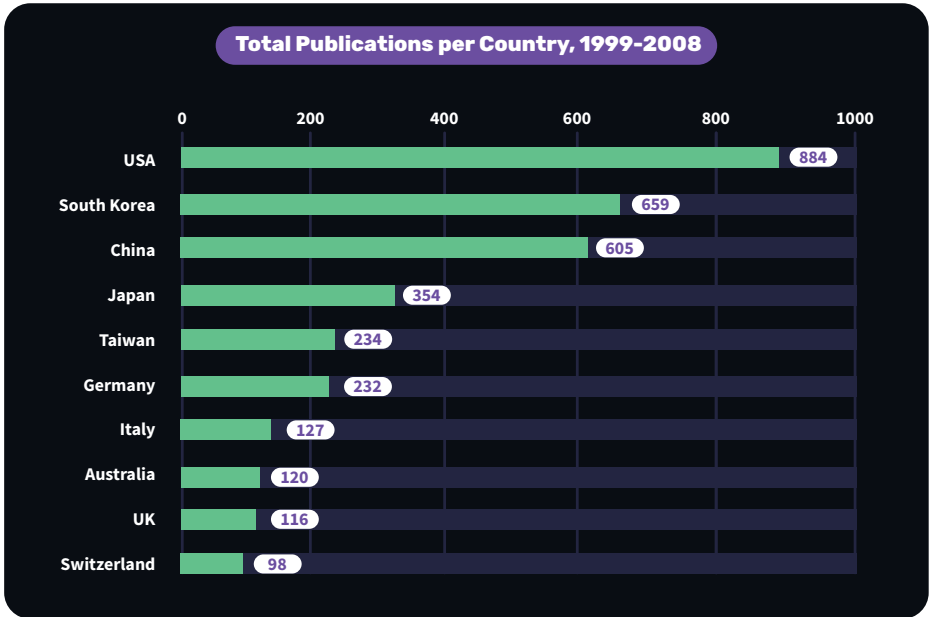
Figure 8. Total Number of Publications per Country from 1990 to 1999



From 1990 to 1999, we can see how the United States dominated RFID research with 16 publications. This is four times more than second-place Germany with 4 publications. From the list of the countries we can see that during 1990 to 1999, RFID research was dominated by North American and European countries. Only Japan and Taiwan came up on the list with one publication each.



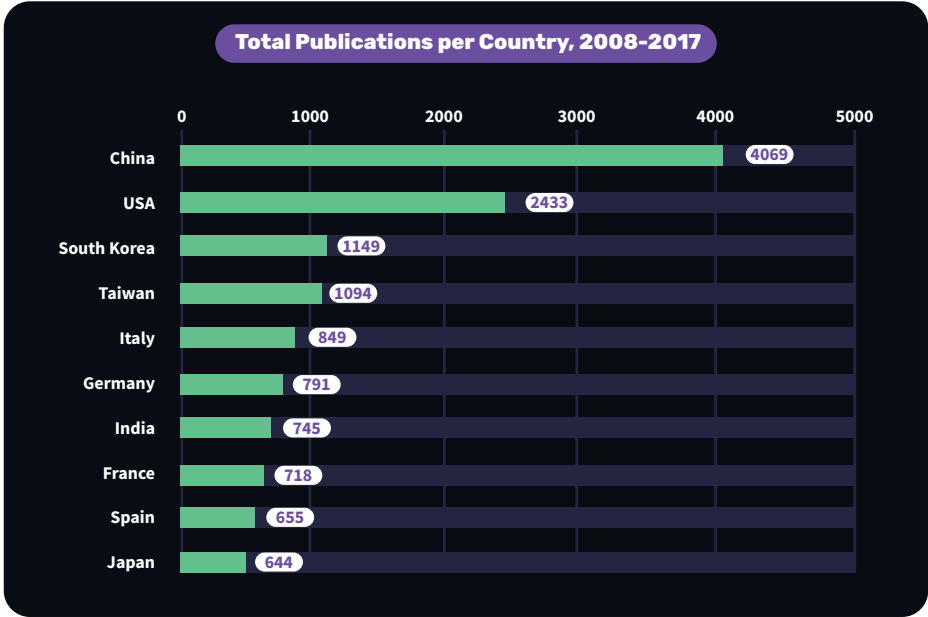
Figure 9. Top 10 Countries Based on Total Number of Publications from 1999 to 2008



From 1999 to 2008, the United States was still the top country in RFID research with 884 total publications. However, now four Asian countries make up the top 5 with South Korea (659 publications) and China (605 publications) behind the United States closely. 4 European countries (Germany, Italy, the United Kingdom, and Switzerland) plus Australia round up the top 10 with nearly all countries contributed more than 100 publications each (except for Switzerland with 98 publications). This period marks the beginning of the rise of Asian countries in RFID research.



Figure 10. Top 10 Countries Based on Total Number of Publications from 2008 to 2017



From 2008 to 2017, we can see how China has finally surprised the United States in total number of RFID publications. China almost doubled the total number of contributions from the United States with 4069 publications versus 2433 publications. Other Asian countries, namely South Korea and Taiwan, follow behind with more than 1000 publications each. Italy moved up a spot to number 5 with 849 publications while three European and two Asian countries round up the top 10, with each of them amassing more than 600 publications during the span of 2008 and 2017. In figure 10 we can see how India had finally joined the other four Asian countries in the top 10 to strengthen the Asian domination in RFID research. In conclusion, we can see how RFID research has shifted from the Western to the Eastern hemisphere over the years.

→ COLLABORATIONS

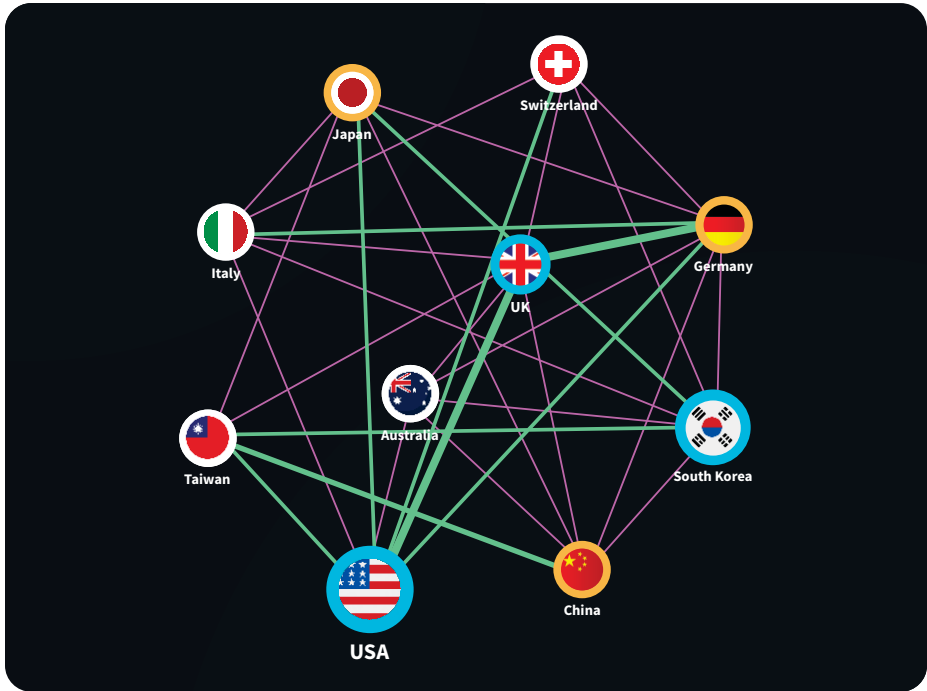
→ INTERNATIONAL COLLABORATIONS

Figure 11. Network Chart of International Collaborations from 1990 to 1999



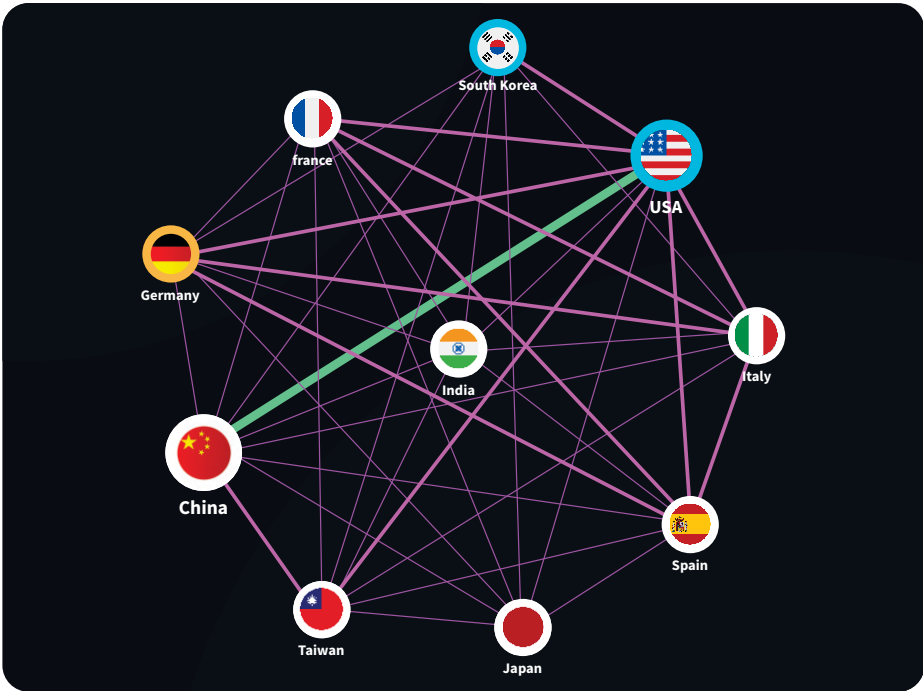
It is difficult to analyze the connections between countries in RFID research during 1990 to 1999. This period of years does not have many publications, which leads to the lack of collaborative publications between authors from different countries. From figure 11 we can see that the only notable international collaboration was between the United States and Italy, with 1 joined-publication. Other than this one publication, there was no other international collaboration between all 12 countries in the dataset.

Figure 12. Network Chart of International Collaborations from 1999 to 2008



From 1999 to 2008, we can see how there was a strong collaboration between the United States. And South Korea and China. Figure 12 shows the quantity of collaborations between countries (represented by the color and thickness of the lines), the size of the country based on the total number of publications, and the degree centrality (represented by the color of the nodes—the darker it gets, the more connections it has). When it comes to the degree centrality, both the United States, the United Kingdom, and South Korea top the list with 9 connections. These three countries also have the most closeness centrality score (1.0), betweenness centrality score (2.83), and eigenvector centrality score (1.0). From this result, it is interesting to highlight how the United Kingdom is only the ninth biggest country when it comes to RFID publications, but it has more collaborations than the other countries sans the United States and South Korea.

Figure 13. Network Chart of International Collaborations from 2008 to 2017

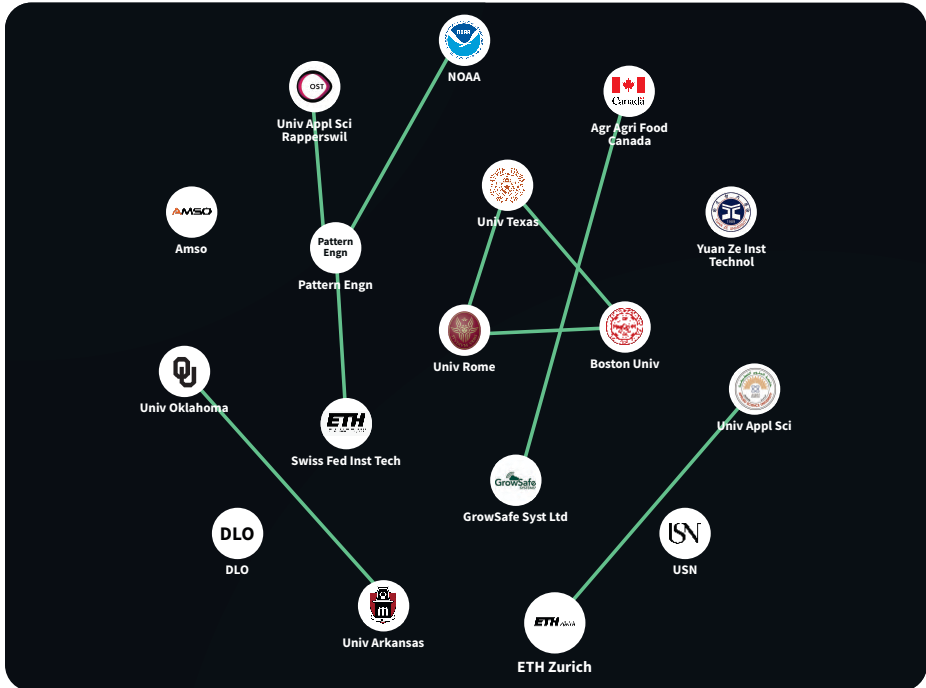


In 2008 to 2017, we can see that China and the United States had close collaborations on RFID research. Other noteworthy links in this period would be the collaborations between the United States and South Korea and between the United States and France. Both the United States and China have the highest scores when it comes to degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality. This finding shows how, even though China has surpassed the United States as the top country in RFID research, the United States still holds an important position in the network of RFID research.



→ ORGANIZATIONAL COLLABORATIONS

Figure 14. Network Chart of Organizational Collaborations from 1990 to 1999



From 1990 to 1999 not many collaborations happen between organizations in RFID research. As we can see, there are three universities with most degree of centrality, which are University of Texas, University of Rome, and Boston University. These three organizations also have the best closeness and eigenvector centrality. We can also see how two out of three leading organizations when it comes to the total number of publications—DLO and US Navy—did not have any collaborative research with other organizations.

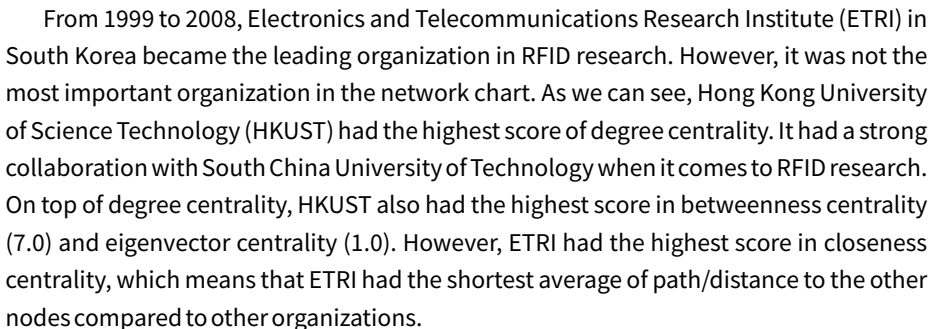
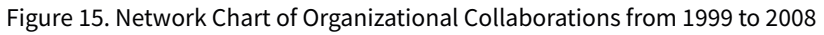
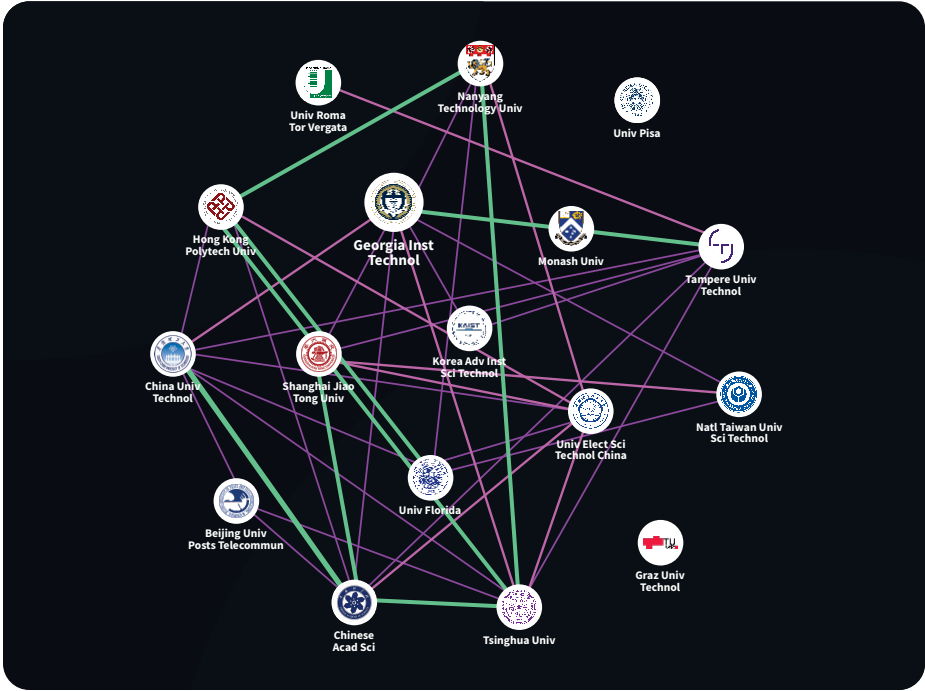
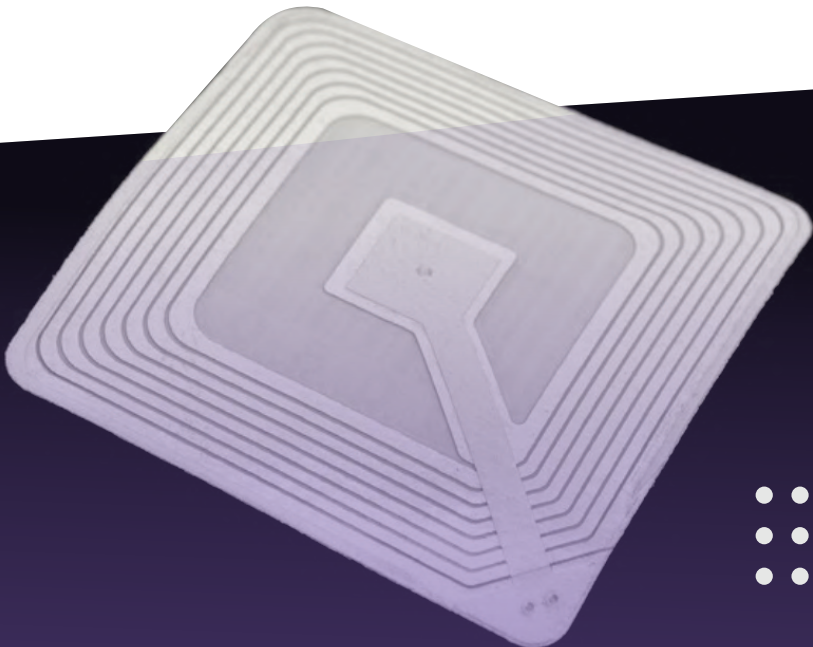


Figure 16. Network Chart of Organizational Collaborations from 2008 to 2017



From 2008 to 2017, we can see that more collaborations were being established as more RFID researches were being published. From figure 16 we can see how Asian organizations were highly collaborative with each other. University of Florida became the only non-Asian university that was involved in this Sino circle of academic collaborations. On the other hand, Georgia Tech and Tampere University of Technology, the first and third most productive organizations from 2008 to 2017, have strong tripartite research collaborations with Monash University. Other than these two circles, there were no other significant links of collaborations except for weak connections between Korea Advance Institute of Science and Technology with a number of other organizations, and a partnership between Tampere University of Technology and University of Roma.

As I have explained in the previous chapter, Georgia Tech became the leading organization in RFID research during the period of 2008 to 2017. However, Georgia Tech was not the most important university in the network analysis. Both South China University of Technology and Tsinghua University had the most degree centrality with 9. These two organizations also had the highest closeness centrality score with 0.76. Tsinghua University had a slightly higher score in eigenvector centrality compared to South China University of Technology with 1.0 and 0.99, respectively. However, these two organizations had less betweenness centrality compared to Tampere University of Technology. Tampere University of Technology scored 17.3 in betweenness centrality, while Tsinghua University and South China University of Technology scored 10.15 and 9.17 each. Meanwhile Georgia Tech, the leading organization in this period, was only eighth in degree centrality with score of 6, sixth in closeness centrality (0.65), fourth in betweenness centrality (7.62), and eighth in eigenvector centrality (0.603).





CONCLUSIONS

By comparing the findings from three periods, we can see how RFID research has grown rapidly over the years. We can see how the total number of RFID publications started increasing rapidly in 2003—from less than 50 publications each year to almost 2000 publications in 2017. For individual authors, we can see how research productivity has increased as the field is growing. During the 10-year period of 1990 to 1999, the top authors only published around 2 to 3 publications. This number increased to over 100 publications for each top two authors in 2008 to 2017.

This increase in RFID publications is in parallel with the rapid proliferation of internet of things and digital technology in general during early 2000s. The findings in this paper have supported this strong linkage of RFID and the internet. We can see computer science categories have steadily increased in the rankings of total publications per academic field. In 1990 to 1999, for instance, there were only two computer science categories in the top 10 of most productive academic fields. However, this number increased three-fold to six categories in 1999 to 2008. Another interesting finding is on how research on the application of RFID technologies in supply chains has increased over the years, especially during the period of 2008 to 2017 where the field of operations research has finally cracked into the top 10.

When it comes to author affiliations, we can see how authors affiliated with Asian organizations dominate the field. More than half of the top 10 organizations are research institutions and universities in Asia. However, there are still some non-Asian academic powerhouses such as Georgia Tech and Tampere University of Technology that consistently rank in the top 10. This Asian domination is also reflected in the list of top countries. The United States started leading the pack between 1990 to 2008. However, it began to lose its steam during the years 2008 and 2017, as China surpassed its total number of publications by nearly twofold. We can also see the rise of other Asian countries such as South Korea, Taiwan, and India over the years. Moreover, when it comes to international and inter-organizational collaborations, we can generate several insights from the network analysis. First, the United States has continued to become one of—if not the most—important country in the network. Even after China surpassed the United States as the top country in RFID research from 2008 to 2017, the United States still holds great authority in the network. Second, we can see a pattern of collaborations between Chinese organizations. For example, from figure 16 we can see how these Chinese organizations have created a circle of collaborations that almost excludes other non-Chinese organizations. Third, we can also conclude that the size of the node (i.e., the total number of publications) barely affects the organization's centrality. Georgia Tech, for example, was the leading organization in RFID research in 2008 to 2017. However, the university is not even in the top 5 in many of the centrality measures.





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ABOUT C F D S

Center for Digital Society (CfDS) is the research center established by the Faculty of Social and Political Sciences, Universitas Gadjah Mada. The institution is created under the concern over the contemporary dynamics of socio-political condition of the world that is accentuated by the impeccable influence of information technology. The phenomenon triggers the new patterns and complexities in the society, and thus requires new approaches in managing such complexities.

CfDS pledged to delve more on the study of contemporary digital society, including related issues surrounding the topic; such as the issues of smart city and urban development. The emphasis is then put on the utilization of technology to shape the society in becoming digitalized, as well as to bring solvency to social issues.

Vision

Solving Social Problem and Accelerating Prosperity through Indonesia Digital Society

Activities

1. Research and Development
2. Dissemination and Publication
3. Education and Policy Advocacy

Research Scopes

1. Digital Governance
2. Digital Economy
3. Future Technology



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