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Identification of key research topics in 5G using co-word analysis

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Project work presented as partial requirement for obtaining the Master's degree in Information Management

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IDENTIFICATION OF KEY RESEARCH TOPICS IN 5G THROUGH CO-WORD ANALYSIS

by

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Project Work presented as partial requirement for obtaining the Master's degree in Information Management/ Master's degree in Statistics and Information Management, with a specialization in Knowledge Management and Business Intelligence

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ABSTRACT

The aim of this research is to better understand the field of 5G by analyzing the more than 10000 publications found in the Web of Science database. To achieve this, a co-word analysis was performed to identify research topics based on the author keywords and a strategic diagram was used to measure their level of maturity and relevance to the field. In total this analysis identified that all the articles can be grouped into seven topics, from which, two are mature but peripheral, one is both well developed and central to the field, and the rest are central, but underdeveloped. The value of this research, was the usage of a well-established technique that has been used in many fields, but never in the field of 5G which is growing in relevance.

KEYWORDS

5G, Co-Word Analysis, Strategic Diagram, Bibliometrics, VOSviewer

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1. INTRODUCTION

5G is the fifth and most recent generation of telecommunication technologies. 5G is an improvement to the previously used 4G technologies due to its increased speed, high potential for innovation and multiple social and economic benefits. Furthermore, a recent study published by the European Investment Bank and the European Commission, states that this technology will be critical for the European Union to stay competitive in the international markets (Gilles & Toth, 2021).

In addition, the number of publications is growing year after year in databases such as the Web of Science (WoS), having reached already more than 10000 publications (the period under analysis in 2005-2020). This growth in in publications makes it increasingly difficult for researchers to have a full understanding of the field of study. It also becomes harder to identify trends, subject areas and or knowledge gaps. In addition, policy makers also have a harder time planning research and making informed decisions (Qin, 1999).

To help solve this problem, researches have been applying mathematical and or statistical methods to analyze and better understand journal articles, books and other types of documentation (Pritchard, 1969). These techniques are usually called bibliometric techniques and can be used for the evaluation of research. Furthermore, they can be applied with reasonable effort to research fields with high volume of data (Bornmann & Leydesdorff, 2014).

Co-word analysis is a bibliometric technique which attempts at identifying the key research topics in a field by clustering the keywords of a field, based on their co-occurrence (Callon et al., 1991). This technique has been performed in various fields of study, such as, Stem Cells (An & Wu, 2011a), iMetrics (Khasseh et al., 2017), Library and Information Science (Hu et al., 2013), medical tourism (de la Hoz-Correa et al., 2018), recommendation systems (Hu & Zhang, 2015) but never in the field of 5G. Due to its growing relevance and interest, applying co-word analysis in this field has great potential.

The objectives of this research are:

1. Identify the main research topics in 5G
2. Measure and map the level of development/maturity of those topics
3. Measure and map the proximity and importance of those topics to the rest of the field
4. Map the relationships between topics and words.

The structure of this thesis is the following: after this introduction, section 2 describes the methods used. Section 3 describes the results and is followed by their discussion in section 4. Lastly, section 5 includes the conclusions, limitations and suggested future works.

2. METHODOLOGY

Bibliometric techniques, such as co-word analysis, are techniques capable of studying and extracting information by looking at the bibliometric data from publications, books and other types of documentation (Pritchard, 1969). These techniques can be applied on the keywords, titles, references, citations, abstracts, titles or any other data related with the documents being studied.

This section explains in more detail how the analysis was performed and its key components.

2.1. DATA COLLECTION

The data was collected from Web of Science (WoS) database, and all journal articles related with 5G were extracted. An article was considered related if their title, abstract or author keywords included the keyword 5G or derivates. However, due to false positives such as confusing 5G with 5 grams, the publications were then reviewed to exclude the articles that were not discussing this subject. In total, 10717 publications were found. In Figure 1 it is possible to see their distribution over the years. In addition, all publications that did not include the necessary author keywords used in this analysis had to be removed. In the end, 9141 (85%) publications moved on to the pre-processing step.

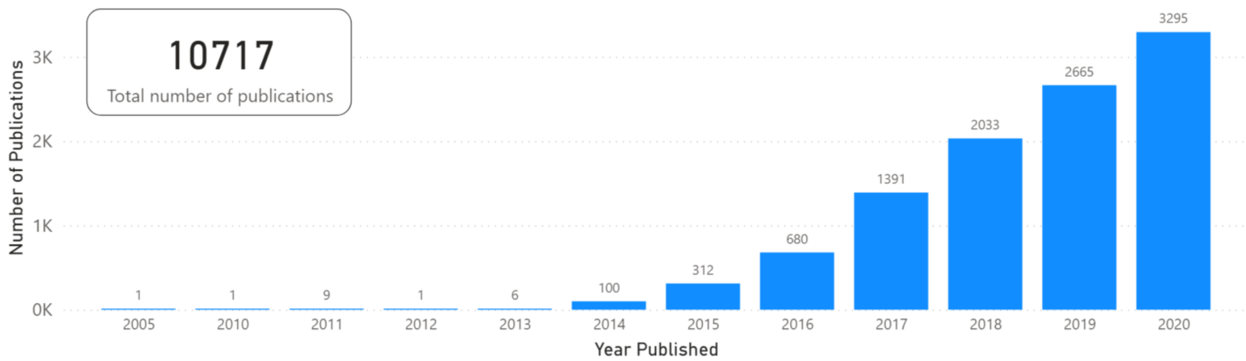

Figure 1 - Number of 5G publications per year available in Web of Science

2.2. DATA PRE-PROCESSING

The following step was the pre-processing of the keywords, where it was necessary to clean and normalize the keywords. The objective is to reduce the number of different keywords that represent the same concept. The following scenarios were taken in consideration:

- Synonyms
- Singular and Plural
- Abbreviations
- Misspellings
- Sentence order and structure
- Special characters

To finish the process, it was necessary to select which keywords were going to be used in the analysis. First, there was a manual process of removing keywords that were too generic or that had no relation with 5G. Then, a threshold was defined to filter keywords that didn't have enough representation to be considered relevant. Only keywords with a frequency higher than 10 were selected for the analysis.

This resulted in a selection of 582 unique keywords, with a total frequency of 28782, which represents 49% of the initial total word frequency. Also, as a result of only using these selected keywords, some more articles had to be excluded from the analysis, as they did not include any of them. In the end, 8407 articles are included in this analysis, which represent 78% of the field.

2.3. Co-word analysis

Co-word analysis is a bibliometric technique that uses the co-occurrence of keyword pairs to measure the relationship strength between the terms describing an article. A keyword pair that appear in the same article across multiple articles are considered as having a strong relationship. Based on those relationships, the keywords are clustered to identify research themes (Callon et al., 1991). One of main usages of co-word analysis is to identify and map patterns and trends in a field of study (Wang et al., 2012).

2.4. Co-occurrence matrix

This analysis uses a co-occurrence matrix to cluster the keywords into topics. In this matrix, each column and each row represent one of the keywords of the analysis and each cell represents the relationship between the keyword in the row and the keyword in the column. The result is a symmetric matrix where the diagonal is considered as missing data (Qin, 1999).

2.5. Clustering Process

VOSviewer was the software used to cluster the keywords, based on the co-occurrence matrix. One of the big advantages of this software is that the clustering algorithm has a similar logic to the network visualization algorithm, resulting in more cohesive outputs. In the clustering algorithm, clusters are optimized to minimize a distance function based on the strength of the links and the distance between the words. High links are more likely to be closer in distance (Waltman et al., 2010).

2.6. Strategic Diagram

To better understand the clusters, a strategic diagram was used as a way of mapping and visualizing the clusters in a two-dimensional graph using centrality and density. Centrality reflects how strong the interaction of the cluster with the rest of the field is. A cluster with high centrality, is a cluster central to the research field, it shows that it has strong connections with the other research topics. Density shows the internal strength of the cluster. It can be interpreted as the maturity or level of development of the cluster (Law et al., 2005).

The center of the graph shows the median of each measure, and it divides the graph in 4 quadrants as it can be seen in Figure 2.

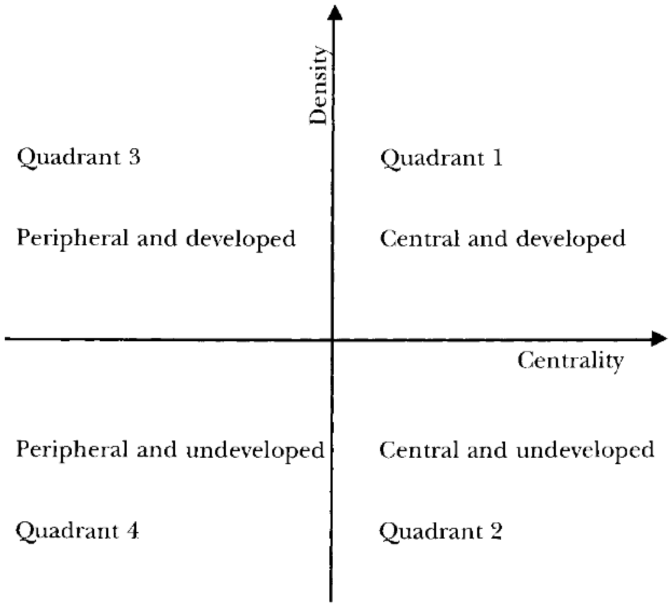

Figure 2 - Quadrants definition in a strategic diagram

Source: Callon et al. (1991, p. 166)

Quadrant 1 includes the clusters more developed and more central to the entire field of study. Quadrant 2 represents topics that haven't achieved their full maturity but are central. Quadrant 3 is for clusters that are mature but peripheral to the rest of the network. This sometimes happens with topics that in the past were central to the field, but that lost the interest of researchers with the passage of time. Quadrant 4 are topics that are not mature and that are peripheral to the subject (Callon et al., 1991).

2.7. NETWORK VISUALIZATION

Network visualizations are an interesting way of mapping the relationships between keywords and to view the proximity between clusters, and how they interact with each other, all in a 2-dimensional graph. These visualizations attempt at minimizing the distance between keywords with strong relationships and are very useful when used as a complement to the previous analysis and they are able to give an extra insight regarding this field (Waltman et al., 2010).

3. RESULTS

3.1. MATRIX CREATION AND STANDARDIZATION

After cleaning the data, the following step was to create the co-occurrence matrix aggregating the data from all years. This is the basis for the entire analysis.

In this step, it is important to standardize the co-occurrence frequency because it is biased towards keywords with high frequency. The objective of the normalization is to reduce the size effect and to increase the similarity effect. The use of direct techniques, such as the Association Strength Index, is suggested by (Van Eck & Waltman, 2009). In addition, that technique is also the default standardization method used in VOSviewer. As a result, this was the method used to standardize this data. The term "co-occurrence strength" used from this point on refers to the co-occurrence calculated based on the standardized data.

The top 20 keywords according to their frequency can be seen in table 1. Even though these are the most frequent keywords, most of them are below average in terms of total co-occurrence strength. The total co-occurrence strength of a word is the sum of the normalized co-occurrence between that word and all other words. The inverse behavior can be seen in table 2, where the top 20 keywords by total co-occurrence strength are below average in terms of frequency. This shows that by applying the standardization process, the size effect of high frequency keywords was successfully reduced.

The top 10 keyword pairs, according to their co-occurrence strength, can be seen in table 3. Similar to what happened to the top keywords by co-occurrence strength, the top keyword pairs do not have a very high frequency, being this once again, the result of standardization process.

Table 1 - Top 10 keywords when sorted by frequency

	Frequency		**Total Co-occurrence Strength**	
Keywords	**Value**	**Rank**	**Value**	**Rank**
MOBILE COMMUNICATION	1020	1	1058,74	83
MILLIMETER WAVES	839	2	646,69	302
NON-ORTHOGONAL MULTIPLE ACCESS	687	3	627,57	328
RESOURCE ALLOCATION	604	4	734,60	234
INTERNET OF THINGS	603	5	552,52	405
MASSIVE MULTIPLE INPUT MULTIPLE OUTPUT	479	6	505,81	459
ENERGY EFFICIENCY	418	7	577,15	376
DEVICE TO DEVICE	400	8	482,96	483
SOFTWARE DEFINED NETWORKS	366	9	514,97	450
MULTIPLE INPUT MULTIPLE OUTPUT	360	10	641,61	309

Table 2 - Top 10 keywords when sorted by total co-occurrence strength

	Frequency		Total Co-occurrence Strength	
Keywords	**Value**	**Rank**	**Value**	**Rank**
RADIO RECEIVERS	13	476	2325,36	1
TELECOMMUNICATION NETWORK RELIABILITY	11	558	1935,42	2
DIVERSITY RECEPTION	11	558	1837,16	3
RADIOFREQUENCY INTERFERENCE	31	212	1779,58	4
TELECOMMUNICATION POWER MANAGEMENT	11	558	1767,18	5
PROBABILITY	39	173,5	1741,23	6
RELAY NETWORKS	21	309,5	1713,69	7
RADIO NETWORKS	15	416,5	1685,80	8
ANTENNA FEEDS	34	195	1626,62	9
MILLIMETRE WAVE ANTENNA ARRAYS	14	444	1614,45	10

Table 3 - Top 10 keyword pairs when sorted by co-occurrence strength

	Co-occurrence		Co-occurrence Strength	
Keyword pair	**Value**	**Rank**	**Value**	**Rank**
PERIODIC STRUCTURES GLIDE SYMMETRY	13	476	2325,36	1
STOCHASTIC PROCESSES GEOMETRY	11	558	1935,42	2
VIRTUAL REALITY AUGMENTED REALITY	11	558	1837,16	3
TOPOLOGY NETWORK TOPOLOGY	31	212	1779,58	4
DIVERSITY RECEPTION TELECOM. NETWORK RELIABILITY	11	558	1767,18	5
RADIO NETWORKS TELECOM. NETWORK RELIABILITY	39	173,5	1741,23	6
RELAY NETWORKS DIVERSITY RECEPTION	21	309,5	1713,69	7
WIMAX MULTIFREQUENCY ANTENNAS	15	416,5	1685,80	8
RADIO RECEIVERS TELECOM. NETWORK RELIABILITY	34	195	1626,62	9
MICROSTRIP ANTENNA ARRAYS MILLIMETRE WAVE ANTENNA ARRAYS	14	444	1614,45	10

3.2. CLUSTERING

With the matrix fully prepared, the next step was to import the data into VOSviewer to create the clusters and the network visualization.

This process resulted in 7 clusters, each labeled according to their top 3 keywords based on their total co-occurrence strength, as it can be seen in table 4. This labelling process is common, but the number of keywords vary between each article (An & Wu, 2011b; C. P. Hu et al., 2013).

The relevant statistics for each cluster can be found in table 5. There, one can find the value for centrality and density, the number of keywords and the total and average keyword frequency. These results will be discussed more in depth in the following sections. In addition, the full list of keywords found in each cluster can be found in the appendix.

Table 4 - Clusters' names

#	Keyword 1	Keyword 2	Keyword 3
1	NETWORK TOPOLOGY	VEHICULAR AD HOC NETWORKS	VEHICLE DYNAMICS
2	ANTENNA FEEDS	MILLIMETRE WAVE ANTENNA ARRAYS	IMPEDANCE
3	RADIO RECEIVERS	TELECOMMUNICATION NETWORK RELIABILITY	DIVERSITY RECEPTION
4	GEOMETRY	STOCHASTIC PROCESSES	GAMES
5	INDEXES	RECEIVERS	OPTICAL FIBER NETWORKS
6	ARRAY SIGNAL PROCESSING	FADING CHANNELS	SATELLITE BROADCASTING
7	HYBRID BEAMFORMING	BEAM SELECTION	

Table 5 - Clusters' statistics

#	Colour	Centrality	Density	Number of keywords	Total Frequency	Average Frequency
1	Red	0,58	207,36	154	9251	60,07
2	Green	0,42	339,46	132	5842	44,26
3	Blue	0,70	247,36	91	4360	47,91
4	Yellow	0,67	138,70	87	5052	58,07
5	Teal	0,73	144,45	63	2296	36,44
6	Purple	0,93	138,75	45	1631	36,24
7	Orange	0,67	53,46	2	69	34,50

3.3. Strategic diagram

With the clusters created the next step was to build the strategic diagram to measure and visualize the level of maturity and centrality of each cluster in relation to the field. The results can be seen in Figure 3. The horizontal line represents the average centrality (0,67), and the vertical line represents the average density (181,46).

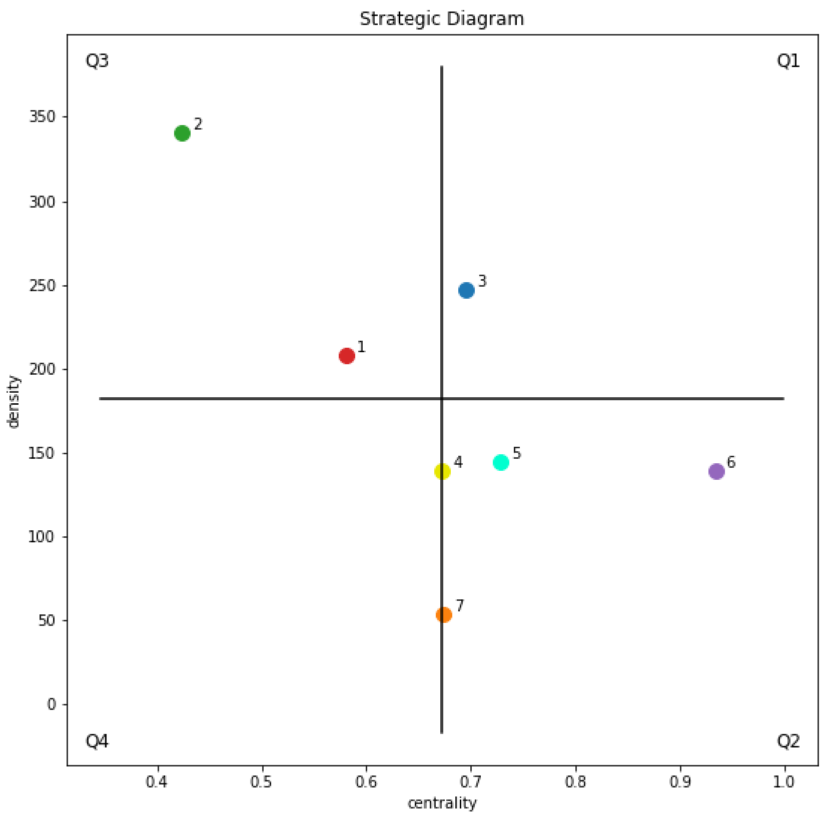

Figure 3 - Strategic Diagram for 5G data

3.4. Network visualization

Figure 4 is the standard visualization of the network. In this figure, the size of the circles, also known as nodes, represent the sum of co-occurrences the node's keyword has with all the other keywords. The lines between nodes, also known as edges, represent the co-occurrence between nodes while their co-occurrence strength is represented by their proximity.

The number of visible edges is limited 1000 to increase legibility. As a result, only the edges with the highest values are shown. Furthermore, the thickness of the edges is also defined by their co-occurrence value. Higher values are represented with thicker lines. To finalize, the colors used in the nodes and edges represent the cluster which they belong to. The cluster's names and statistics can be found in tables 4 and 5.

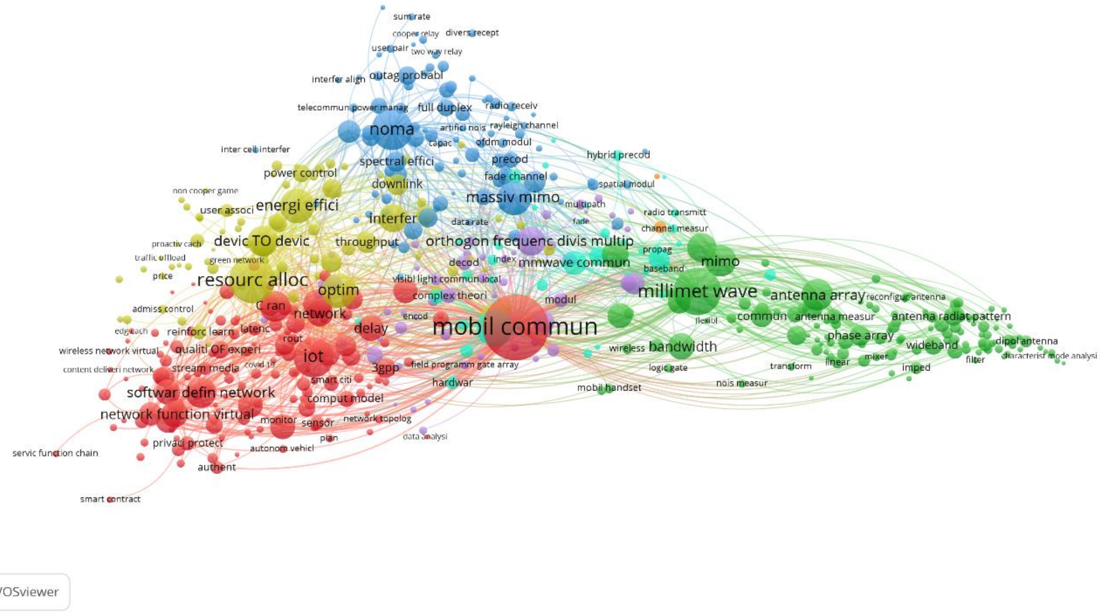

Figure 4 - Network visualization

In this figure, the previous results can be more easily digested as they can be visualized in a map, instead of tables. From this image, it can be seen that “mobile communication” is the most frequent keyword and that it is also right in the middle of the network. This is most likely caused by its high frequency. Other frequent keywords are “millimeter wave”, “resource allocation” and “N.O.M.A”, all in different clusters.

In this figure it can also be noticed that the 4 bigger clusters (red, green, blue and yellow) are better defined than the other 3 smaller clusters. Teal, purple and orange are mixed in the middle of the network and don’t have a clear area where they are concentrated.

This figure is also useful to understand the position of the clusters in relation to the other ones. For example, the green cluster, which is also the cluster with lowest centrality, is the one that is more isolated from the rest of the network.

4. DISCUSSION

The first thing that can be noticed is that there are no clusters in quadrant 4. This means that there are no topics that are both underdeveloped and peripheral to this field.

In quadrant 3(Q3) there are two clusters that can be identified, cluster 1 and 2. These are the topics that are well developed but peripheral to the rest of the field. Despite that, they are still different, as cluster 1 is close to the center while cluster 2 is close to the corner of its quadrant, meaning that it is much more mature and peripheral than the prior.

Quadrant 2(Q2) includes the clusters 4, 5, 6 and 7, making it the quadrant with the highest number of topics. This quadrant represents the topics that are central to the field, but that are still underdeveloped and that would benefit the most by being more researched, due to its relevance to the entire field.

Furthermore, it is interesting to highlight that even though all four topics belong in the same quadrant, just like in Q3, there is a significant difference between them. Cluster 6 is the cluster with the highest centrality in the entire network. This is the topic which is more connected to the rest of the field. However, it is lacking in terms of maturity, when compared with clusters on Q1 and Q3. This makes it a very relevant topic for researchers to invest their time and resources in, due to it being so relevant to the rest of the network. Clusters 4 and 5 are similar to 6 in terms of maturity but in contrast, their centrality is much closer to the average, meaning that their interactions with other topics aren't as strong as the ones topic 6 has. Cluster 7's centrality is similar with cluster 4 and 5 but in contrast it is the least mature topic in the whole network. This lack of maturity can be justified by the weakness of the cluster itself, as it only includes 2 keywords and has a much lower total frequency when compared to any other cluster.

Quadrant 1(Q1) consists of topic 3. This topic distinguishes himself from the rest of the network by being the only one that is both mature and central to the rest of the network. This is a very important topic in the field, but due to its already high level of maturity, it might be more interesting to invest more research in other topics.

5. CONCLUSIONS

In this research, co-word analysis was performed to identify research topics and a strategic diagram was drawn to measure how central and developed those topics are in the field of 5G. The basis of this analysis were author keywords retrieved from the Web of Science database. The earliest article found was published in 2005, and the latest publication included was from early 2021.

During the pre-processing step the association strength index was used to normalize the co-occurrence frequency between keywords. By using it, it was possible to reduce the size effect that tends to give more importance to keywords with high frequency. The keywords and keywords pairs considered more relevant for this study can be found in table 2 in the results section.

The clustering algorithm used identified 7 clusters. This clusters were named based on their more relevant keywords. Cluster 3 was considered central and developed, clusters 3 4 6 and 7 were considered central but underdeveloped, clusters 1 and 2 were considered developed but peripheral. No cluster was considered both underdeveloped and peripheral.

The clusters that distinguish themselves from the rest were cluster 2 and 6. Cluster 2, also called, "Antenna Feeds; Millimeter Wave Antenna Arrays; Impedance" is the most developed topic in the whole field but is also the most peripheral topic. Cluster 6, also called, "Array Signal Processing; Fading Channels; Satellite Broadcasting" is the most central topic but is still underdeveloped. This is most likely the most interesting topic for researchers as this topic is relevant to the whole field but still requires more research to be considered mature.

This research allows researchers and policy makers to have a better understanding of what is happening in the academic field regarding 5G, allowing them to make better informed decisions. In here, they can understand what topics are being developed and what are the most relevant keywords at the current time.

One of the main limitations of this work was the percentage of articles not included in the analysis because of missing keywords. In the beginning of the analysis 15% of the articles didn't have author keywords and were removed before the preprocessing. Then, after the preprocessing step, another 7% of the original articles had to be removed as they did not contain any of the keywords selected for this analysis.

In some future work, the author keywords can be complimented or even be replaced by a natural language algorithm capable of extracting the keywords based on the title, abstract and or the body of the articles. This will reduce to 0 the number of articles without keywords, however, it is still possible for some of the articles to be removed if none of their keywords are selected for the analysis.

Also, in the future, it might be interesting to complement this analysis with a co-citation analysis or other bibliometric technique, in order to have a more in depth view and understanding of this field (Chang et al., 2015).

To finalize, it might be compelling to compare and correlate the findings of this research with the trends of 5G identified by the European Commission and the European Investment Bank in the article (Gilles & Toth, 2021). It might be possible to match the topics identified with the trends to see if the EU and the academic world have the same view regarding 5G.

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7. APPENDIX

Table 6 - List of keywords per cluster

Cluster	Keyword
1	MOBILE COMMUNICATION; INTERNET OF THINGS; QUALITY OF SERVICE; SOFTWARE DEFINED NETWORKING; CELLULAR NETWORKS; NETWORK FUNCTION VIRTUALIZATION; NETWORKS; DELAYS; COMPUTER ARCHITECTURE; NETWORK SLICING; SECURITY; CLOUD COMPUTING; WIRELESS NETWORKS; EDGE COMPUTING; MACHINE LEARNING; RELIABILITY; UNMANNED AERIAL VEHICLES; 3GPP; MOBILE EDGE COMPUTING; C RAN; RADIO ACCESS NETWORKS; DEEP LEARNING; URLLC; PROTOCOLS; QUALITY OF EXPERIENCE; MULTI ACCESS EDGE COMPUTING; SERVERS; ARTIFICIAL INTELLIGENCE; TASK ANALYSIS; MOBILITY; COMPUTATIONAL MODELING; ENERGY CONSUMPTION; HANDOVER; PRIVACY; HEURISTIC ALGORITHMS; WIRELESS SENSOR NETWORKS; LATENCY; SENSORS; V2X; VIRTUALIZATION; FOG COMPUTING; BLOCKCHAIN; AUTHENTICATION; STREAMING MEDIA; MACHINE TO MACHINE COMMUNICATIONS; CACHING; DEEP REINFORCEMENT LEARNING; COMPUTATION OFFLOADING; ANALYTICAL MODELS; REAL TIME SYSTEMS; MMTC; MOBILITY MANAGEMENT; ROUTING; TACTILE INTERNET; SMART CITY; VEHICULAR NETWORKS; SOFTWARE; BIG DATA; MACHINE TYPE COMMUNICATION; RADIO RESOURCE MANAGEMENT; COMMUNICATION SYSTEM SECURITY; NETWORK ARCHITECTURE; DYNAMIC SCHEDULING; DRONES; VEHICULAR AD HOC NETWORKS; VEHICULAR COMMUNICATIONS; CLOUD; OFFLOADING; MONITORING; INDUSTRIES; NEXT GENERATION NETWORKING; STANDARDIZATION; SCALABILITY; DATA MODELS; MOBILE COMPUTING; VEHICLE DYNAMICS; LOW LATENCY; MATHEMATICAL MODEL; INTERNET; MICROPROCESSORS; ORCHESTRATION; AD HOC NETWORKS; LICENSES; MULTI CONNECTIVITY; ACCESS CONTROL; NETWORK CODING; VANET; DATA CENTERS; NETWORK TOPOLOGY; INTERNET OF VEHICLES; COMMUNICATION NETWORKS; PLANNING; INFORMATION CENTRIC NETWORKING; LYAPUNOV OPTIMIZATION; INDUSTRY 4.0; FEATURE EXTRACTION; AUTONOMOUS VEHICLES; TECHNOLOGY; MTC; NETWORK VIRTUALIZATION; INTELLIGENT TRANSPORTATION SYSTEMS; OPENFLOW; CRYPTOGRAPHY; NARROWBAND; MOBILE CLOUD COMPUTING; CONTENT CACHING; MULTI RAT; DECISION MAKING; SMART GRID; CONTEXT AWARENESS; SERVICE FUNCTION CHAIN; WIRELESS NETWORK VIRTUALIZATION; TRUST; MULTI TENANCY; SLICING; CONGESTION CONTROL; MOBILE NETWORK OPERATOR; SMART CONTRACTS; ANOMALY DETECTION; NB IOT; ARCHITECTURE; SAFETY; AUGMENTED REALITY; VIRTUAL REALITY; NETWORK MANAGEMENT; CLOUDLET; TCP; EDGE CACHING; CONTENT DELIVERY NETWORK; RAN SLICING; NETWORK OPTIMIZATION; CYBER PHYSICAL SYSTEMS; ROBUSTNESS; OPTICAL NETWORKS; SURVEY; RAN; CONNECTIVITY; CONNECTED VEHICLES; NETWORK DENSIFICATION; SUPPORT VECTOR MACHINE; CONVOLUTIONAL NEURAL NETWORK; SOCIAL NETWORKS; COOPERATIVE CACHING; REGULATION; DEPLOYMENT; ENCRYPTION; DATA ANALYSIS; CONTENT CENTRIC NETWORKING; TIME SENSITIVE NETWORKING; CONTENT DELIVERY; BUSINESS MODEL; OPPORTUNISTIC NETWORKS; COVID 19; VIRTUAL NETWORK EMBEDDING; VIRTUAL NETWORK EMBEDDING
2	MILLIMETER WAVE; MIMO; ANTENNA ARRAYS; MIMO COMMUNICATION; BEAMFORMING; BANDWIDTH; BASE STATIONS; RADIO FREQUENCY; COMMUNICATION; PHASED ARRAY; ANTENNAS; POWER AMPLIFIER; ANTENNA RADIATION PATTERNS; WIDEBAND; 28 GHZ; CMOS; ANTENNA MEASUREMENTS; HIGH GAIN; BROADBAND ANTENNAS; ANTENNA FEEDS; WIRELESS LAN; DUAL POLARIZATION; SWITCHES; PHASE SHIFTER; BEAM STEERING; DIPOLE ANTENNAS; LINEARITY; HIGH EFFICIENCY; TRANSCEIVER; IMPEDANCE; SUBSTRATES; MIMO ANTENNA; MUTUAL COUPLING; BROADBAND; BROADBAND COMMUNICATION; SUBSTRATE INTEGRATED WAVEGUIDE; SLOT ANTENNAS; MICROSTRIP ANTENNAS; MICROSTRIP ANTENNA ARRAYS; ERROR VECTOR MAGNITUDE; SATELLITE COMMUNICATION; ISOLATION; DUAL BAND; MOBILE ANTENNAS; WIRELESS; DIGITAL PREDISTORTION; MOBILE HANDSETS; KA BAND; LOW NOISE AMPLIFIER; RESONANT FREQUENCY; TOPOLOGY; MILLIMETRE WAVE ANTENNA ARRAYS; CIRCULAR POLARIZATION; QUADRATURE AMPLITUDE MODULATION; RECONFIGURABLE ANTENNA; COMMUNICATION SYSTEMS; LOGIC GATES; PATCH ANTENNA; DIELECTRIC RESONATOR ANTENNA; MILLIMETER WAVE ANTENNAS; CALIBRATION; MULTIBAND; USER EQUIPMENT; MIMO SYSTEMS; NOISE MEASUREMENT; SIGE; SUB 6 GHZ; COUPLINGS; INTEGRATED CIRCUITS; MULTIFREQUENCY ANTENNAS; TRANSFORMER; METALS; 60 GHZ; MICROSTRIP; MIXER; ENVELOPE CORRELATION COEFFICIENT; FEEDS; APPLICATIONS; PHASE NOISE; METASURFACE; BANDPASS FILTER; WIMAX; METAMATERIAL; LOW PROFILE; MONOPOLE ANTENNA; MOBILE TERMINAL; SMARTPHONE; CAPACITANCE; PHASED ARRAY ANTENNA; LINEAR ANTENNA ARRAYS; BUTLER MATRIX; RADIATION PATTERN; DEFECTED GROUND STRUCTURE; FILTERS; LOW POWER; IMPEDANCE MATCHING; DIELECTRICS; DECOUPLING; PLANAR ANTENNA; ATTENUATION; TERAHERTZ; RECONFIGURABLE; DOHERTY POWER AMPLIFIER; PATTERN DIVERSITY; PIN DIODES; CHARACTERISTIC MODE ANALYSIS; DIGITAL BEAMFORMING; LENS ANTENNA; MAGNETO ELECTRIC DIPOLE; PERIODIC STRUCTURES; MULTIBEAM; SMARTPHONE ANTENNA; MINIATURIZATION; FLEXIBILITY; ANTENNA IN PACKAGE; FREQUENCY SELECTIVE SURFACES; FREQUENCY RECONFIGURABLE; DUAL POLARIZED ANTENNA; WIDEBAND ANTENNA; ULTRA WIDEBAND; COMPACT; GALLIUM NITRIDE; FILTERING ANTENNA; SPECIFIC ABSORPTION RATE; MOBILE PHONE; ELECTROMAGNETIC FIELDS; COMPACT ANTENNA; MOBILE TERMINAL ANTENNAS; PHASE LOCKED LOOP; MICROSTRIP PATCH ANTENNA; GLIDE SYMMETRY; MULTIBAND ANTENNA

3	NON ORTHOGONAL MULTIPLE ACCESS; MASSIVE MIMO; POWER ALLOCATION; CHANNEL ESTIMATION; SPECTRAL EFFICIENCY; COGNITIVE RADIO; PERFORMANCE ANALYSIS; OUTAGE PROBABILITY; INTERFERENCE MANAGEMENT; PHYSICAL LAYER SECURITY; RELAYS; FULL DUPLEX; ENERGY HARVESTING; PRECODING; CELLULAR RADIO; COOPERATIVE COMMUNICATION; PROBABILITY; SIGNAL TO NOISE RATIO; WIRELESS CHANNELS; RADIOFREQUENCY INTERFERENCE; BIT ERROR RATE; COMPUTATIONAL COMPLEXITY; SILICON CARBIDE; SYSTEMS; SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER; COMPRESSED SENSING; CHANNEL CAPACITY; SUCCESSIVE INTERFERENCE CANCELLATION; INTERFERENCE CANCELLATION; TRANSMITTING ANTENNAS; RANDOM ACCESS; ERROR STATISTICS; RELAY NETWORKS; MULTIPLE ACCESS; POWER SYSTEM RELIABILITY; RADIO SPECTRUM MANAGEMENT; RADIO NETWORKS; RADIO RECEIVERS; RELAY SELECTION; IMPERFECT CHANNEL STATE INFORMATION; OFDM MODULATION; ITERATIVE METHODS; TELECOMMUNICATION POWER MANAGEMENT; MULTIUSER DETECTION; SPATIAL MODULATION; TELECOMMUNICATION NETWORK RELIABILITY; ERGODIC CAPACITY; DIVERSITY RECEPTION; CHANNEL STATE INFORMATION; RECEIVING ANTENNAS; DECODE AND FORWARD; USER PAIRING; TELECOMMUNICATION TRAFFIC; SIC; JAMMING; COORDINATED MULTIPOINT; LOW COMPLEXITY; SUM RATE; AMPLIFY AND FORWARD; HALF DUPLEX; USER SELECTION; MASSIVE CONNECTIVITY; RAYLEIGH CHANNELS; DATA RATE; ARTIFICIAL NOISE; DETECTORS; INTER CELL INTERFERENCE; INTERFERENCE ALIGNMENT; COOPERATION; SIGNAL DETECTION; MESSAGE PASSING; ANTENNA SELECTION; POWER CONSUMPTION; MU MIMO; CAPACITY; TERAHERTZ COMMUNICATION; SCMA; PILOT CONTAMINATION; FULL DUPLEX RELAYING; PROBABILITY DENSITY FUNCTION; HARDWARE IMPAIRMENTS; WIRELESS POWER TRANSFER; MESSAGE PASSING ALGORITHM; ZERO FORCING; COOPERATIVE NOMA; ERGODIC SUM CAPACITY; COOPERATIVE RELAYING; INTERCARRIER INTERFERENCE; SPATIAL CORRELATION; TWO WAY RELAYING; MULTI USER DETECTION
4	RESOURCE ALLOCATION; ENERGY EFFICIENCY; OPTIMIZATION; DEVICE TO DEVICE COMMUNICATION; LTE; INTERFERENCE; HETEROGENEOUS NETWORKS; DOWNLINK; SMALL CELL; THROUGHPUT; STOCHASTIC GEOMETRY; UPLINK; POWER CONTROL; ULTRA DENSE NETWORKS; HETNETS; REINFORCEMENT LEARNING; WIFI; SPECTRUM SHARING; GAME THEORY; USER ASSOCIATION; CLOUD RADIO ACCESS NETWORK; CARRIER AGGREGATION; BACKHAUL; GREEN COMMUNICATION; LTE A; WIRELESS BACKHAUL; GAMES; SELF ORGANIZING NETWORKS; HETEROGENEOUS CELLULAR NETWORKS; SPECTRUM EFFICIENCY; STOCHASTIC PROCESSES; CLUSTERING; PARTICLE SWARM OPTIMIZATION; COVERAGE PROBABILITY; POISSON POINT PROCESS; COGNITIVE RADIO NETWORKS; LOAD BALANCING; ADMISSION CONTROL; Q LEARNING; GEOMETRY; COEXISTENCE; TASK OFFLOADING; GENETIC ALGORITHM; FAIRNESS; COMP; POWER SAVING; SMALL CELL NETWORKS; CHANNEL ALLOCATION; MATCHING THEORY; PRICING; EFFECTIVE CAPACITY; MODE SELECTION; CROSS LAYER DESIGN; DUAL CONNECTIVITY; NASH EQUILIBRIUM; HETEROGENEOUS WIRELESS NETWORKS; USER SCHEDULING; CLUSTERING ALGORITHMS; CONVEX OPTIMIZATION; FOG RADIO ACCESS NETWORKS; FEMTOCELL; STACKELBERG GAME; DISTRIBUTED ALGORITHM; TIME DIVISION DUPLEX; SPECTRUM ALLOCATION; FUZZY LOGIC; UNLICENSED SPECTRUM; MARKOV DECISION PROCESS; CELL ASSOCIATION; MULTI OBJECTIVE OPTIMIZATION; RADIO RESOURCE ALLOCATION; AREA SPECTRAL EFFICIENCY; SUCCESSIVE CONVEX APPROXIMATION; NON COOPERATIVE GAME; H CRAN; COVERAGE; UNLICENSED BAND; NETWORK SELECTION; USER MOBILITY; GREEN NETWORKS; USER CENTRIC; LICENSED ASSISTED ACCESS; PROACTIVE CACHING; TRAFFIC OFFLOADING; ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS; MARKOV CHAIN; PROPORTIONAL FAIRNESS
5	OFDM; RECEIVERS; NEW RADIO; FRONTHAUL; TRANSMITTERS; SCHEDULING; COMPLEXITY THEORY; MODULATION; DECODING; PEAK TO AVERAGE POWER RATIO; RADIO OVER FIBER; NEURAL NETWORKS; VISIBLE LIGHT COMMUNICATION; PHYSICAL LAYER; SOFTWARE DEFINED RADIO; INDEX MODULATION; MULTIPLEXING; FBMC; GFDM; EMBB; INDEXES; FPGA; MULTICAST; WAVEFORM; SELF INTERFERENCE; POLAR CODES; PROTOTYPES; APPROXIMATION ALGORITHMS; CHANNEL CODING; OPTICAL FIBER NETWORKS; MICROWAVE PHOTONICS; FUNCTIONAL SPLIT; TESTBED; SPECTRUM SENSING; DISTRIBUTED ANTENNA SYSTEM; OPTICAL FIBER COMMUNICATION; PASSIVE OPTICAL NETWORK; CONVERGENCE; UFMC; BANDWIDTH ALLOCATION; FREQUENCY DIVISION DUPLEXING; NUMERICAL MODELS; ITERATIVE DECODING; ENCODING; OPTICAL FIBERS; FREE SPACE OPTICAL COMMUNICATION; NONLINEAR DISTORTION; IN BAND FULL DUPLEX; DIGITAL SIGNAL PROCESSING; LDPC CODES; WAVELENGTH DIVISION MULTIPLEXING; BROADCAST; FILTERED OFDM; MULTICARRIER MODULATION; MIXED NUMEROLOGY; HETEROGENEOUS CLOUD RADIO ACCESS NETWORK; FBMC OQAM; FREE SPACE OPTICS; FIELD TRIAL; BELIEF PROPAGATION; MULTIPLE ANTENNAS; SEMIDEFINITE RELAXATION; SILICON PHOTONICS
6	WIRELESS COMMUNICATION; MILLIMETER WAVE COMMUNICATION; ARRAY SIGNAL PROCESSING; CHANNEL MODELING; FADING CHANNELS; SATELLITES; TRAINING; HARDWARE; ESTIMATION; DIRECTIVE ANTENNAS; POWER DEMAND; HYBRID PRECODING; SATELLITE BROADCASTING; SYNCHRONIZATION; CORRELATION; PATH LOSS; THREE DIMENSIONAL DISPLAYS; CHANNEL MEASUREMENT; MEASUREMENT; PROPAGATION; BASEBAND; POSITIONING; LOCALIZATION; RADIO TRANSMITTERS; RAY TRACING; BLOCKAGE; SOLID MODELING; SIMULATION; DISTORTION; CELL FREE MASSIVE MIMO; QUANTIZATION; MULTIPATH; INITIAL ACCESS; SCATTERING; DIVERSITY; RICIAN CHANNELS; MILLIMETER WAVE PROPAGATION; MULTIPATH CHANNELS; MOBILE DEVICES; FADING; LINE OF SIGHT; LIMITED FEEDBACK; MODELING; ANGLE OF ARRIVAL; PATH LOSS MODELS
7	HYBRID BEAMFORMING; BEAM SELECTION