SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I11P120

Volume 11 Issue 11, 188-202, November 2024

Original Article

Millimeter Wave (mmWave) for 5G Networks, Technologies, and Applications: A Comprehensive Bibliometric Analysis

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Received: 11 September 2024 Revised: 12 October 2024 Accepted: 10 November 2024 Published: 30 November 2024

Abstract - *The integration of Millimeter-Wave (mmWave) technologies within fifth-generation (5G) networks represents a pivotal advancement in telecommunications, enabling high data rates, ultra-reliable, low latency, and massive connectivity. This study presents a comprehensive bibliometric analysis of the global research landscape on mmWave technologies for 5G Applications, covering 986 peer-reviewed journal articles published from 2014 to 2024, sourced from the Scopus database. The study demonstrates significant growth in yearly document distribution and annual cited publications and strong global and local collaboration networks reflecting the increasing importance and impact of mmWave technologies in 5G networks. The analysis identifies the contributions of leading institutions such as Universiti Teknologi Malaysia and Southeast University and highlights the influential work of prominent authors, including Wang H and Imran MA. The results also identify the most-cited papers, such as those by Z. Ding and Y. Niu, and emphasize the dominance of journals like IEEE Access and IEEE Transactions on Antennas and Propagation in publishing impactful research in this domain. The findings reveal a robust and evolving research ecosystem dominated by significant contributions from China, the United States, and India through global and local collaboration networks. Finally, the study uncovers central research themes through keyword co-occurrence analysis, with millimeter waves, 5G mobile communication systems, and MIMO systems emerging as focal points.*

Keywords - *Bibliometric analysis, Millimeter-wave, Fifth-Generation (5G), MIMO.*

1. Introduction

The fifth-generation (5G) wireless networks mark a new era in telecommunications typically characterized by unprecedented data rates, ultra-reliable, low-latency communication, and massive machine-type communications. Highlighting all these developments is the millimeter-wave spectrum, which spans from 30 GHz to 300 GHz. This spectrum is huge in bandwidth, which forms the core requirement for the high data throughputs required in 5G applications. The integration of mmWave technology into 5G, however, comes not only with several technical challenges and opportunities but also requires in-depth research to achieve its optimization in implementation and performance. It is important to note that millimeter-wave communication has advantages in meeting the overall requirements for the bandwidth of the 5G network.

Despite substantial research on individual technical challenges in mmWave such as high path loss and interference, which demand solutions like beamforming and massive MIMO few studies provide a holistic overview of the research landscape. Thus, such an analysis is important for the orientation of further research directions in the field, for the promotion of the adoption of the technologies, and the development of policies regarding the deployment of mmWave for 5G. Undefined: Carry out a comprehensive literature review on mmWave communications, giving a description of the benefits as well as the drawbacks of the technology. Authors indicate that, although the mmWave frequencies are capable of delivering high data rates, they are characterized by high path loss and penetration, which require techniques such as beamforming and MIMO to support strong link connections [1]. Similarly, another study discusses the challenges of employing physical layer security in 5G networks with mmWave and calls for new cryptography methods and strong security measures that could protect against potential threats [2].

One of the critical applications of mmWave technology in 5G is position and orientation estimation. MmWave MIMO systems can hugely enhance the accuracy of positioning, one of the key requirements in applications such as autonomous driving and augmented reality [3]. On the other hand, a broader role of mmWave in both the 5G and future 6G wireless communications, stating that mmWave is one of the main means to reach high speed and low latency in next-generation communication networks [4]. Another study brings together massive MIMO combined with mmWave for high capacity and efficiency gains in heterogeneous networks [5]. The feasibility and challenges of implementing mmWave for 5G wireless networks are further investigated in [6]. Their comprehensive survey underlines the technological advances that need to be made in order to deal with issues such as signal blockage and interference that are exacerbated at higher frequencies. Another study presented an application of mmWave massive MIMO to wireless backhaul in ultra-dense 5G networks, putting forward novel solutions to enhance network performance and reliability [7].

One of the key applications of mmWave technology in 5G is within vehicular networks. Researchers Investigate 5G mmWave positioning, showing that it can enhance V2X communication, which is important for developing intelligent transportation systems [8]. Furthermore, other researchers delve into the design of MIMO antennas for mmWave applications, presenting advancements in antenna technology pivotal for achieving the high performance expected of 5G networks [9]. Technological innovations supporting mmWave in 5G include advanced antenna systems [10]. Introduce a MIMO dielectric resonator antenna with enhanced isolation for 5G mmWave applications, significantly enhancing signal quality and system performance. The role of mmWave in smart railways exemplifies its diverse applications by integrating 5G technologies to improve operational efficiency and passenger experience [11]. Additionally, another study presents a broadband mmWave microstrip array antenna with enhanced radiation characteristics, crucial for diverse 5G applications [12]. The versatility of mmWave for backhaul applications is explored by [13]; authors discuss point-to-multipoint, in-band mmWave backhaul solutions for 5G networks. Another significant advancement is a metasurface-based, low-profile, wideband, circularly polarized patch antenna for 5G mmWave systems introduced which addresses the need for compact and efficient antenna designs in modern 5G networks [14]. Photonic-based mmWave signal generation for 5G access fronthaul is proposed for enhancing capacity and efficiency [15].

Innovations in mmWave antenna designs continue to push the boundaries of 5G capabilities. A conformal antenna array based on millimeter-wave liquid crystal polymer for 5G applications, highlighting the material's suitability for flexible and high-performance antenna systems [16]. To explore proactive caching for mobile video streaming in mmWave 5G networks, demonstrating how advanced caching strategies can alleviate network congestion and enhance user experience [17, 18]. Demonstrate a high-gain, cost-effective, differently fed circularly polarized planar aperture antenna for broadband millimeter-wave applications, underscoring the importance of cost-effective solutions in deploying 5G networks. Further extending the potential of mmWave technology, to investigate a deep-learning approach for prediction-based conditional handover in 5G mmWave networks, enhancing mobility management by predicting and preemptively managing handovers to ensure seamless connectivity [19]. Other authors propose strategies for the allocation of resources and interference management in opportunistic relaying across integrated mmWave/sub-6 GHz 5G networks, addressing the need for efficient spectrum utilization and interference mitigation [20]. Integrating caching and mmWave communications is discussed to enhance mobility management, highlighting its potential through strategic content placement and retrieval [21]. Further researchers explore full-duplex relaying for Device-to-Device (D2D) communication in mmWave-based 5G networks, presenting solutions to develop spectral efficiency and decrease latency [22]. A dual-band millimeter-wave MIMO antenna for 5G applications is presented, enhancing network capacity and coverage [23]. The development of advanced antenna technologies is further illustrated by introducing a high-gain, low-profile circularly polarized slotted substrate-integrated waveguide cavity antenna for millimeter-wave applications, offering significant improvements in gain and radiation efficiency [24]. An in-depth analysis of the main issues and solutions for handling mobility in 5G networks is provided, focusing on integrating mmWave and sub-6 GHz technologies to achieve seamless connectivity [25].

The potential of the millimeter-wave frequency band for 5G network architecture is reviewed, discussing the advantages and challenges of utilizing this spectrum [26]. Researchers investigate ultra-reliable and low-latency communication in mmWave-enabled massive MIMO networks, highlighting the importance of advanced communication techniques to meet stringent 5G requirements [27]. Millimeter-wave massive MIMO wireless backhaul for ultra-dense 5G networks is explored, proposing solutions to enhance backhaul capacity and reliability [7].

Furthermore, a Millimeter-wave multibeam aperture-coupled magnetoelectric dipole array featuring a planar substrate integrated beamforming network for 5G applications is presented, achieving high beamforming gain and flexibility [28]. SIW cavity-fed filtennas for 5G millimeter-wave applications are discussed, showcasing their potential for Compact and effective antenna designs [21]. [29] Introduce a compact, wideband, four-element optically transparent system. MIMO antenna for mmWave 5G applications, addressing the demand for high-performance, aesthetically pleasing antenna solutions [30], presents a high-gain, wideband, and low mutual coupling AMC-based millimeter-wave MIMO antenna for 5G NR networks, demonstrating significant improvements in antenna performance and integration. Millimeter-wave backhaul solutions for 5G networks were explored, proposing strategies to overcome high-frequency signal propagation challenges [31]. Similarly, another study discussed a 4-port MIMO antenna featuring a defective ground construction for 5G millimeter-wave applications, presenting innovative designs to enhance antenna performance and network capacity [9]. Authors investigate a dual-polarized filtering antenna operating in the millimeter-wave spectrum for 5G applications, enhancing signal quality and dependability [32].

This study examines the research landscape of millimeter-wave technology within the context of 5G technologies and applications. The study will analyze publication trends, identify key research themes, and evaluate the contributions of influential authors and institutions in the field. By addressing these elements, the study provides a unique resource to guide future mmWave research, foster cross-institutional collaborations, and inform the development and deployment strategies for mmWave in 5G and beyond. The study also seeks to uncover emerging research areas, understand the distribution of scientific production across different countries, and provide insights into the global research collaboration network surrounding mmWave technologies.

2. Materials and Methods

The bibliometric analysis in this study focuses exclusively on the Scopus database, covering the period from 2014 to 2024. The researchers utilized the Scopus database due to its wide-ranging coverage of peer-reviewed literature across multiple disciplines [33]. The methodology involved a systematic data collection and analysis approach, focusing exclusively on journal articles published in English. The search was conducted on July 23, 2024, and only documents available on or before this date were considered, with subsequent publications excluded from the analysis. The search strategy employed specific keywords related to the research topic, "Millimeter Wave (mmWave) for 5G Technologies and Applications," using the query: "(TITLE-ABS-KEY ("mmwave" OR "millimeter wave") AND TITLE-ABS-KEY ("5g network" OR "5g technology" OR "5g application*" OR "fifth generation network*" OR "fifth generation technology*" OR "fifth generation application*")). This search resulted in an initial total of 2,855 documents. To ensure the relevance and quality of the data, language limitations were applied, restricting the selection to English-language publications, which reduced the number to 2,840 documents.

Further filtering to include only peer-reviewed articles resulted in 1,001 documents, and limiting the source type to journal articles narrowed the dataset to 986 documents. These documents were then exported for analysis in CSV and RIS formats. In this study, a combination of advanced bibliometric tools and metrics was employed to analyze the research landscape on mmWave technologies for 5G comprehensively. The study utilized VOSviewer to visualize networks of co-authorship, keyword co-occurrence, and citation patterns, allowing the identification of collaborative networks and key research themes. Publish or Perish was also used to retrieve citation data, enhancing the accuracy in identifying highly influential authors and institutions within the field. For statistical analysis and visualization, the Bibliometrix package in R provided robust tools to quantify publication and citation trends over time [34-36]. The metrics chosen, including publication counts, citation metrics, h-index, and g-index, were integral to assessing the influence of authors, journals, and institutions. These metrics provided a structured approach to highlight the growth of mmWave research and its critical contributors. This combination of tools and metrics ensured a thorough and detailed examination of the mmWave research domain, from publication trends to international collaboration patterns. Figure 1 explains the study's search strategy.

3. Results and Discussion

3.1. Yearly Document Distribution and Annual Cited Publications

The yearly document distribution trends related to mmWave for 5G technologies and applications have been increasing, as shown in Figure 2. There has been a steady increase in documents, which reflects increasing interest and growing research activities in this area. From 2014 to 2016, the number of records was relatively low, resulting in 2 publications in 2014 and 14 in 2015. Thus, this time can be considered an exploratory time where technology was still nascent, and research on the same was much less. However, a sharp increase in publications from 2017 to 43 documents marks the beginning of more focused research and development activities in mmWave technology for 5G. The trend in growth continued, reaching 73 papers in 2018 and 99 in 2019, meaning it was already in the expansion phase. Another surge in research can be expected due to developments in 5G technology and the realization of the mmWave potential for higher data rates and network capacities. The peak years were 2022 and 2023, with 167 and 168 documents, respectively. This period represents a high-yield phase, underpinning the maturity of research into mmWave technologies and their application in 5G networks. The slight decline in 2024, with 87 documents, may indicate a stabilization in the research output or a shift towards more specialized or applied research areas within the domain. However, it is important to note that the apparent decline in 2024 is likely because the year is still ongoing, with only partial data available. Therefore, the final output for 2024 could potentially match or exceed previous years once all publications are accounted for.

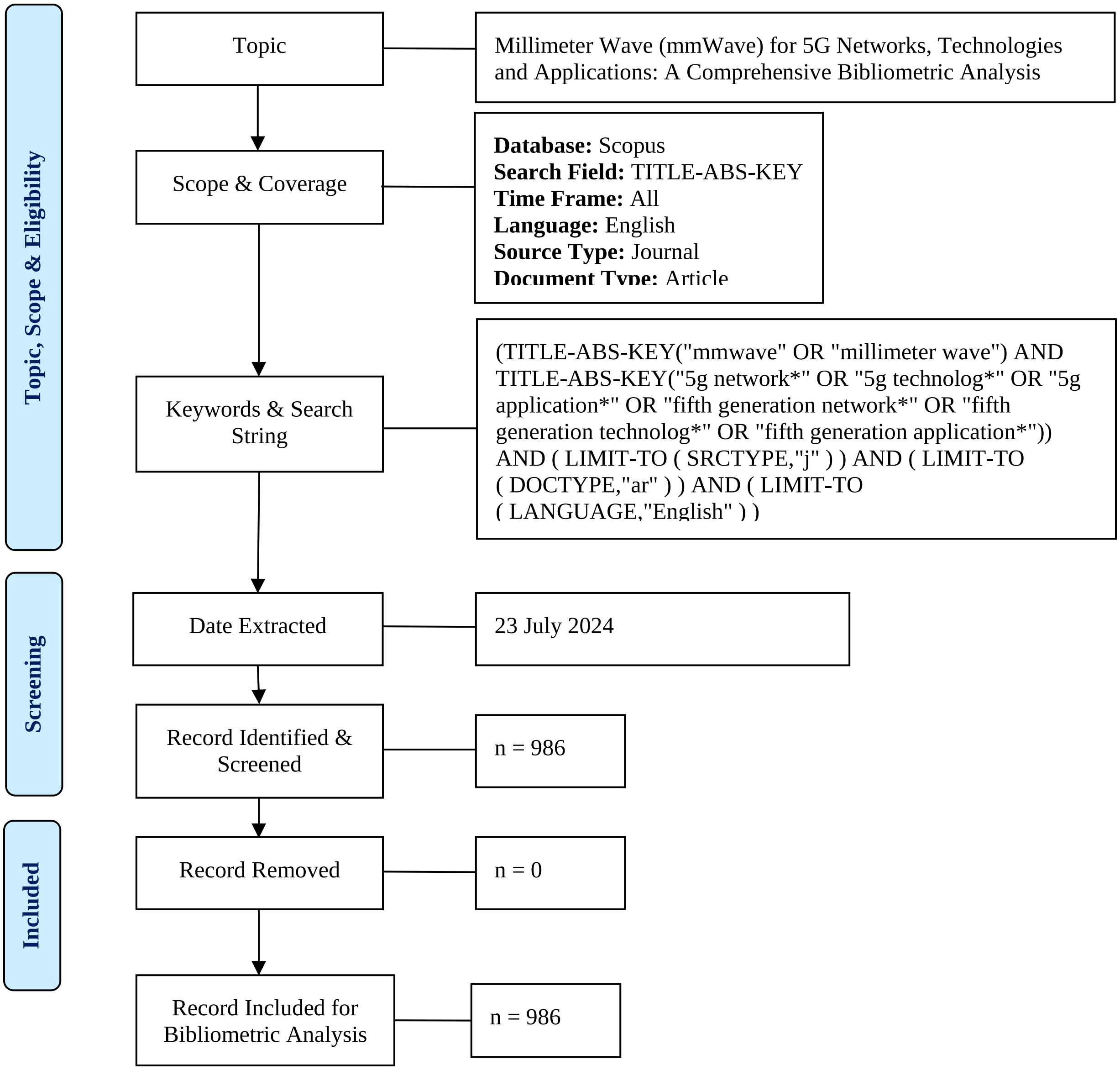

Fig. 1 Flow diagram of the search strategy source: [37]

Figure 3 shows the annual cited papers on mmWave technologies in 5G from 2014 to 2024. The citation data indicates a gradual increase from 2014 to 2016, with citations rising from 984 to 2,777, corresponding to a modest rise in published documents from 2 in 2014 to 28 in 2016. A sharp increase in citations in 2017, reaching 4,104, aligns with the publication of 43 papers, suggesting significant foundational works were released that year, drawing considerable attention from the research community. Rising citations continued, peaking at 4,629 in 2020, as publications surged from 73 2018 to 150 in 2020. However, a subsequent decline in citations, dropping to 3,410 in 2021 and 1,803 in 2022, occurred despite a record high in publications, with 167 and 168 documents in 2022 and 2023, respectively. This suggests that while research activity remained robust, the impact or novelty of new publications may have decreased, indicating a saturation point in foundational research or a shift towards more specialized advancements. The sharp decline in citations to 568 in 2023 and 35 in 2024, despite a still substantial number of publications (87 in 2024), may reflect the maturation of mmWave technology and a potential shift in research focus towards integrating these technologies with others, like Massive MIMO, or exploring new areas such as terahertz communications.

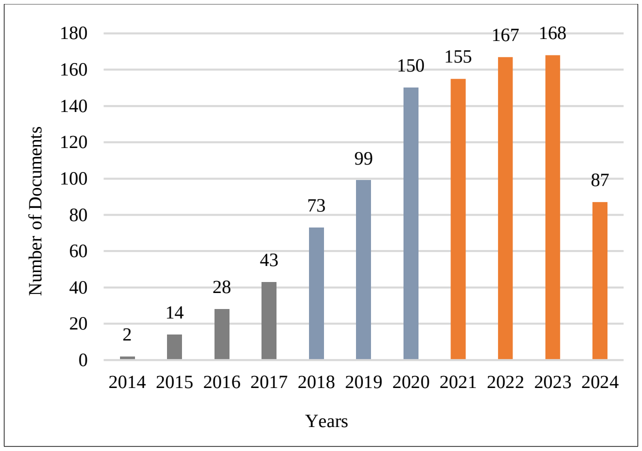

Fig. 2 Documents published from 2014-2024

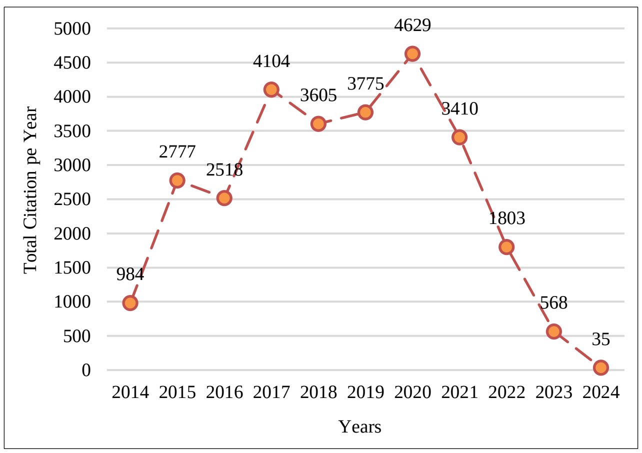

Fig. 3 The number of annual cited papers

3.2. Analysis of Most Local / Global Papers

Table 1 highlights the top 10 most local cited papers in mmwave that were published in the journal from 2014 to 2024. These documents have garnered the most attention within a local dataset, showcasing a mix of foundational and recent works. Notably, the document by Niu Y (2015) published in Wireless Networks stands out with 30 Local Citations (LC) and a Global Citation (GC) count of 995. This paper's moderate LC/GC ratio of 3.02% suggests a strong global influence relative to its local impact.

Similarly, the work by Khalilly M (2018) in IEEE Transactions on Antennas and Propagation has an LC of 16 and a GC of 195, with a notable LC/GC ratio of 8.21%, indicating significant recognition within the local dataset. However, the highest LC/GC ratio is observed in the document by POLESE M (2017) from IEEE Internet Computing, at 20.31%, highlighting its particular relevance and influence in local discussions despite having a lower global citation count (64 GC). This table underscores the diverse impact of these documents, with some achieving broad global recognition. In contrast, others are more locally influential, reflecting varying degrees of relevance and specialization within the field.

Table 2 shows the list of papers with the highest Top 10 Most Global Cited papers in mmwave published in this journal. The total global citations provide a much broader view of their international impact. Ding Z (2017), with its overwhelming 1879 total citations, averaging 234.88 citations per year, published in IEEE Journal on Selected Areas in Communications, shows its extraordinary influence in the international academic society. The paper by Niu Y (2015) is the first one on this list due to its double effects in both local and global spheres, and hence, it has received a total of 995 citations, averaging 99.50 annually.

The list includes Yang N (2015) and Wu Y (2018). Still, they have also gained significant attention in the citation report, which means they also contributed significantly to their research areas. In effect, Ghosh A's highly cited work in IEEE Access bears an annual citation of 99.17, which shows it is a new work but under high influence. The variation in total and per-year citations across these documents illustrates the different degrees of influence and dissemination these key papers have achieved in advancing the understanding and application of mmWave technologies in 5G systems.

3.3. Evaluation of Key Researchers

The study identified a total of 3126 authors contributing to the field. Among these, 2497 authors have authored only one paper, 516 authors have contributed to 2–3 papers, 104 authors have published 4–7 papers, and 6 authors have made significant contributions with 8–9 papers. From the perspective of paper numbers, the most influential authors in the field are highlighted in the study, as shown in Table 3.

Leading with an h-index of 8, a g-index of 11, and an m-index of 1.143, WANG H has garnered 736 total citations from 11 papers since 2018, showcasing a solid impact and significant presence in mmWave research. IMRAN MA, with an h-index of 7, a g-index of 8, and an m-index of 0.7, has accumulated 534 citations from 8 papers since 2015, indicating a consistent contribution to the field.

Despite starting relatively recently in 2020, DAS S has achieved an h-index of 6 and a g-index of 13, with 321 total citations from 13 papers, highlighting his research's high quality and relevance. Denidni TA, Li W, Rahman TA, Rebeiz GM, Tafazolli R, Wang J, and Yu C also made notable contributions, each with an h-index of 6 and varying g-indexes and total citations, reflecting their impactful research in mmWave technologies.

Table 1. Top 10 most local cited papers

Paper	DOI	Year	LC	GC	LC/GC Ratio (%)	NLC	NGC
Niu Y, 2015, Wireless Networks	10.1007/s11276-015-0942-z	2015	30	995	3.02	6.46	5.02
Khalily M, 2018, IEEE Trans Antennas Propag	10.1109/TAP.2018.2845451	2018	16	195	8.21	15.37	3.95
Bogale TE, 2016, IEEE Veh Technol Mag	10.1109/MVT.2015.2496240	2016	16	385	4.16	7.11	4.28
Uwaechia AN, 2020, IEEE Access	10.1109/ACCESS.2020.2984204	2020	15	290	5.17	20.64	9.4
Zhang Y, 2019, IEEE Antennas Wirel Propag Lett	10.1109/LAWP.2019.2901961	2019	15	256	5.86	13.38	6.71
Saad AAR, 2019, Aeu Int J Electron Commun	10.1016/j.aeue.2018.11.029	2019	15	107	14.02	13.38	2.81
Zhu Q, 2017, IEEE Trans Antennas Propag	10.1109/TAP.2017.2723080	2017	14	145	9.66	6.62	1.52
Polese M, 2017, IEEE Internet Comput	10.1109/MIC.2017.3481348	2017	13	64	20.31	6.14	0.67
Ali W, 2021, Microsyst Technol	10.1007/s00542-020-04951-1	2021	12	106	11.32	19.58	4.82
Hong W, 2021, IEEE J Microw	10.1109/JMW.2020.3035541	2021	12	388	3.09	19.58	17.64

Table 2. Top 10 most global cited papers

Paper	DOI	Year	TC	TC per Year	NTC
Ding Z, 2017, IEEE J Sel Areas Commun	10.1109/JSAC.2017.2725519	2017	1879	234.88	19.69
Niu Y, 2015, Wireless Networks	10.1007/s11276-015-0942-z	2015	995	99.5	5.02
Yang N, 2015, IEEE Commun Mag	10.1109/MCOM.2015.7081071	2015	778	77.8	3.92
Wu Y, 2018, IEEE J Sel Areas Commun	10.1109/JSAC.2018.2825560	2018	604	86.29	12.23
Ghosh A, 2019, IEEE Access	10.1109/ACCESS.2019.2939938	2019	595	99.17	15.6
Basar E, 2016, IEEE Commun Mag	10.1109/MCOM.2016.7509396	2016	545	60.56	6.06
Ge X, 2014, IEEE Network	10.1109/MNET.2014.6963798	2014	514	46.73	1.04
Sulyman A, 2014, IEEE Commun Mag	10.1109/MCOM.2014.6894456	2014	470	42.73	0.96
Shahmansoori A, 2018, IEEE Trans Wireless Commun	10.1109/TWC.2017.2785788	2018	404	57.71	8.18
Elbamby MS, 2018, IEEE Network	10.1109/MNET.2018.1700268	2018	404	57.71	8.18

Figure 4 illustrates the author's production over time. The size of the circles represents the number of documents published, while the shade of the color indicates the total number of citations. For instance, Wang H and Imran MA have larger circles with bold shades, indicating both a high volume of publications and significant citation impact. This visualization provides a clear depiction of the leading researcher's contributions and their impact on the field of mmWave research. Wang H has been particularly prolific, starting his contributions in 2018 and rapidly accumulating citations, indicative of high-impact research. His work has become a cornerstone in developing mmWave technologies for 5G. Das S has also shown remarkable productivity and impact in a short period, starting in 2020 and achieving significant citation counts, reflecting the relevance and importance of his research findings.

Table 3. Top 10 influential authors in the field

Author	h_index	g_index	m_index	TC	NP	PY_start
Wang H	8	11	1.143	736	11	2018
Imran MA	7	8	0.7	534	8	2015
Das S	6	13	1.2	321	13	2020
Denidni TA	6	8	0.75	174	8	2017
Li W	6	6	0.857	110	6	2018
Rahman TA	6	8	0.6	129	8	2015
Rebeiz GM	6	6	1.2	208	6	2020
Tafazolli R	6	6	0.857	339	6	2018
Wang J	6	7	0.667	355	7	2016
Yu C	6	7	1.5	551	7	2021

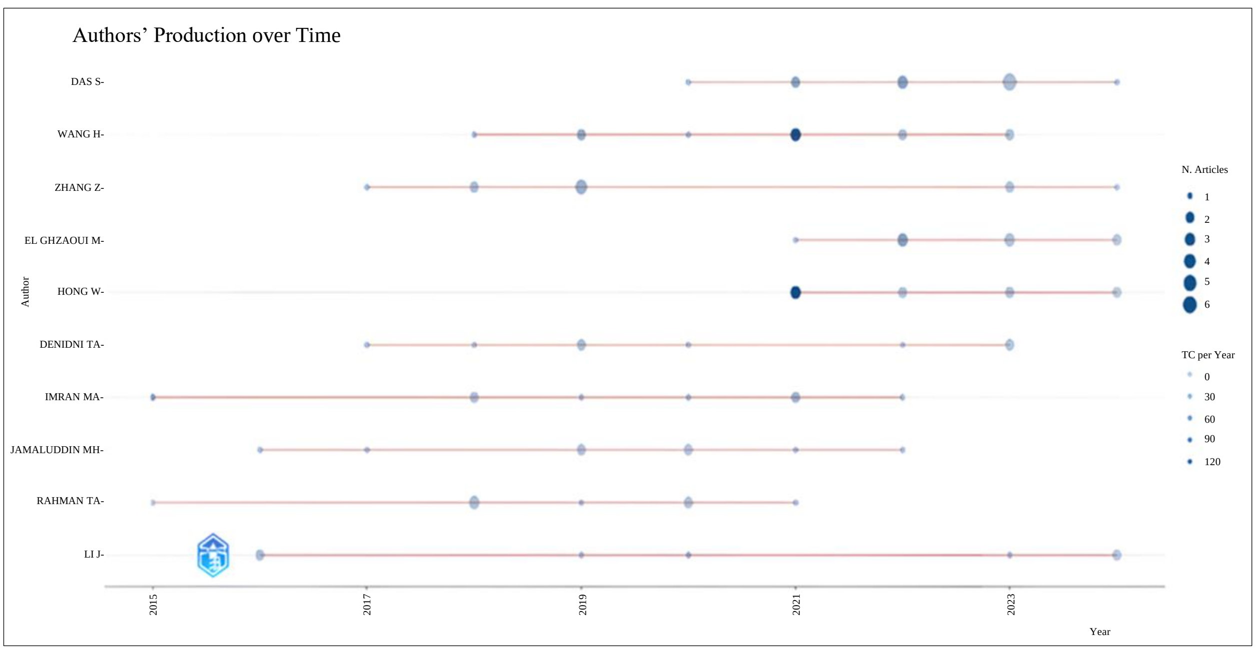

Fig. 4 Authors' production over time

The collaboration map co-authorship depicts the network of scientific cooperation among researchers in mmWave technologies for 5G applications. The analysis includes 155 authors, with each author's total strength of co-authorship links with other authors calculated. This network selected authors with the greatest total link strength, adhering to the criteria of a minimum of 3 documents per author and 3 citations. In Figure 5, the largest set of connected items comprises 27 authors, highlighting the interconnectedness within the field. The map reveals several distinct clusters, each represented by different colors. The green cluster, which includes prominent figures such as Imran Muhammad Ali, Tafazolli Rahim, and Pervaiz Haris, indicates a highly interconnected group, suggesting a cohesive core of researchers collaborating extensively. This group's strong internal connections indicate coordinated research efforts and possibly joint projects contributing significantly to the field. The red cluster, featuring Denidni Tayeb A., Sebak Abdel-Razik, and Afifi Islam, also shows a dense network of collaborations. This cluster likely represents another major research group actively contributing to mmWave technology research. The yellow cluster, including authors like Wang Ning and Li Weiwei, is smaller but still significant, pointing to focused research efforts within a specialized area of the field. The blue cluster, which includes Rodriguez Jonathan, Mewada Hiren, and Mahanti Keyur, highlights another segment of the research community, though with less extensive collaborations compared to the green and red clusters. This indicates diverse research interests and collaborative networks within the field. The map also shows several inter-cluster connections, suggesting cross-collaboration between research groups. This cross-pollination of ideas and shared expertise is vital for advancing knowledge and innovation in the field. The presence of central figures like Imran Muhammad Ali and Tafazolli Rahim as key nodes in the network underscores their significant influence and leadership roles in driving research and collaboration.

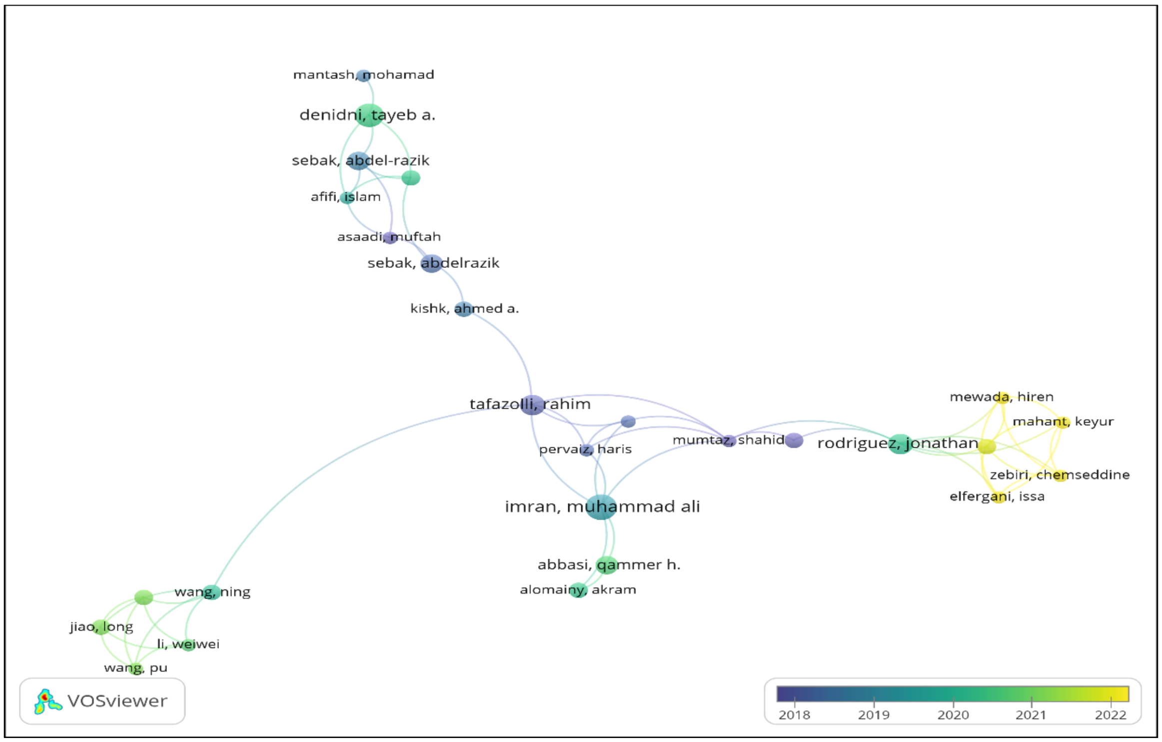

Fig. 5 Collaboration map co-authorship

3.4. Evolution of Most Influential Institutions and Journals

Table 4 presents the top institutions that have contributed significantly to millimeter wave technologies for 5G, with at least 16 publications. Universiti Teknologi Malaysia is ranked first with 79 publications (2.22%), followed by Southeast University, which has 74 publications (2.08%). One notable contributing institution is Concordia.

University and University of Engineering and Technology, both with 35 publications, and South China University of Technology and Xidian University, with 33 each. The list represents a good geographical spread, with key institutions representing Asia, North America, Europe, and Africa. It reflects the global interest taken in mmWave research. Furthermore, emerging research hubs like the National Institute of Technology and Tampere University reflect growing capacity. It is a dataset that underlines just how significant a role these institutions have played in terms of developing mmWave technologies for 5G, and Asian institutions, especially China and Malaysia, are to the fore. These leading institutions are crucial in shaping the research agenda and innovations in this evolving field and are expected to maintain or expand their influence globally.

Since this study focuses only on journals, Table 5 ranks the top 15 journals in millimeter wave (mmWave) technologies for 5G applications using bibliometric indicators such as g-index, h-index, m-index, total citations, number of publications, and the starting year. *IEEE ACCESS* has a significant impact, including an h-index of 31 and 3,544 citations from 100 publications since 2016. IEEE Antennas and Wireless Propagation and IEEE Transactions on Antennas and Propagation also play critical roles in advancing research in antennas, propagation, and wireless communications.

Table 4. Top most influential institutions with a minimum of 16 publications

Institution	Total Publications	Percentage (%)
Universiti Teknologi Malaysia	79	2.22
Southeast University	74	2.08
Concordia University	35	0.98
University of Engineering and Technology	35	0.98
South China University of Technology	33	0.93
Xidian University	33	0.93
University of Electronic Science and Technology of China	29	0.81
Multimedia University	28	0.79
Tsinghua University	27	0.76
City University of Hong Kong	26	0.73
Sidi Mohamed Ben Abdellah University	26	0.73
Beijing University of Posts and Telecommunications	23	0.64
Czech Technical University in Prague	20	0.56
National Institute of Technology	19	0.53
Tampere University	19	0.53
Menoufia University	18	0.50
University of Malaya	18	0.50
Moulay Ismail University	16	0.45
National Taipei University of Technology	16	0.45
School of Electrical and Computer Engineering	16	0.45
Tianjin University	16	0.45

Emerging journals like Electronics (Switzerland) and IEEE Transactions on Microwave Theory and Techniques highlight growing interests in electronics and microwave technologies. The journals cover diverse topics, emphasizing the interdisciplinary nature of mmWave and 5G research. Specialized journals such as Journal of Lightwave Technology and Sensors address specific areas within the field. Additionally, despite having fewer publications, IEEE Journal on Selected Areas in Communications demonstrate a high impact. These journals are crucial in shaping the future of mmWave technologies and advancing academic and technological innovations in this rapidly evolving field. This bibliometric the analysis also highlights journal production over Time. It represents the cumulative production of scholarly publications from key journals in the field of millimeter wave spanning from 2014 to 2024, as shown in Figure 6. The figure demonstrates a clear upward trend across all journals, indicating an increasing volume of research output in this field. It clearly indicates that IEEE Access leads with a sharp and consistent upward rise, much more distinct since 2017, proving it to be one of the largest outlets for research publications in mmWave technologies. A likely consequence of this trend is the growing recognition and expansion of research within this journal because of its impact and relevance in the academic community. Other journals, such as IEEE Antennas and Wireless Propagation Letters and IEEE Transactions on Antennas and Propagation, have a steady growth. However, the trend is far less significant compared to that of IEEE Access. Those journals never grow to zero and have the smoothest trend among the three, again corresponding with their unique positions in disseminating significant research on antennas and propagation technologies, some of the underlying technologies for 5G innovations. For instance, an increase in the number of papers published is observed for the titles Electronics.

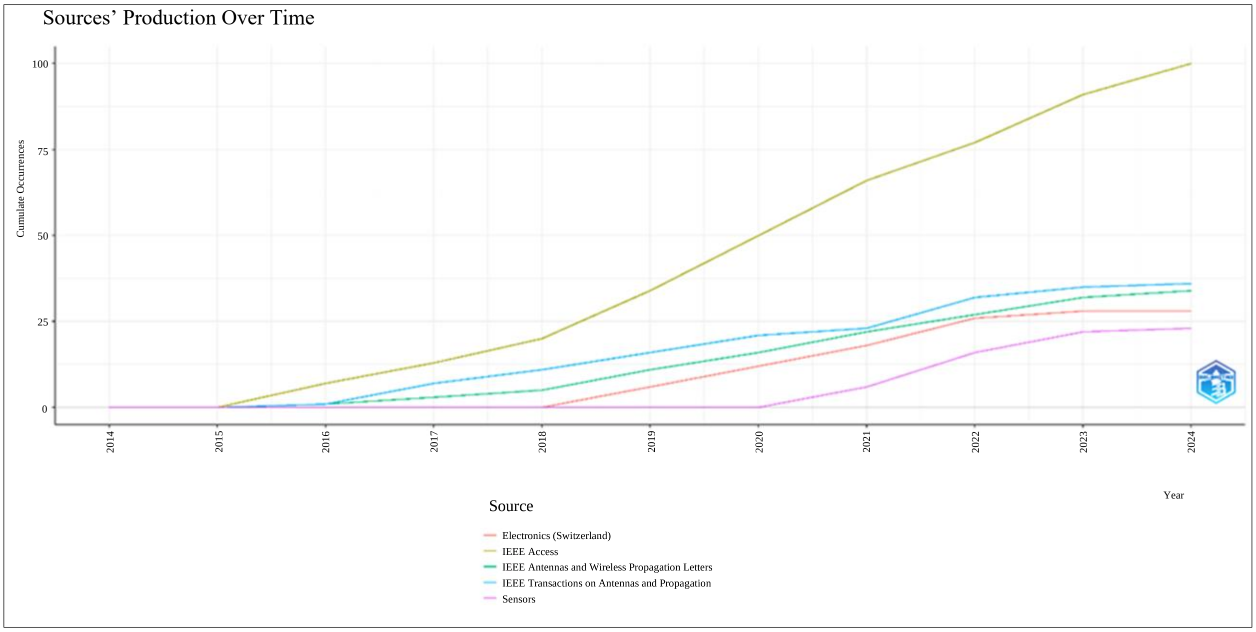

Fig. 6 Journal production over time

Table 5. Top 15 leading journals in mmwave technologies for 5G applications

Source	h_index	g_index	m_index	TC	NP
IEEE Access	31	58	3.444	3544	100
Ieee Transactions on Antennas and Propagation	22	36	2.444	1877	36
IEEE Antennas and Wireless Propagation Letters	18	34	2	1289	34
Electronics (Switzerland)	13	26	2.167	711	28
IEEE Transactions on Microwave Theory and Techniques	13	18	1.444	633	18
IEEE Transactions ON Vehicular Technology	12	17	1.333	338	17
IEEE Communications Magazine	10	14	0.909	2176	14
IEEE Transactions on Wireless Communications	10	15	1	917	15
IEEE Wireless Communications	10	10	1	1445	10
IEEE Journal on Selected Areas in Communications	9	9	1.125	2808	9
Sensors	9	14	2.25	233	23
IEEE Network	8	9	0.727	1368	9
IEEE Microwave and Wireless Components Letters	7	8	0.875	169	8
IEEE Transactions on Communications	7	8	1	294	8
Journal OF Lightwave Technology	7	10	1	287	10

(Switzerland) and Sensors, especially in and after 2018, which would imply there is an increasing interest in researching electronic and sensor technologies within the 5G context. This shows that the dynamics of research concerning mmWave technologies within different journals cumulate in an increasing rise of a body of knowledge. The continuous rising tendencies for the named journals reflect a strong expansion of research activities and an ever-growing focus on 5G technologies. Better technologies, more funding, and interdisciplinary collaborations that foster a rich exchange of knowledge and innovation are very likely.

3.5. Analysis of Research Distribution Patterns in Key Countries / Regions

In millimeter wave (mmWave) technologies for 5G applications, the global distribution of scientific production and citations reflects a significant concentration of research efforts in certain key countries. As indicated in Figure 7, China leads the field with 708 published documents, demonstrating its substantial investment in advancing mmWave technologies. However, the average citation per document is 34.5, suggesting that while there is a high volume of research, the impact and recognition of these publications vary. India, with 443 documents, is another significant contributor to the field. Nevertheless, the citation impact, averaging 7.1 citations per document, indicates that Indian research in this area, while voluminous, may not be as influential globally. The United States, producing 339 documents, stands out for its high average citation rate of 35.2 per document, highlighting its research quality and global impact. This is consistent with the USA's technological innovation and research leader role, particularly in cutting-edge fields like mmWave technologies for 5G.

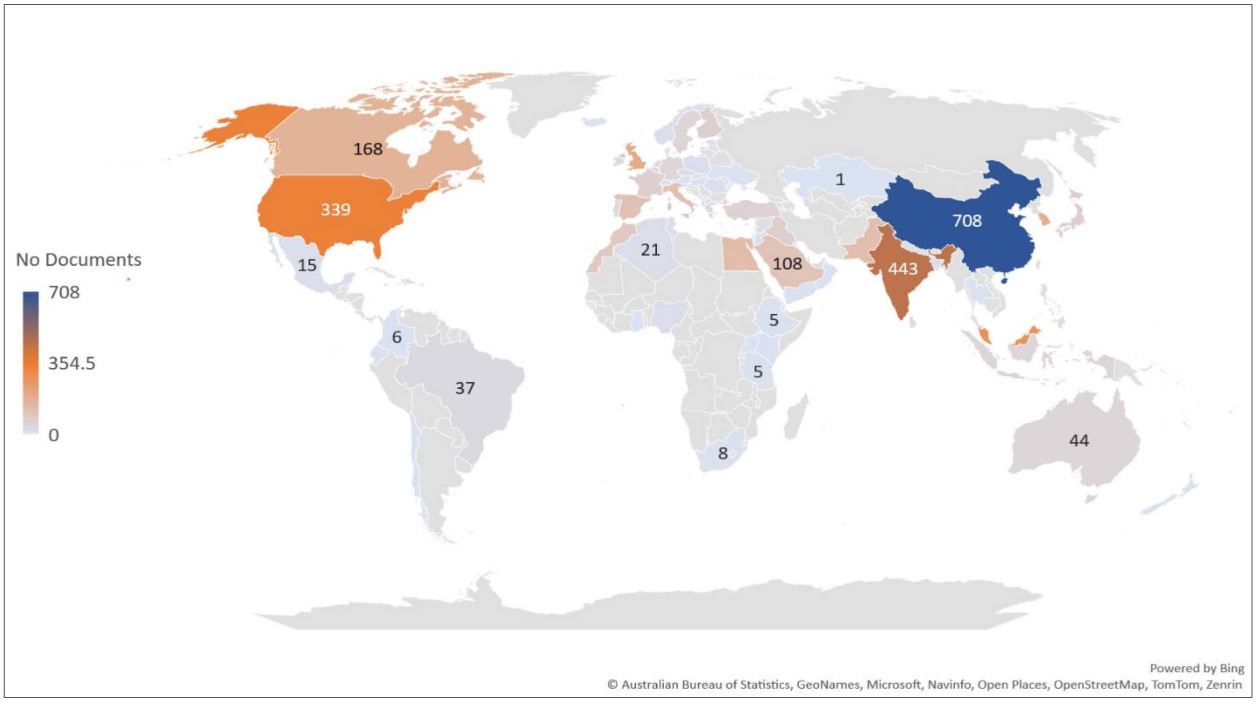

Fig. 7 Distribution of scientific production

Other notable contributors include Malaysia and Canada, with 280 and 168 documents, respectively. Although the number of publications in these countries is lower, they have made significant contributions with outstanding citation impacts, averaging 18.5 for Malaysia and 25.6 for Canada. Such a really devastating impact on their research outputs could be due to the specialist or good-quality studies conducted in these countries. Developed countries, especially the USA and Europe, surpass others in terms of the number of publications or the impact revealed through the number of citations. This pattern suggests the given advanced nature of the technological infrastructure of these regions, including significant research funds, which enables the major role they play in the development and application of mmWave technologies for 5G.

Meanwhile, countries like China such as China and India are already generating significant volumes of research. However, quality and international collaboration enhancement could further escalate the relative impact and recognition of their contribution. In this respect, it perfectly fits into a trend that occurs in all other fields of advanced technology: it is precisely collaboration and access to advanced research infrastructure that determines scientific output in global terms. The analysis of the global research landscape in mmWave technologies for 5G applications reveals several key observations about the distribution of publications and the extent of international collaborations.

Figure 8 illustrates the interconnectedness of global research efforts in this field. Each node represents a country, and their connecting lines indicate cooperative relationships. The thickness of these lines corresponds to the strength of these collaborations; thicker lines denote stronger partnerships. In Figure 9, China has the highest number of publications, comprising 106 single-country and 39 international collaborative papers. This indicates that while China is deeply involved in global research, most of its work is conducted independently, reflecting a strong local research infrastructure. India follows with 90 single-country and 24 international collaborative publications, showcasing a robust domestic research base alongside substantial international partnerships.

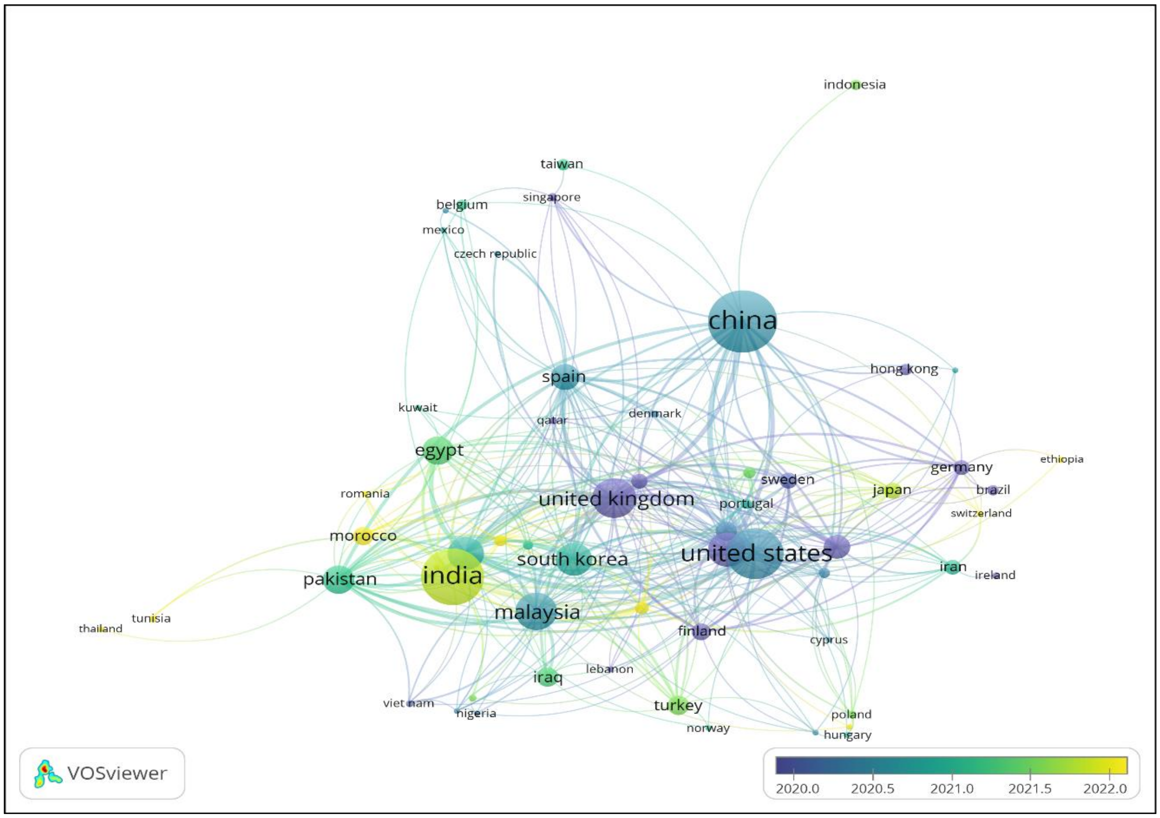

Fig. 8 Country collaboration map

Malaysia presents a balanced contribution with 29 single-country and 19 international collaborative papers, highlighting its active engagement in global research networks. The United States, with 35 single-country and 15 international collaborative publications, plays a crucial role in international research despite having fewer total publications than China and India. The U.S. is a pivotal hub in the global network, with strong collaborative links with China, the UK, South Korea, and Japan.

This central position underscores the importance of the U.S. in fostering international partnerships, which is essential for advancing mmWave technologies. Other countries, including South Korea, Canada, and the United Kingdom, exhibit a mix of single-country and international collaborative publications.

For example, South Korea has 9 single-country and 8 international collaborations, indicating a nearly balanced approach to domestic and international research efforts. However, countries like Iran, Japan, Iraq, Australia, Brazil, and France show fewer international collaborations than their total output. This suggests potential areas for enhancing global research engagement, which could lead to more significant contributions to the field.

3.6. Analysis of Keywords

Keyword co-occurrence analysis is valuable for understanding the research areas and trends in mmWave technology for 5G applications. It supports knowledge mining and provides insights into the knowledge structure. The co-occurrence keyword network for mmWave technology in 5G applications, visualized using VoS viewer, reveals significant insights into the research landscape and thematic areas.

This method is widely used in bibliometric analysis to identify and analyze core research topics, emerging trends, and the interrelationships between different themes. We identified 6729 keywords in journal publications from 2014 to 2024, of which 540 have at least 5 occurrences, as shown in Figure 10. The network shows a prominent presence of core keywords such as "millimeter waves," "5G mobile communication system," "microwave antennas," "mimo systems," and "mm-wave communications," which are central to the study of mmWave technology in 5G applications. The color-coded clusters represent distinct thematic areas: the red cluster focuses on communication systems and infrastructure, the green cluster highlights antenna design and bandwidth optimizing, the blue cluster deals with advanced transmission techniques, and the yellow cluster provides a broader context of 5G technology.

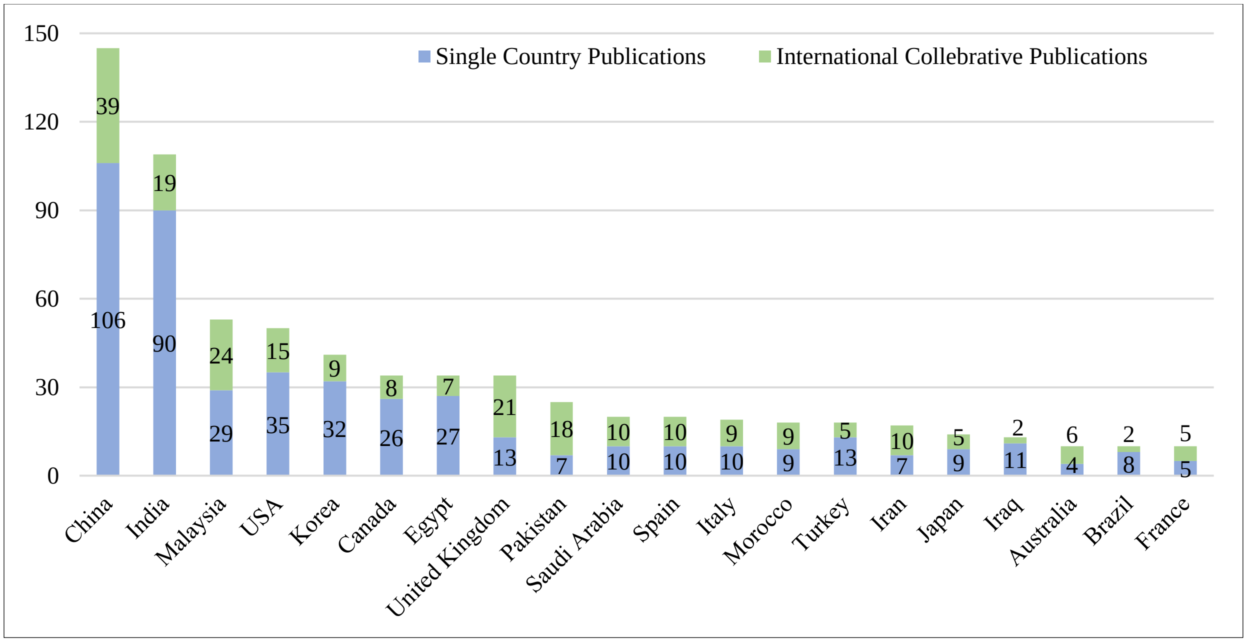

Fig. 9 20 most-prolific collaboration countries

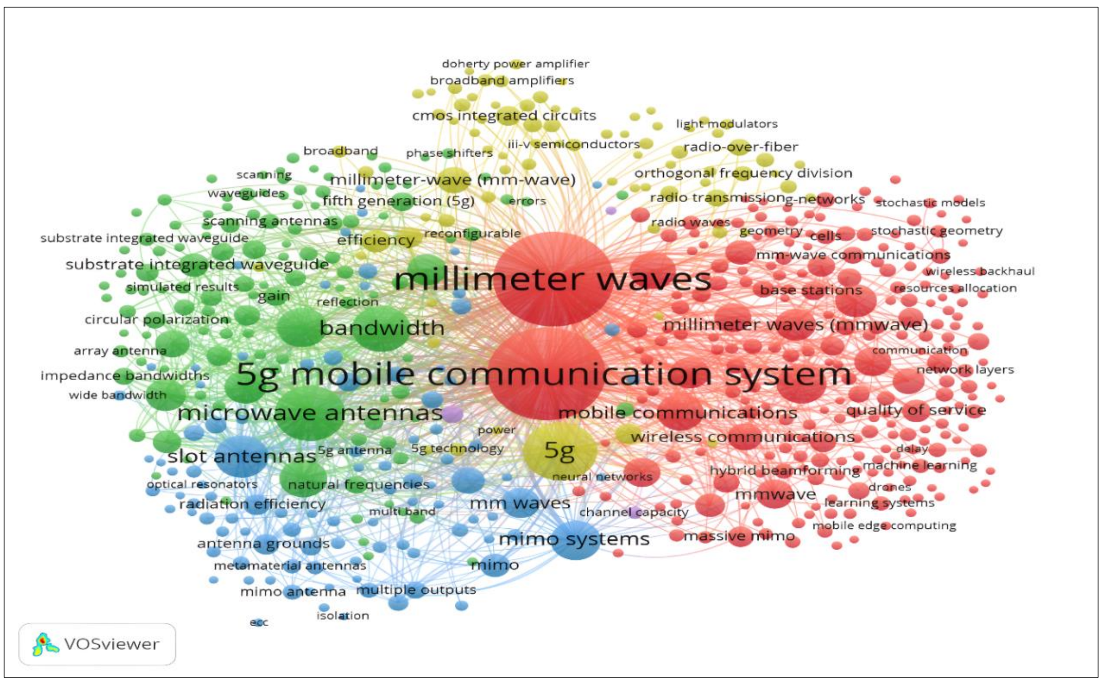

Fig. 10 Co-occurrence keyword network

4. Limitations

The bibliometric analysis of this study has certain limitations: relying on the Scopus database alone might not fully represent the research landscape since crucial publications could be indexed in other databases like Web of Science or IEEE Xplore. Moreover, since only journal articles in English were considered, non-English publications and other types of research, such as conference papers, could be relevant and therefore excluded. Further, reliance solely on citation metrics to measure influence could cause bias, as sometimes things unrelated to the quality of research become functions of citation count, such as self-citations or currently fashionable topics. Finally, the keyword-based search strategy might miss key research employing different concepts or using broader contexts in which the issue may have been embedded; this would reduce the analytical scope. The limitations pointed out here suggest that while the insights gained may be valuable, they must be interpreted carefully.

5. Conclusion

This bibliometric analysis provides a comprehensive overview of the research landscape in millimeter-wave (mmWave) technologies within the context of 5G networks. The study reveals significant growth in publication output from 2014 to 2024, reflecting the increasing interest and critical importance of mmWave technologies in advancing 5G networks. The analysis identifies key research themes, influential authors, and leading institutions that have contributed substantially to the field. The dominance of countries such as China, the USA, and India in research output is evident, with each country exhibiting different levels of impact and international collaboration. The keyword co-occurrence analysis highlights the central topics of mmWave research, including communication systems, antenna design, and advanced transmission techniques, underscoring the multifaceted nature of this technology. The findings suggest that mmWave technology will continue to play a pivotal role in the evolution of 5G networks and beyond, particularly in enhancing data rates, reducing latency, and supporting the massive connectivity required for next-generation applications. However, the research also indicates challenges, such as signal attenuation and the need for advanced antenna designs, which require continued innovation and collaboration. The analysis recommends enhancing global collaboration, especially among emerging research hubs, and focusing on producing high-quality, impactful research. It suggests that continued investment in advanced research infrastructure is crucial for maintaining leadership in this field. Researchers are encouraged to explore emerging areas such as the integration of mmWave with other advanced technologies. Additionally, the study calls for robust policy and regulatory support to facilitate the development and deployment of mmWave technologies, ensuring their successful implementation in 5G networks and future communication systems.

Acknowledgment

The authors acknowledge financial support from SIMAD University's Centre for Research and Development (CRD). Additionally, the authors thank all participants.

Reference

[1] Yong Niu et al., “A Survey of Millimeter Wave Communications (mmWave) for 5G: Opportunities and Challenges,” *Wireless Networks*, vol. 21, pp. 2657-2676, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[2] Yongpeng Wu et al., “A Survey of Physical Layer Security Techniques for 5G Wireless Networks and Challenges Ahead,” *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 4, pp. 679-695, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[3] Arash Shahmansoori et al., “Position and Orientation Estimation through Millimeter-Wave MIMO in 5G Systems,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 1822-1835, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[4] Wei Hong et al., “The Role of Millimeter-Wave Technologies in 5G/6G Wireless Communications,” *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 101-122, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[5] Tadilo Endeshaw Bogale, and Long Bao Le, “Massive MIMO and mmWave for 5G Wireless HetNet: Potential Benefits and Challenges,” *IEEE Vehicular Technology Magazine*, vol. 11, no. 1, pp. 64-75, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[6] Anthony Ngozichukwuka Uwaechia, and Nor Muzlifah Mahyuddin, “A Comprehensive Survey on Millimeter Wave Communications for Fifth-Generation Wireless Networks: Feasibility and Challenges,” *IEEE Access*, vol. 8, pp. 62367-62414, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[7] Zhen Gao et al., “MmWave Massive-MIMO-Based Wireless Backhaul for the 5G Ultra-Dense Network,” *IEEE Wireless Communications*, vol. 22, no. 5, pp. 13-21, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[8] Henk Wymeersch et al., “5G mmWave Positioning for Vehicular Networks,” *IEEE Wireless Communications*, vol. 24, no. 6, pp. 80-86, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[9] Mahnoor Khalid et al., “4-Port MIMO Antenna with Defected Ground Structure for 5G Millimeter Wave Applications,” *Electronics*, vol. 9, no. 1, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[10] Yin Zhang et al., “A MIMO Dielectric Resonator Antenna with Improved Isolation for 5G mm-Wave Applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 4, pp. 747-751, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Bo Ai et al., “5G Key Technologies for Smart Railways,” *Proceedings of the IEEE*, vol. 108, no. 6, pp. 856-893, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[12] Mohsen Khalily et al., “Broadband mm-Wave Microstrip Array Antenna with Improved Radiation Characteristics for Different 5G Applications,” *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 9, pp. 4641-4647, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[13] Rakesh Taori, and Arun Sridharan, “Point to Multi-Point, In-Band mmWave Backhaul for 5G Networks,” *Towards 5G: Applications, Requirements and Candidate Technologies*, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[14] Niamat Hussain et al., “A Metasurface-Based low-Profile Wideband Circularly Polarized Patch Antenna for 5G Millimeter-Wave Systems,” *IEEE Access*, vol. 8, pp. 22127-22135, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] S.E. Alavi et al., “Towards 5G: A Photonic Based Millimeter Wave Signal Generation for Applying in 5G Access Fronthaul,” *Scientific Reports*, vol. 6, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[16] Syeda Fizzah Jilani et al., "Millimeter-Wave Liquid Crystal Polymer Based Conformal Antenna Array for 5G Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 1, pp. 84-88, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] Jian Qiao, Yejun He, and Xuemin Sherman Shen, "Proactive Caching for Mobile Video Streaming in Millimeter Wave 5G Networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 10, pp. 7187-7198, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[18] Dia'aaldin J. Bisharat, Shaowei Liao, and Quan Xue, "High Gain and Low Cost Differentially Fed Circularly Polarized Planar Aperture Antenna for Broadband Millimeter-Wave Applications," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 1, pp. 33-42, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[19] Changsung Lee et al., "Prediction-Based Conditional Handover for 5G mm-Wave Networks: A Deep-Learning Approach," *IEEE Vehicular Technology Magazine*, vol. 15, no. 1, pp. 54-62, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[20] Junquan Deng et al., "Resource Allocation and Interference Management for Opportunistic Relaying in Integrated mmWave/sub-6 GHz 5G Networks," *IEEE Communications Magazine*, vol. 55, no. 6, pp. 94-101, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[21] Rong Lu et al., "SIW Cavity-Fed Filtennas for 5G Millimeter-Wave Applications," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 9, pp. 5269-5277, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[22] Bojiang Ma, Hamed Shah-Mansouri, and Vincent W.S. Wong, "Full-Duplex Relaying for D2D Communication in Millimeter Wave-Based 5G Networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 7, pp. 4417-4431, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[23] Wael Ali et al., "Planar Dual-Band 27/39 GHz Millimeter-Wave MIMO Antenna for 5G Applications," *Microsystem Technologies*, vol. 27, no. 1, pp. 283-292, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[24] Muftah Asaadi, and Abdelrazik Sebak, "High-Gain Low-Profile Circularly Polarized Slotted SIW Cavity Antenna for MMW Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 752-755, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[25] Ibraheem Shayea et al., "Key Challenges, Drivers and Solutions for Mobility Management in 5G Networks: A Survey," *IEEE Access*, vol. 8, pp. 172534-172552, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[26] Naser Al-Falahy, and Omar Y.K. Alani, "Millimetre Wave Frequency Band as a Candidate Spectrum for 5G Network Architecture: A Survey," *Physical Communication*, vol. 32, pp. 120-144, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[27] Trung Kien Vu et al., "Ultra-Reliable and Low Latency Communication in mmWave-Enabled Massive MIMO Networks," *IEEE Communications Letters*, vol. 21, no. 9, pp. 2041-2044, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[28] Yujian Li, Junhong Wang, and Kwai-Man Luk, "Millimeter-Wave Multibeam Aperture-Coupled Magnetoelectric Dipole Array with Planar Substrate Integrated Beamforming Network for 5G Applications," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6422-6431, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[29] Arpan Desai et al., "Compact Wideband Four Element Optically Transparent MIMO Antenna for mm-Wave 5G Applications," *IEEE Access*, vol. 8, pp. 194206-194217, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[30] Ahmed A. Ibrahim, and Wael A.E. Ali, "High Gain, Wideband and Low Mutual Coupling AMC-Based Millimeter Wave MIMO Antenna for 5G NR Networks," *AEU - International Journal of Electronics and Communications*, vol. 142, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[31] Wei Feng et al., "Millimetre-Wave Backhaul for 5G Networks: Challenges and Solutions," *Sensors*, vol. 16, no. 6, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[32] Sheng Jie Yang et al., "Millimeter-Wave Dual-Polarized Filtering Antenna for 5G Application," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 7, pp. 5114-5121, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[33] Philip Hallinger, and Jasna Kovačević, "A Bibliometric Review of Research on Educational Administration: Science Mapping the Literature, 1960 to 2018," *Review of Educational Research*, vol. 89, no. 3, pp. 335-369, 1960. [CrossRef] [Google Scholar] [Publisher Link]

[34] Nees Jan van Eck, and Ludo Waltman, "Visualizing Bibliometric Networks," *Measuring Scholarly Impact*, pp. 285-320, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[35] Nees Jan van Eck et al., "A Comparison of Two Techniques for Bibliometric Mapping: Multidimensional Scaling and VOS," *Journal of the American Society for Information Science and Technology*, vol. 61, no. 12, pp. 2405-2416, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[36] Icy Lee, "Publish or Perish: The Myth and Reality of Academic Publishing," *Language Teaching*, vol. 47, no. 2, pp. 250-261, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[37] Rahimah Zakaria et al., "Worldwide Melatonin Research: A Bibliometric Analysis of the Published Literature between 2015 and 2019," *Chronobiology International- The Journal of Biological and Medical Rhythm Research*, vol. 38, no. 1, pp. 27-37, 2021. [CrossRef] [Google Scholar] [Publisher Link]