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Trends and Mapping of Research on Artificial Intelligence-Based Antenna Optimisation: A Bibliometric Analysis

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ABSTRACT

Objective: *This study aims to map the global research landscape on artificial intelligence (AI)-based antenna optimisation using a bibliometric approach. The objective is to identify publication trends, key contributors, collaborative networks, and emerging themes that define the development of this research domain.* ***Method:*** *The analysis was based on 4,814 documents retrieved from the Scopus database for the period 2010–2025. Data preprocessing included deduplication and keyword harmonisation. Bibliometric analysis was conducted using performance metrics (publication trends, influential authors, journals, countries) and science mapping (co-authorship, co-occurrence, co-citation) with VOSviewer and Bibliometrix.* ***Results:*** *Findings reveal three distinct publication phases: initial stagnation (2010–2016), growth (2017–2019), and exponential expansion (2020–2024), with a peak in 2023. China dominates global research output, followed by the United States and India. IEEE journals, particularly IEEE Access and IEEE Transactions on Antennas and Propagation, serve as the primary publication platforms. Co-authorship analysis indicates a highly centralised collaboration network with hubs like Zhang and Wang. At the same time, thematic mapping shows a strong focus on machine learning, deep learning, 5G or 6G technologies, and adaptive antenna design.* ***Novelty:*** *This paper provides a systematic, data-driven overview of the intellectual structure and thematic evolution of AI-based antenna optimisation research. It identifies gaps such as limited experimental validation, standardisation issues, and the need for AI-driven inverse design methods for next-generation communication systems.*

INTRODUCTION

Antennas are at the heart of modern wireless systems from micro-scale IoT to macro cellular networks. The demands of 5G, which operates in the millimetre wave range, massive MIMO, and the move towards 6G are forcing antenna designs to become increasingly complex: more compact, multi-band, efficient, with precise radiation patterns in fragile channels. The challenge is not just designing the geometry but balancing multiple objectives with high computational costs, as each evaluation requires a full EM simulation. Classical literature and recent surveys highlight the escalating demands and their impact on antenna design (Rappaport et al., 2013; Andrews et al., 2014; Larsson et al., 2014; Heath et al., 2016; Letaief et al., 2019; Alsharif et al., 2020; Saad et al., 2020; Abbas & Ali, 2021).

On the method side, the antenna community has long utilised two families of techniques: deterministic (gradient-based) optimisation and stochastic evolutionary optimisation. Genetic algorithm (GA), particle swarm optimisation (PSO), and differential evolution (DE) have become mainstream for tasks such as array thinning, miniaturisation, and sidelobe suppression, but remain computationally expensive because ‘each step’ is a call to the EM solver. Classical representations and textbooks highlight both the strengths and limitations of these approaches (Haupt, 1995; Kennedy & Eberhart, 1995; Storn & Price, 1997; Weile & Michielssen, 1997; Deb et al., 2002; Robinson & Rahmat-Samii, 2004; Oliveri et al., 2009; Goudos et al., 2011).

In recent years, research has shifted to artificial intelligence: machine learning (ML) and deep learning (DL) as accelerators for design or optimisation. The idea is simple: replace some solver calls with surrogate models (kriging, GP, NN) or perform inverse design directly from target specifications to geometric parameters, thereby accelerating design exploration by several orders of magnitude. Extensive surveys and experimental studies demonstrate significant reductions in EM evaluation time, as well as competitive or better design quality for patches, UWB antennas, and mmWave arrays (Liu, Tan, Khoram, & Yu, 2018; Jiang, Chen, & Fan, 2020; Elmisilmani & Trinchero, 2020; Ma et al., 2021; Montaser & Mahmoud, 2021; Islam et al., 2023).

Technically, there are two main approaches. First, surrogate-assisted optimisation: build a metamodel from a small number of EM samples, then apply global optimisation (PSO or DE or NSGA-II) on the surrogate, sometimes followed by local gradient-based tuning. This approach has been shown to reduce costs by hundreds to thousands of EM evaluations (Sacks et al., 1989; Jones et al., 1998; Bandler et al., 2004; Forrester et al., 2008; Dong et al., 2019; Koziel et al., 2024). Second, inverse or generative design: use deep neural networks or generative models to map targets (S-parameters or bandwidth or gain) to antenna geometry or parameters, including inverse scattering and metamaterial or metasurface concepts. Proof-of-concept studies in EM and photonics point toward more 'direct' design automation (Liu, Tan, Khoram, & Yu, 2018; Liu, Zhu, Rodrigues, Lee, & Cai, 2018; Malkiel et al., 2018; Jiang, Chen, & Fan, 2020; Chen, Sun, & Wang, 2025).

However, amid the explosion of publications, the broader landscape of this field remains fragmented: who are the key actors, which topics are rising or falling, what thematic clusters form the 'core' of the field, and how citation relationships evolve. Narrative reviews address some of these questions but are prone to bias and challenging to scale. Bibliometric analysis offers a systematic approach to mapping the landscape: performance (authors or journals or countries), science mapping (co-authorship, co-occurrence, co-citation, bibliographic coupling), and theme evolution. Established guidelines and methodologies, along with tools like VOSviewer, Bibliometrix, and CiteSpace, make this practice reproducible (Kessler, 1963; Small, 1973; van Eck & Waltman, 2010; Waltman & van Eck, 2010; Župič & Čater, 2015; Aria & Cuccurullo, 2017; Chen, 2017; Donthu et al., 2021).

Data sources are also important, Web of Science (WoS) and Scopus are two primary bibliographic 'engines,' but their coverage, languages, and prioritised fields differ, the choice of database can alter analysis results. Comparative literature highlights variations in coverage and structural biases; therefore, transparency in data curation (period, document type, field) is crucial (Burnham, 2006; Falagas et al., 2008; Gavel & Iselid, 2008; Archambault et al., 2009; Mongeon & Paul-Hus, 2016).

Objectives and contributions. This study maps the research landscape of 'artificial intelligence-based antenna optimisation' through a transparent and replicable bibliometric approach. Specifically, authors: (1) build a corpus of articles from Scopus and WoS for the period 2010–2025; (2) perform data cleaning (deduplication, keyword harmonisation) and performance analysis (publication trends, most influential authors or journals or countries); (3) map the intellectual structure through co-occurrence (keywords), co-citation or bibliographic coupling (documents or authors or journals), and theme dynamics (topic evolution); (4) identifying gaps, such as the lack of inverse design studies for complex antennas, industrial-scale experimental validation, or dataset as well as simulation reporting standards for the following research agenda. The framework, metrics, and analytical tools follow best practices in bibliometrics.

RESEARCH METHOD

This study uses a bibliometric analysis approach to map trends and structures in research related to artificial intelligence-based antenna optimisation between 2010 and 2025. Bibliometric analysis was chosen because it provides a quantitative and visual overview of publication patterns, scientific relationships, and the evolution of research topics, thereby helping to understand the direction of development in this field (Moral-Muñoz et al., 2020; Donthu et al., 2021). Research data were obtained from the Scopus database, which was selected for its broad coverage, structured metadata, and support for data export in a format suitable for bibliometric analysis, as shown in Figure 1 (Martín-Martín et al., 2021). The search was conducted using the keywords 'antenna optimization' OR 'antenna design' in the title, abstract, and keywords sections, with a publication timeframe between 2010 and 2025. This initial search yielded 137.434 documents, reflecting the extensive literature on antenna optimisation during this period. This range was selected based on the relevance of current trends in antenna development for modern communication systems that are increasingly integrated with artificial intelligence technology (Letaief et al., 2019; Saad et al., 2020).

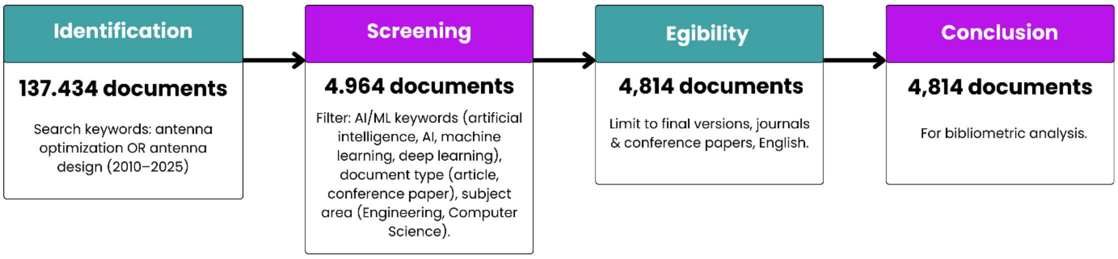

Figure 1. Graph of average pre-test and post-test scores for science process skills

The next stage was the screening process, which was carried out by adding special filters to include only documents containing AI-related keywords such as 'artificial intelligence', 'machine learning', and 'deep learning'. This screening also limited the types of documents to journal articles and conference papers in the subject areas of engineering and computer science, resulting in 4.964 documents. This process was carried out to ensure that only publications relevant to the research topic were analysed (Martín-Martín et al., 2021). After that, in the eligibility stage, the documents were further selected to ensure that only the final version in English was used. After this screening, 4.814 documents were declared eligible for analysis in this study.

The analysis was conducted using two main approaches. First, performance analysis, which aimed to measure quantitative indicators such as publication trends per year, distribution of authors, countries, institutional affiliations, and the most productive journals. Second, science mapping analysis involves the identification of author collaboration networks (co-authorship), relationships between references through co-citation analysis, and interrelationships between keywords through co-occurrence analysis. To visualise these networks, VOSviewer software was used due to its ability to display bibliometric maps clearly and accurately (Perianes-Rodriguez et al., 2020), as well as the R-based Bibliometrix package for advanced analysis such as historiography, thematic maps, and topic evolution (Aria & Cuccurullo, 2017). Before analysis, data cleaning was performed to remove duplicates and standardise keywords. This procedure followed best practices recommended in the literature to ensure the validity and reproducibility of the research.

RESULTS AND DISCUSSION

Results

An analysis of 4.814 selected documents shows a highly dynamic development in publications on the topic of artificial intelligence-based antenna optimisation, as presented in Figure 2. Based on the distribution of publications per year, a clear pattern consisting of three main phases can be observed. The first phase, between 2010 and 2016, was characterised by low and stagnant publication rates, averaging less than 50 documents per year. This condition illustrates that research related to the application of artificial intelligence for antenna optimisation was not yet a primary focus, so traditional optimisation approaches such as genetic algorithms and particle swarm optimisation still dominated.

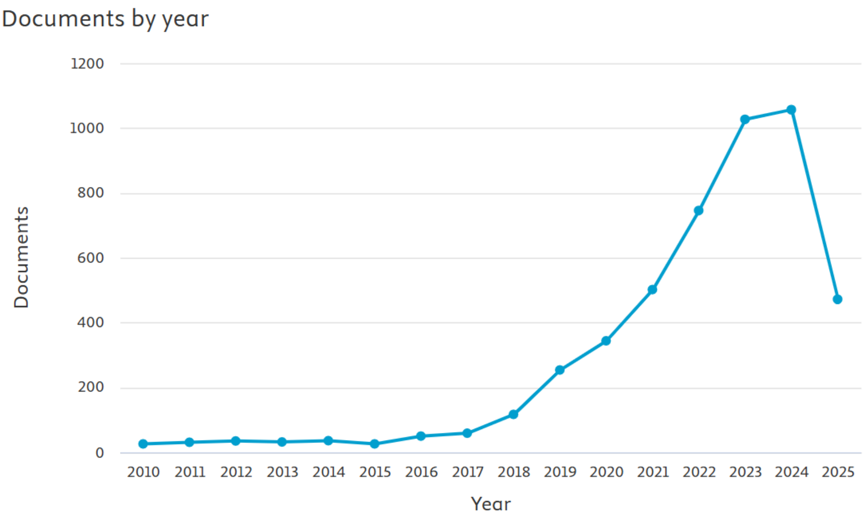

Figure 2. Trends in the number of publications per year related to artificial intelligence-based antenna optimisation in the period 2010–2025

The second phase began in 2017 and lasted until 2019, with a sharp increase in the number of publications, from around 70 documents to more than 250 publications per year. This increase coincided with the initial adoption of machine learning to accelerate antenna design, particularly through the surrogate modelling approach, which can reduce the computational load of electromagnetic simulations. The third phase, from 2020 to 2023, shows an even more dramatic surge, with the number of publications exceeding 500 documents in 2021 and peaking at around 1.050 documents in 2023. The year 2024 continues to show high volume, around 1,000 publications, before declining in

2025 to around 450 publications. This decline is likely due to indexing delays, as 2025 has not yet fully concluded (Donthu et al., 2021).

The second analysis related to the distribution of publications by country shows that research contributions on the topic of artificial intelligence-based antenna optimisation are dominated by several major countries, as presented in Figure 3. China ranks first with 2.117 documents, far surpassing other countries. The United States ranks second with 770 publications, followed by India with 612 publications. European countries such as the United Kingdom (331 publications) and Canada (281 publications) also made significant contributions, followed by South Korea (267 publications). Meanwhile, contributions from Middle Eastern countries such as Saudi Arabia (143 publications) and other Asian countries such as Singapore (132 publications) were also notable, albeit in smaller numbers. Australia (118 publications) and Germany round out the top ten list of the most productive countries.

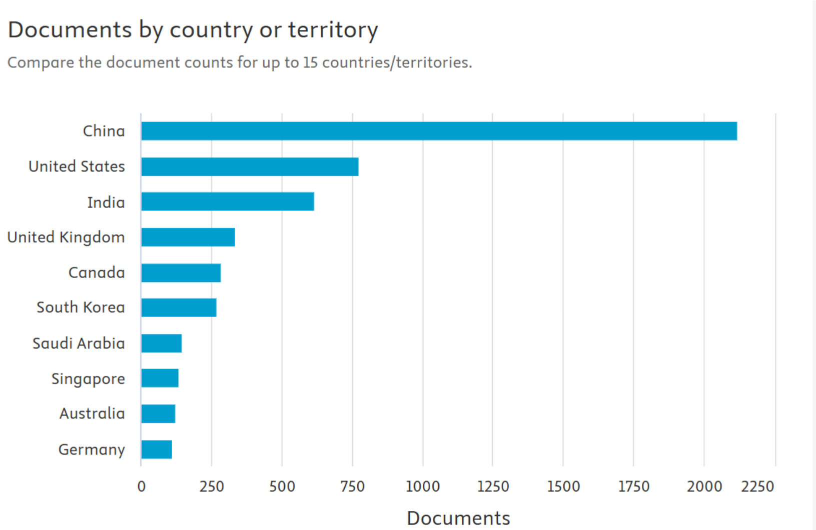

Figure 3. Distribution of publications by country related to artificial intelligence-based antenna optimisation (2010–2025)

Furthermore, regarding the analysis of publication distribution based on affiliation, it shows that universities and research institutions from China dominate research contributions. Southeast University ranks highest with more than 140 publications, followed by Beijing University of Posts and Telecommunications with around 135 publications. The University of Electronic Science and Technology of China is in third place with nearly 120 publications. Furthermore, the Ministry of Education of the People's Republic of China, Xidian University, and Nanjing University of Aeronautics and Astronautics each recorded more than 90 publications. Other institutions that also made significant contributions include Beihang University, the Chinese Academy of Sciences, and Tsinghua University. Meanwhile, Nanyang Technological University is the only institution outside China to make it into the top ten, with around 70 publications.

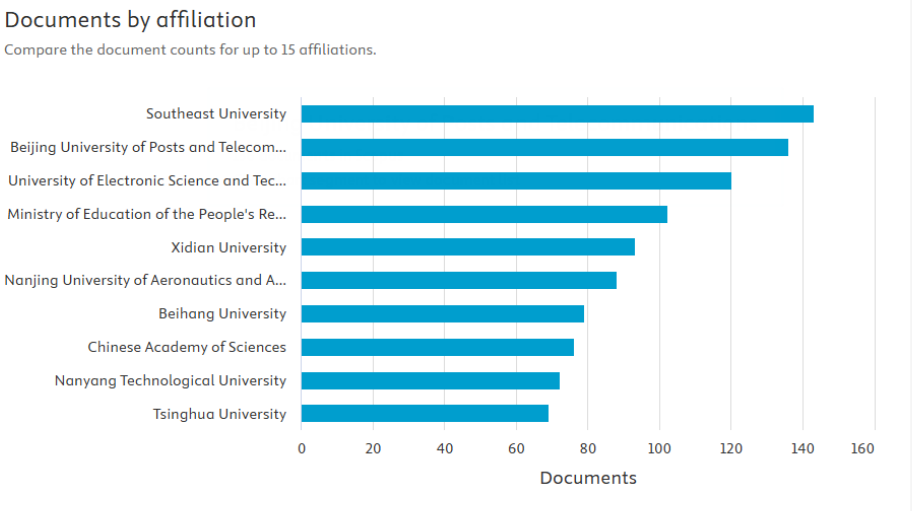

Figure 4. Top ten institutions with the most publications related to artificial intelligence-based antenna optimisation (2010–2025)

The following results are related to the most published authors, where author Niyato, D., ranks first with approximately 39 documents, making him the primary contributor to research on artificial intelligence-based antenna optimisation, as presented in Figure 5. He is followed by Wu, Q. (31 publications) and Wang, H. (30 publications). Other high-contributing authors include Han, Z., Hong, W., and Guizani, M., each with over 25 publications. These names are primarily associated with antenna research for 5G and 6G networks, as well as the integration of AI in antenna design.

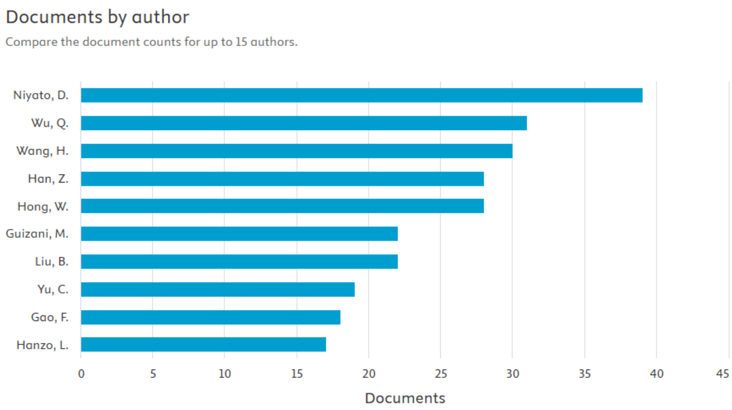

Figure 5. The ten most productive authors in the field of artificial intelligence-based antenna optimisation (2010–2025)

Further analysis of publication sources shows that IEEE journals and proceedings dominate research contributions, as shown in Figure 6. IEEE Access ranks highest with 182 documents, followed by IEEE Internet of Things Journal (161 documents) and IEEE Transactions on Vehicular Technology (146 documents). Other important journals include IEEE Transactions on Wireless Communications (123 documents), Sensors (84 documents), and IEEE Transactions on Antennas and Propagation (82 documents). The publication trend in the graph shows a significant increase starting in 2019, with peak contributions occurring in 2023 and 2024.

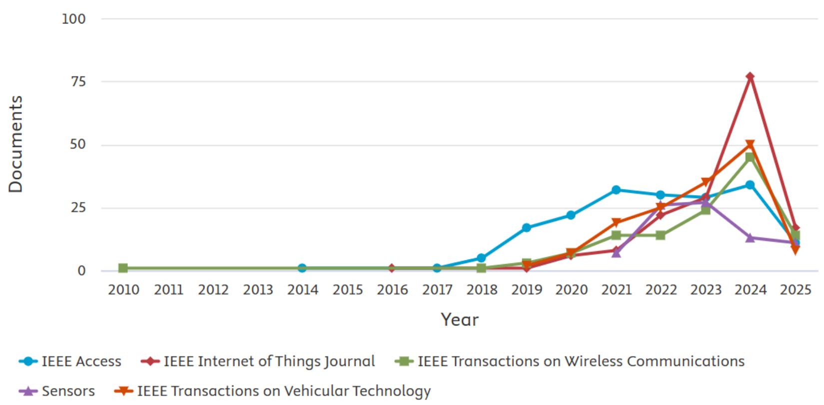

Figure 6. Primary publication sources in the field of artificial intelligence-based antenna optimisation (2010–2025)

Furthermore, the co-authorship network visualisation in Figure 7, generated by VOSviewer, shows the connections between authors who are active in artificial intelligence-based antenna optimisation research. Larger nodes, such as Zhang, Wang, Han, and Niyato, indicate authors with a high number of publications and a central role in the collaboration network. The network is dominated by several large clusters representing major collaboration groups, mainly from East Asia, including China and Singapore, in line with the country distribution trend that dominates the results of this study.

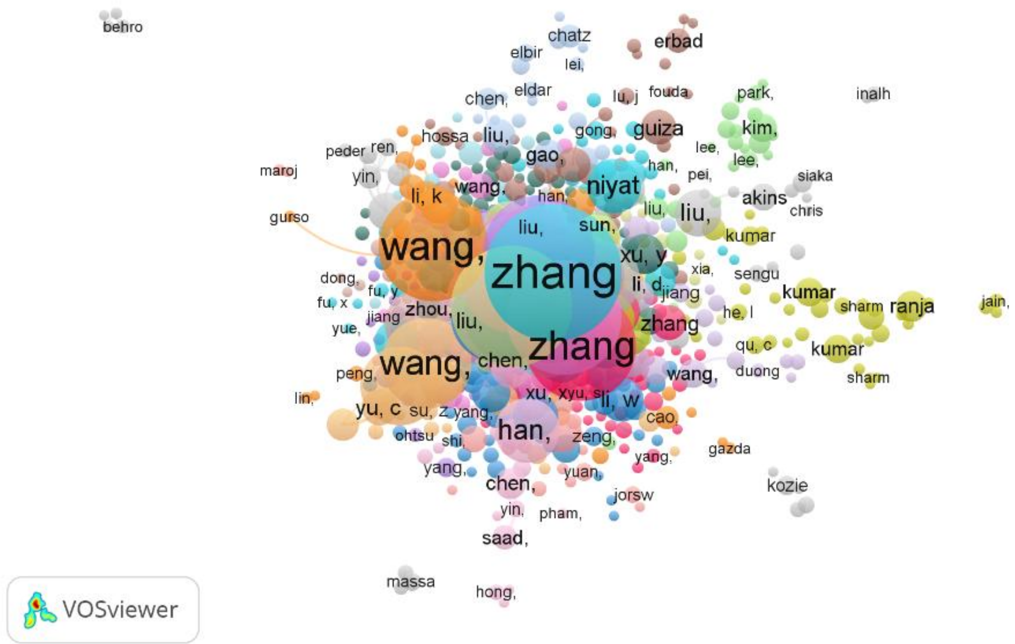

Figure 7. Visualisation of co-authorship networks in research related to artificial intelligence-based antenna optimisation (2010–2025)

The visualisation of keyword co-occurrence is shown in Figure 8. This observation shows the thematic structure of research in the field of artificial intelligence-based antenna optimisation. Keywords with large node sizes, such as antennas, deep learning, machine learning, and 5G mobile communication systems, indicate the highest frequency of occurrence and are the central topics of research. In addition, keywords such as microstrip antennas, MIMO systems, convolutional neural networks, and deep reinforcement learning also occupy important positions in this network. The map shows several clusters of different colours, which represent the main research themes.

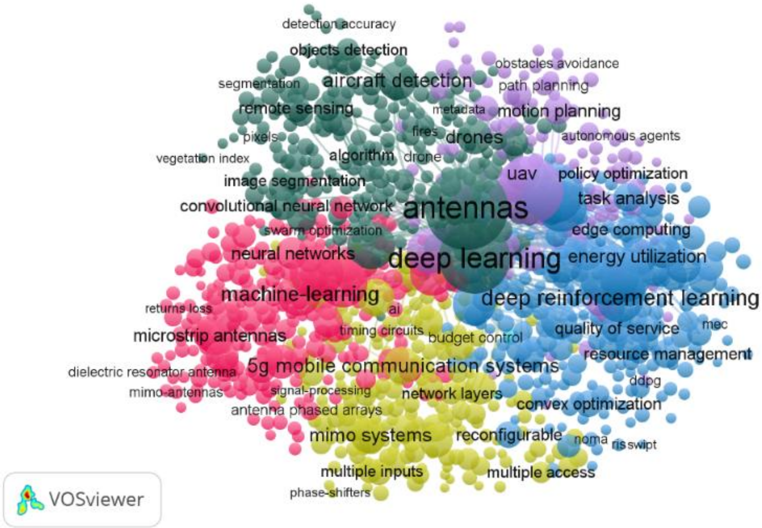

Figure 8. Visualisation of keyword co-occurrence networks in artificial intelligence-based antenna optimisation research (2010–2025)

Next, an analysis of the keyword network shown in Figure 8 reveals four dominant clusters. The first cluster (dark green) focuses on antennas and AI technology integration, including terms like antennas, deep learning, and convolutional neural networks. This theme indicates an in-depth exploration of AI applications to accelerate antenna design and optimisation processes, including surrogate models and inverse design. The second cluster (pink) emphasises antenna design and hardware technology, with keywords such as microstrip antennas, dielectric resonator antennas, and return loss. This focus is relevant to the development of compact and efficient antennas for wireless communication systems (Islam et al., 2023).

The third cluster (yellow) is closely related to fifth-generation (5G) communication technology and preparations for 6G, including keywords such as 5G mobile communication systems, MIMO systems, reconfigurable, and multiple access. This indicates the need for antennas capable of supporting high capacity, massive connectivity, and adaptability for future networks (Letaief et al., 2019; Saad et al., 2020). The fourth cluster (blue and purple) is related to AI-based optimisation and innovative network concepts, including keywords such as deep reinforcement learning, resource management, edge computing, and policy optimisation. This indicates the integration of antennas with intelligent system approaches to improve network efficiency, including through power optimisation and spectrum management (Adhikari et al., 2024). Overall, this keyword analysis confirms the direction of future research: the integration of precision antenna design and AI algorithm integration to meet the demands of next-generation communication technology.

Discussion

Figure publication trends and topic evolution

Figure 2 shows a significant transformation in the number of publications related to artificial intelligence (AI)-based antenna optimisation over less than a decade. Initially, this research was exploratory, limited to conceptual studies. However, since 2017, the number of publications has increased sharply, marking a shift towards widespread adoption. This surge is closely related to the development of machine learning (ML) and deep learning (DL) technologies, which provide solutions to the complexity of modern antenna design. The application of surrogate-assisted optimisation has emerged as one of the key strategies. This approach enables the reduction of electromagnetic simulation costs, which are typically very expensive and time-consuming (Elmisilmani & Trinchero, 2020). Furthermore, the development of DL-based inverse design methods supports the automation of antenna design, enabling the exploration of complex configurations with high accuracy (Chen et al., 2025). This trend reinforces the role of AI as a catalyst in the transformation of the antenna design paradigm. In line with this, these advances are closely related to the needs of the telecommunications industry.

The implementation of 5G networks requires adaptive antennas that support massive multiple-input multiple-output (MIMO), beamforming, and compact high-performance antennas for IoT and satellite communications (Saad et al., 2020). Anticipation of the transition to 6G further increases the urgency of developing AI-based antenna design (Letaief et al., 2019). Publications peaked in 2023 and remained stable until 2024. The decline observed in 2025 is not an indication of waning research interest but rather a result of indexing delays. Overall, this pattern confirms that AI-based antenna optimisation is a strategic area that will continue to grow alongside innovations in next-generation communications (Gajbhiye et al., 2025; Koziel et al., 2024).

Geographical distribution and driving factors

Figure 3 shows China's dominance in the number of publications related to this topic. This phenomenon is not coincidental but a logical consequence of national strategies prioritising the development of 5G and 6G, supported by significant investments in AI (Letaief et al., 2019). Additionally, government support for AI integration in the telecommunications sector accelerates research progress. The United States ranks second, with significant contributions to the development of AI algorithms, antenna hardware, and industry-academic collaboration (Saad et al., 2020). India plays an important role, particularly in adaptive antenna research and IoT technology, which is linked to national programmes to strengthen communication infrastructure (Adhikari et al., 2024).

Europe and Asia (including the United Kingdom, Canada, South Korea, and Singapore) demonstrate active participation, although their contributions are more fragmented. This analysis indicates that research distribution is heavily influenced by a country's level of investment in new-generation communication infrastructure. Countries with a strong commitment to 5G implementation and 6G development tend to have higher research productivity.

Major research institutions and centres

Figure 4 reveals the concentration of research institutions in China. Universities such as Southeast University and Beijing University of Posts and Telecommunications (BUPT) dominate publications, demonstrating strong synergies between academic institutions, industry, and government support. This dominance is in line with national strategies for the development of advanced communication technologies, including AI-based adaptive antennas to support the 6G ecosystem (Letaief et al., 2019). The presence of Nanyang Technological University (NTU) in Singapore in the top 10 indicates the role of Southeast Asia, although its contribution is still relatively small. This pattern suggests that global research distribution follows investment patterns and technological priorities. As the complexity of antenna requirements for IoT, autonomous vehicles, and low-earth orbit (LEO) satellites increases, international cross-institutional collaboration will become the primary driver of future innovation.

Dominant journals and publication channels

Figure 6 confirms the role of IEEE as the primary publication platform, particularly journals such as IEEE Transactions on Antennas and Propagation and IEEE Transactions on Vehicular Technology. This dominance is understandable given IEEE's focus on multidisciplinary research and the application of cutting-edge technologies. Related publications also appear in journals such as Electronics (MDPI), marking the growing interest in the academic community. The decline in the number of publications observed in 2025 is primarily due to indexing delays rather than a decrease in research activity. Overall, this pattern confirms that AI in antenna design remains a key topic on high-impact platforms.

Author collaboration patterns

Figure 7 shows a collaboration network structure dominated by several author hubs, such as Zhang and Wang, connecting various research subclusters. This pattern indicates that intensive collaboration among top researchers is a key factor in accelerating innovation and increasing the number of publications (Islam et al., 2023). However, the visualization also highlights the presence of small clusters and relatively isolated authors, indicating room for strengthening cross-institutional and cross-national collaboration. Increased global collaboration is predicted to enrich methodological approaches, accelerate innovation, and amplify the impact of research, particularly in supporting next-generation communication technologies.

Strategic implications and future directions

The strategic implications of these research findings indicate that AI-based antenna optimisation will remain a key focus of future research. Developments are directed towards the integration of generative AI to enable more autonomous and flexible adaptive antenna designs. In addition, federated learning approaches are considered important for overcoming distributed data limitations and maintaining privacy, which are critical issues in modern communication ecosystems. Optimisation will also focus on large-scale applications such as the Internet of Things (IoT), vehicle-to-everything (V2X) communication, and low-earth orbit (LEO) satellite systems, which require high-performance antennas and adaptive designs. However, significant challenges remain, particularly regarding the limitations of representative datasets, AI model interpretability, and the need for energy-efficient antenna designs. Given the increasing complexity of networks and performance demands, the combination of AI methods, multiobjective optimisation, and physics-based approaches is predicted to be a key research direction in the coming decade.

CONCLUSION

Fundamental Finding : Bibliometric analysis shows strong growth in AI-based antenna optimisation over the past decade, driven by wireless system complexity and design automation needs. The surge after 2017 highlights machine learning and deep learning as key enablers for adaptive design. **Implication :** China and the US dominate, reflecting heavy 5G or 6G investment. The concentration in top IEEE journals underscores the field's position at the forefront of telecom engineering and AI convergence. **Limitation :** This study relies only on Scopus, excluding other databases. It also does not assess design quality or experimental validation. **Future Research :** Future work should explore generative AI, federated learning, and physics-informed models, while also standardising datasets and addressing energy efficiency in IoT, V2X, and LEO satellite antenna optimisation.

AUTHOR CONTRIBUTIONS

Riski Ramadani contributed to the conceptualization, project management, and writing and editing of the manuscript. **Afiyah Nikmah** contributed to the methodology and preparation of the initial draft. **Nisaul Fadhilah** was involved in data collection and formal analysis. **Rohim Aminullah Firdaus**, as the corresponding author, was responsible for the supervision, validation, and finalization of the manuscript. **Noer Risky Ramadhani** provided additional support during the research process. All authors have read, reviewed, and approved the final version of this article and declare full responsibility for all aspects of the research.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest, either financial or personal, that could influence the content or results of this study.

ETHICAL COMPLIANCE STATEMENT

This article has met the standards of research and publication ethics. The author affirms that this research is original, conducted with academic integrity, and free from unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The final responsibility for the content of the manuscript rests entirely with the authors. The author declares that this manuscript was prepared entirely without the assistance of artificial intelligence (AI) or other digital tools. The entire process, from planning, data processing, analysis, to writing and editing the manuscript, was carried out manually by the author. Thus, full responsibility for the content and authenticity of this article rests solely with the author.

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