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Towards Intelligent Communication Systems for High-Speed Railways: Themes, Challenges and Future Perspectives

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Abstract

Background: The rapid development of high-speed railway (HSR) systems requires advanced and reliable communication infrastructure to support operational safety, passenger services and intelligent transportation functions. Despite growing attention, comprehensive reviews of scientific developments in HSR communication systems remain limited.

Objective: This article seeks to explore the development, thematic landscape and prospective directions of HSR communication studies through bibliometric analysis, emphasizing the identification of core technologies, prevailing research trends and promising avenues for future investigation.

Methods: A total of 352 articles published between 2005 and 2024 were retrieved from the Scopus database to examine research development in the field. The dataset was cleaned using OpenRefine and analysed through keyword co-occurrence techniques in VOSviewer and Biblioshiny. This analysis identified thematic clusters, temporal trends and core technologies shaping the research domain.

Results: The study highlights four major research clusters: artificial intelligence (AI) and adaptive communication technologies, fifth-generation (5G) network architecture and mobility solutions, signal processing and quality of service (QoS) optimization and channel modelling with propagation characteristics. Massive multiple-input multiple-output (massive MIMO) and millimetre-wave (mmWave) technologies emerge as key enablers for addressing high-mobility challenges. Furthermore, the findings reveal a growing integration of AI, edge computing and real-time communication protocols in recent research.

Conclusion: This overview offers a macro-level perspective on the scientific landscape of HSR communication studies. The findings underscore the growing adoption of adaptive, intelligent and energy-efficient technologies, providing strategic guidance for future scholarly work and policymaking in advancing next-generation railway communication systems.

Index Terms

High-speed railway; HSR; Communication systems; Bibliometric analysis; Massive MIMO; 5G communication; Artificial intelligence; AI.

1 INTRODUCTION

HSR systems have the ability to run at speeds exceeding 200 kilometres per hour. This mode of transportation has experienced rapid global expansion, offering a host of advantages, including reduced energy consumption, minimal environmental impact, extensive transportation capacity, enhanced safety measures, swift travel speeds and efficient land utilization (Fang & Ma, 2023; Lin, 2023). The development of HSR requires the integration of cutting-edge technologies from various fields such as AI, electrical engineering and materials science (Jia et al., 2022). Infrastructure for HSR may involve building entirely new lines or upgrading existing conventional routes, supported by trains with augmented power-to-weight ratios and advanced in-cab signalling systems (Watson, 2021). As a strategic sector within sustainable transportation, HSR development emphasizes environmental responsibility, improved mobility and continuous technological innovation (Zheleznov et al., 2021). Nonetheless, challenges persist, including substantial investment requirements and the necessity for additional projects to enhance interconnected transport infrastructure.

One of the critical infrastructures of HSR is the communication system (X. Li et al., 2024). Enhancing communication in HSR poses a considerable challenge, demanding optimization of wireless signal transmission environments to bolster signal robustness while curbing signal degradation (C. Lu et al., 2023). One strategy involves employing reconfigurable intelligent surfaces (RIS) to coherently overlay signals at the recipient's end via beamforming strategies (Agheli et al., 2022; Elsawy et al., 2024; Gao et al., 2023). Another way to do this is to combine sensor monitoring and remote communication in a self-powered multi-sensor monitoring system. This can help tasks get done faster and make sure that transmissions are of good quality (Ling et al., 2023). Also, using a precoding-based handover mechanism reduces ping-pong handover triggers and makes HSR communication frameworks more reliable (Ding et al., 2023). These methods work better than traditional ones when it comes to system reliability, signal robustness and computational complexity.

Existing bibliometric studies on railway systems have predominantly examined general engineering innovations, sustainability practices, logistics performance and railway digitalization (Steele et al., 2024). More recent analyses extend this landscape by providing specialised insights, such as a comprehensive review of safety issues in high-speed railways (Anagnostopoulos, 2024), the thematic evolution of railway safety with a growing emphasis on AI-driven monitoring and cyber-physical systems (Umar et al., 2025) and the socioeconomic implications of HSR development through large-scale science mapping (Albano & Pagliara, 2025). In addition, emerging research from 2025 highlights the growing role of digital twin technologies in railway operations, including applications for predictive maintenance and infrastructure optimisation (Thompson et al., 2025) as well as studies that summarise the key challenges of digital twin implementation and propose future research directions (Z.-Y. Zhang et al., 2026).

Although these studies highlight the rapid expansion of railway research, none have examined the thematic structure, research dynamics, technological directions or evolutionary patterns of communication systems within the HSR environment. Existing reviews tend to focus on broader aspects such as safety, operational efficiency or socioeconomic outcomes, leaving limited understanding of communication-centric advancements such as AI-driven handover mechanisms, RIS, next-generation train control systems and heterogeneous network integration. This lack of a targeted bibliometric synthesis represents a significant gap, as it restricts the ability of researchers and policymakers to evaluate technological maturity, identify emerging trends and set priorities for future research. To the best of our knowledge, this study is the first to provide a comprehensive bibliometric analysis dedicated specifically to communication technologies in the HSR domain, integrating conceptual evolution, collaboration structures and technological trajectories within this rapidly advancing field.

This study offers a significant contribution to the field of HSR communication systems by providing a comprehensive and in-depth synthesis of existing scholarly work through a bibliometric approach. Unlike previous bibliometric or fragmented technical studies, this research integrates conceptual, technological and methodological insights into a unified analysis. The analysis is conducted using the bibliometric tools VOSviewer and Biblioshiny, based on data retrieved from the Scopus database. The analysis is required to get a sense of the research direction and landscape around HSR communication systems, with a particular emphasis on technological themes, publication dynamics and future directions. By examining trends in scientific publications, international collaboration patterns and co-occurring keywords, this study provides a macro-level overview and highlights promising directions for future research.

In particular, this research addresses the following questions:

RQ 1. What is the evolution of scientific publications on HSR communication systems?
RQ 2. What are the main thematic clusters and research trends emerging from keyword co-occurrence in HSR communication literature?
RQ 3. What are the key technical challenges identified in the literature and what future research directions are suggested to advance HSR communication systems?

This method is supposed to help academics properly understand the content of the information, as well as the demands and direction for future research projects. Furthermore, a better understanding of the potential impact of this system can assist in the decision-making process for future HSR communication systems.

2 RESEARCH METHODOLOGY

This study employs a bibliometric analysis approach to systematically examine publication patterns, thematic structures and technological developments within HSR communication systems. Scopus was selected as the primary database due to its broad coverage across engineering, telecommunications and transportation fields, which aligns with the multidisciplinary nature of HSR communication research. Scopus is also the largest repository of peer-reviewed literature and offers extensive subject-area representation, making it a suitable choice for comprehensive bibliometric analysis (Wangsa et al., 2022). Compared to Web of Science, Scopus indexes a larger number of journals on wireless communication and intelligent transport systems and provides richer bibliometric metadata (citations, keywords, affiliations), enabling more robust analytical procedures recommended in bibliometric methodology. Methodological guidelines also suggest that using a single, well-established database reduces duplication, minimizes human error during screening and ensures consistency in data extraction (Donthu et al., 2021). Through bibliometric mapping, this study identifies thematic keywords, tracks scientific output and visualizes the evolution of knowledge structures in the field (Irawan et al., 2023; Gazali and Saad, 2023) It also can be used to analyse the most and least popular keywords that are discussed (Kunharyanto et al., 2025). This methodological design provides a structured and replicable foundation for analysing trends and developments in HSR communication research.

2.1 Data collection

Precise selection of relevant keywords is paramount, as keyword accuracy significantly affects the breadth and depth of bibliometric results (Gao et al., 2023). The final search query included:

“high-speed rail*” OR “high speed rail*” OR “high speed train” OR “high speed trains” OR “high-speed train” OR “high-speed trains” AND “communication system*” OR “communications network*”

A preliminary synonym analysis was conducted to ensure optimal query formulation and topic relevance. These keywords were entered into the Scopus search system. Scopus was chosen as the database because it indexes more than 14,000 publications and is globally trusted (Ling et al., 2023). Before entering the keywords into the Scopus search system, the process of identifying synonyms for each keyword had to be carried out to optimize the search system, ensuring that it aligns with the desired topic. The keywords to be used in the search engine focused only on the title, abstract and keyword. From the search results, 1,138 documents were obtained.

After obtaining a total of 1,138 documents, the filtering process was carried out based on the year, document type, language, source type and publication stage. The filtering process involved limiting the release year of the articles, selecting only the last 20 years, from 2005 to 2024. The document type focused solely on articles, excluding conference papers, books, reviews, book chapters, etc. Subsequently, only documents in English were chosen, with the source type being a journal and the publication stage marked as final. In the next step, secondary research articles were excluded by applying the following exclusion keywords:

bibliometric* OR scientometric* OR infometric* OR webometric* OR alt?metric* OR patentometric* OR "systematic literature review*" OR "systematic review*" OR scorba OR "scoping review*" OR "umbrella review*" OR slr OR slna OR balr OR meta-analys?s.

2.2 Data search strategy

The review process follows PRISMA guidelines, encompassing identification, screening, eligibility assessment and inclusion to ensure methodological transparency and reliability (Amo Larbi et al., 2024). The workflow of the analysis is illustrated in Figure 1, which outlines the sequential stages of data collection, processing and visualization.

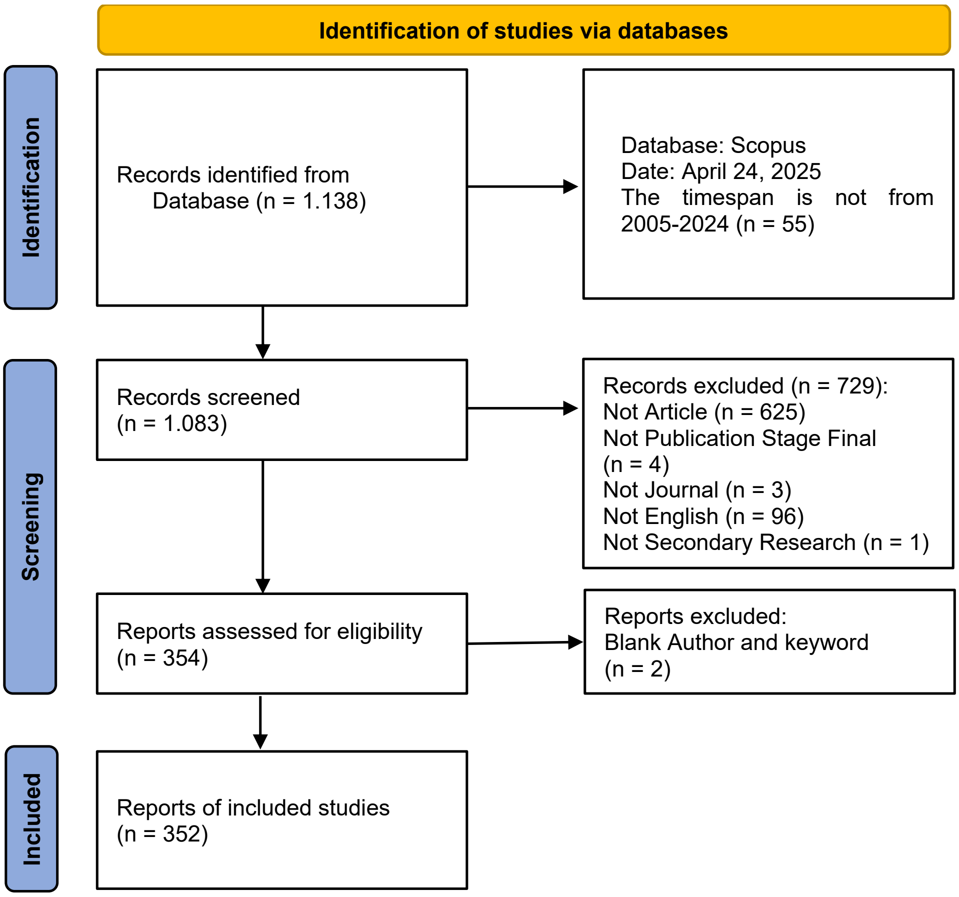

Figure 1. *PRISMA-based on HSR communication.*

2.3 Data analysis

The analysis was employed to explore the evolution, thematic clusters and technical challenges associated with communication systems in HSR environments. Based on this filtering, one relevant article was identified, which systematically reviewed the challenges, modelling, design and analysis of high-mobility communication systems, emphasizing the unique characteristics of high-mobility environments (Wu & Fan, 2016). Manual filtering was also performed using the OpenRefine application to ensure the dataset usability and to eliminate records with missing key metadata such as author names, author keywords and abstracts.

Based on the screening process, a total of 352 articles were identified as eligible for analysis. This was followed by visualization and network analysis to identify thematic clusters and research trends in the field of HSR communication systems (Oyewola & Dada, 2022). Co-occurrence analysis was performed on author keywords. The resulting network maps illustrated the relationships between frequently co-occurring keywords, forming clusters that represent key thematic areas. Overlay visualizations were also employed to examine temporal trends and highlight high-intensity topics, providing insights into the evolution, core focus areas and potential research gaps within the HSR communication literature.

3 RESULTS

3.1 Evolution of scientific publications on HSR communication system (RQ 1)

Based on data from 2005 to 2024, the research trend for the topic "HSR communication system" shows a significant growth pattern, as seen in Figure 2. In 2005, only a single scientific article on this subject was published. The number of published articles gradually increased over time. A notable surge occurred in 2012, with 11 articles, marking the beginning of a more consistent and rapid growth in the number of publications. A particularly sharp increase occurred after 2015, a period that coincides with the global expansion of HSR infrastructure and the growing demand for reliable wireless communication systems on HSR. This surge in research activity reflects a heightened awareness of the critical role of communication technology in ensuring operational safety, passenger connectivity and the realization of intelligent transport systems within the HSR domain.

The upward trajectory continued, reaching its peak in 2021 with a total of 43 published articles. The period between 2012 and 2021 thus represents a phase of rapid development and scholarly engagement with the subject, although a slight decline in publication numbers was observed in the subsequent years (42 in 2022, 41 in 2023 and 39 in 2024).

Overall, the linear trend visible from these data (Figure 2) indicates strong growth in research interest related to HSR communication. Despite fluctuations and a slight decline in recent years, the long-term trend still shows positive development. The decrease in publication numbers in recent years may reflect stabilization or shifts in research focus; however, the consistent growth pattern from 2005 to 2024, demonstrates a significant increase in contributions and attention to this field. Building on this growth pattern, the next section explores the thematic clusters and research trends that have emerged within HSR communication studies.

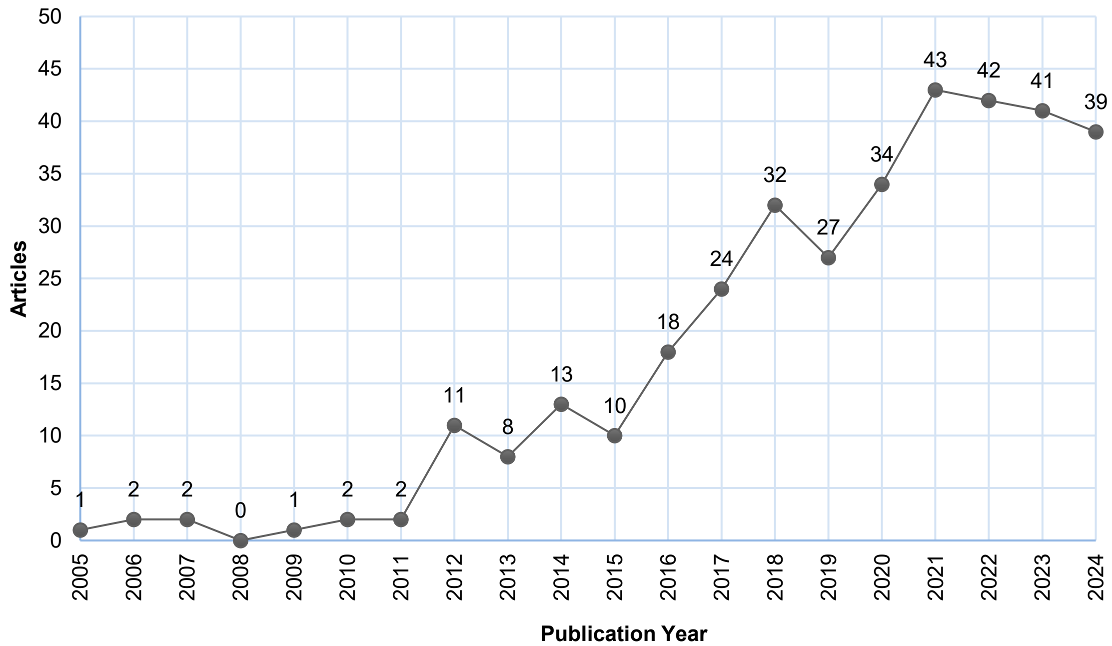

Figure 2. *Annual publication trend of HSR communication.*

3.2 Thematic clusters and research trends (RQ 2)

3.2.1 Thematic clusters

In this study, a bibliometric approach was employed to identify the main thematic areas within HSR communication systems. The dataset was thoroughly cleaned and filtered to ensure its relevance to the HSR communication domain. Thematic clusters were derived from a co-occurrence analysis of the author keywords. From the Scopus database, a total of 1,000 keywords were extracted from 352 articles, of which 106 keywords met the minimum threshold of three co-occurrences and were included in the analysis. The visualization categorizes the keywords into four separate clusters, each marked by a unique colour and illustrating diverse but interrelated technological strategies and research directions aimed at advancing modern, adaptive and efficient communication systems for high-speed railways. Each cluster highlights a particular and evolving area of interest within the field. The visualization of the clustering results, as shown in Figure 3, is then analysed qualitatively to construct narratives and identify the direction of scientific development within each group.

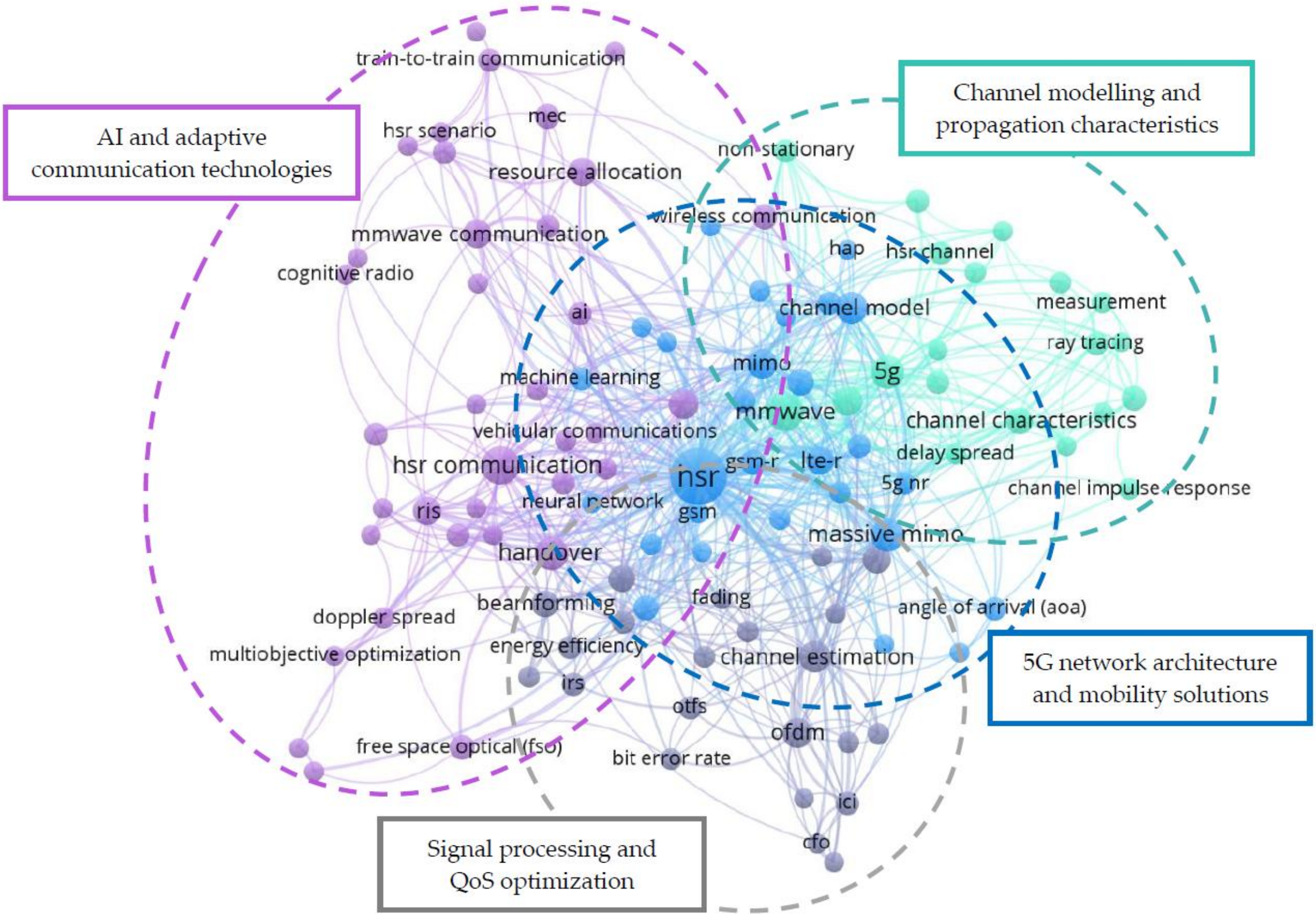

Figure 3. Thematic cluster map of HSR communication.

Table 1. Cluster-based analysis of HSR communication system.

Research focus	Key technologies / topics	Challenges	Contribution to HSR systems
Purple cluster – AI and adaptive communication technologies			
Application of AI for designing intelligent, flexible and reliable communication systems in high-speed environments	• Reinforcement learning (e.g., Q-learning, DRL) (Yan et al., 2020) • Resource allocation (X. Zhang et al., 2021) • Reconfigurable intelligent surface (RIS) • Multi-access edge computing (MEC) • Train-to-train communication	• Rapid changes in environment and network conditions • Real-time learning and decision-making • Integration with smart infrastructure	• Improved adaptability and performance of HSR communication • AI-driven dynamic resource management • Enhanced signal quality in mobility scenarios
Blue cluster – 5G network architecture and mobility solutions			
Designing future communication infrastructures for HSR based on 5G technologies to reduce latency and improve reliability	• Massive MIMO, LTE-R, GSM-R • Network slicing • Ultra-reliable and low-latency communication (URLLC) (Y. Feng et al., 2024; Salmeno & Zakia, 2024) • Dual-link soft handover (Zhao et al., 2018) • Rotating transceivers (J. Zhang et al., 2021)	• Frequent handovers due to high speeds • Signal degradation from Doppler effects and obstacles (Ko et al., 2022) • mmWave path loss and beam coverage limits (J. Feng et al., 2024)	• Reliable and scalable 5G-based HSR communication architecture • Low-latency systems for critical train operations • Solutions to reduce handover failures and latency

Research focus	Key technologies / topics	Challenges	Contribution to HSR systems
Grey cluster – Signal processing and QoS optimization			
Enhancing communication reliability and efficiency at the physical and data link layers in high-speed scenarios	• Channel estimation (e.g., BEM, ML-based) (Deng et al., 2016; Xiyu Wang et al., 2018) • OFDM, beamforming, bit error rate (BER) • Orthogonal time frequency space (OTFS) (Ma et al., 2022) • Power allocation strategies (X. Chen et al., 2017; Prananto et al., 2023)	• High computational overhead for real-time estimation • Interference suppression and directional control • Frequent beam realignment (Yan et al., 2018)	• Better signal accuracy and robustness • QoS enhancement in extreme mobility • Improved energy efficiency
Green cluster – Channel modelling and propagation characteristics			
Modelling signal propagation in complex HSR environments (e.g., tunnels, viaducts) to improve system planning and deployment	• Channel measurement and ray tracing (J. Li et al., 2022; Y. Liu et al., 2019) • Spatial correlation and delay spread • Geometry-based stochastic models (GBSM) (Zhou et al., 2020) • High-frequency (mmWave) propagation modelling (Cui & Fang, 2016; Guan et al., 2018)	• Severe multipath effects in tunnels • LOS obstruction in viaducts/open areas • High variation in environmental conditions	• Realistic channel models for simulation and system design • Better planning for antenna deployment and signal coverage • Foundations for mmWave and 6G HSR applications

The four clusters from the co-occurrence analysis show complementary research directions in HSR communication, as seen in Table 1. These include the development of adaptive systems driven by AI (purple cluster), the construction of next-generation infrastructure (blue cluster), the enhancement of signal transmission quality (grey cluster) and the formulation of accurate channel models (green cluster). All of these affirm that the HSR communication ecosystem is a complex system that demands the integration of various technical and strategic approaches. This mapping can serve as an important reference for formulating further research directions and policy-making in the development of smart transportation systems based on HSR.

3.2.2 Research trends

Figure 4 illustrates the thematic evolution of research into HSR communication systems between 2005 and 2024. This visualization captures the progression and interconnection of key research keywords across different time periods. In the early phase (2005–2017), research predominantly centred around foundational communication technologies. Keywords such as HSR communication, OFDM and massive MIMO, were prominent, representing the technological basis for wireless transmission in high-mobility environments. The focus during this stage was largely on enhancing spectrum efficiency and improving signal transmission reliability (C.-X. Wang et al., 2020).

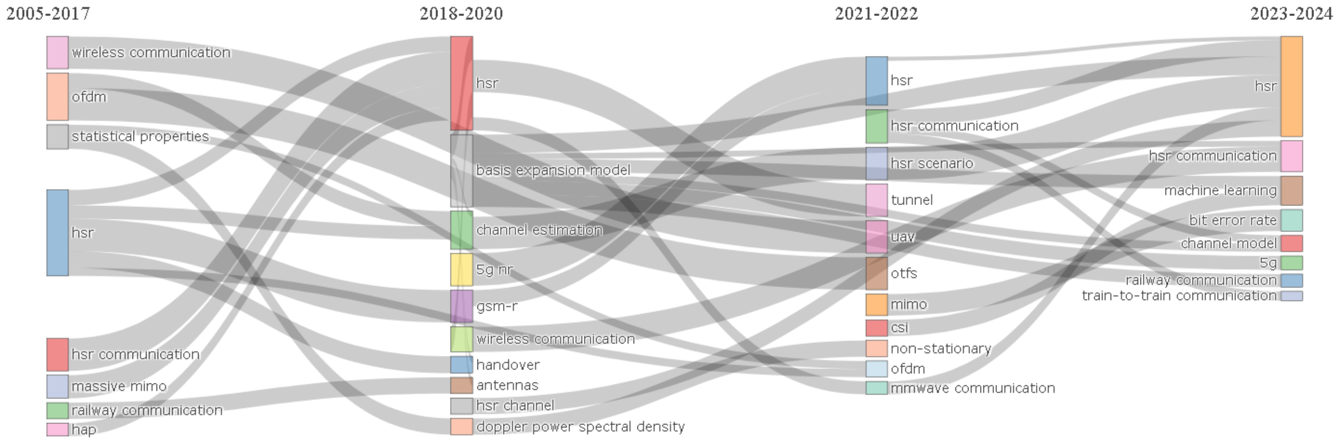

Figure 4. *Thematic evolution of HSR communication.*

A shift in research priorities is evident in the period 2018–2020, characterized by the emergence of more specialized topics. Keywords such as channel estimation, basis expansion model, handover and 5G NR signal a transition towards addressing real-time communication challenges posed by high-speed mobility. This reflects a growing emphasis on optimizing communication performance under high-mobility conditions and enhancing handover stability (Z. Li et al., 2016; Noh et al., 2020).

In the period 2021–2022, research attention increasingly turned towards environmental and topographical factors affecting communication performance. The rise of keywords such as tunnel, non-stationary and HSR scenario points to growing concern over signal propagation in complex terrains such as tunnels and viaducts. These developments highlight the necessity of accurate channel models tailored to the unique characteristics of various HSR environments (Y. Liu et al., 2020).

The latest phase (2023–2024) marks a pronounced integration of AI into HSR communication systems. Keywords including machine learning, channel model and train-to-train communication suggest a growing emphasis on developing adaptive, intelligent systems capable of real-time decision-making and self-optimization. This reflects an evolving vision of smart railway infrastructure underpinned by AI-driven communication strategies (Yan et al., 2018).

Collectively, the outlined progression underscores the dynamic and interdisciplinary nature of HSR communication systems. The evolution from basic wireless technologies to AI-enhanced adaptive systems demonstrates how the increasing complexity of HSR operations continues to drive innovation across multiple technical domains. While thematic evolution highlights the progression of research, several persistent technical challenges remain, as discussed below.

3.3 Technical challenges and future research directions (RQ 3)

3.3.1 Technical challenges

3.3.1.1 Overview of core technologies and interrelationships

Based on the bibliometric analysis, the most frequently co-occurring technologies in HSR communication include mmWave, massive MIMO and handover. These three technologies collectively serve as the backbone of current innovation efforts, aiming to deliver ultra-high data rates and low-latency communication in high-mobility environments. Their frequent co-occurrence highlights their interdependent roles in shaping the next generation of railway communication infrastructures.

While mmWave communication offers extremely large bandwidth, its susceptibility to signal and blockage necessitates the use of smaller cell sizes, dense deployment and precise beamforming techniques. In parallel, massive MIMO plays a pivotal role in 5G and emerging 6G architectures along HSR routes by enhancing spectral efficiency, network capacity and link reliability (Uwaechia & Mahyuddin, 2020). When integrated, these technologies form a complementary approach to overcome the limitations of conventional wide-area wireless systems, especially under extreme mobility.

One prominent enabler of 5G is the integration of massive MIMO with mmWave frequencies, which harnesses both the vast bandwidth available in mmWave bands and the spatial multiplexing capabilities of large antenna arrays. This combination holds significant potential to increase user throughput, improve energy and spectral efficiencies and expand the overall capacity of mobile networks (Busari et al., 2018).

The bibliometric analysis summarizes the occurrence frequency of author keywords across HSR communication research. From a total of 352 articles, 1,000 keywords were identified. After applying a minimum threshold of three co-occurrences across sources, 106 relevant keywords were retained for analysis. Only author-defined keywords with at least three inter-journal connections were considered. As expected, “high speed railways (HSR)” appear most frequently with 176 times. The next most frequent terms were “high-speed railway communication” (n = 37), “mmWave” (n = 35), “5G” (n = 20), “handover” (n = 20) and “massive MIMO” (n = 20). This distribution reinforces the central role of these technologies in advancing the HSR communication agenda.

3.3.1.2 Key challenges identified

The main objective of 5G systems is to achieve a 1,000-fold increase in data rates compared to 4G (Q. C. Li et al., 2014). Within HSR communication, achieving this objective involves navigating several technical barriers associated with mmWave communication, massive 5G and handover management.

Firstly, mmWave communication stands out for its large bandwidth, high data rate capabilities and narrow beam directivity. However, its short wavelength makes it particularly sensitive to path loss, shadowing and obstructions (Das & Kolangiammal, 2017; Xiong Wang et al., 2018). This necessitates high-gain antennas and beam-steering mechanisms to maintain reliable connectivity. Dense deployment of mmWave cells, often within heterogeneous networks with small cells and relays, can help mitigate these challenges (Engda et al., 2020), though concerns such as hardware complexity, energy consumption and signal degradation persist (Xiao et al., 2017).

Meanwhile, massive MIMO technology, which utilizes large antenna arrays to enable spatial multiplexing, has shown promise for enhancing performance in high-mobility environments. It contributes to increased capacity, robust signal transmission and reduced processing burden at the receiver side (Albreem et al., 2019). Further advantages include enhanced link security, energy efficiency and cost-effectiveness, all of which are critical in rail operations (Björnson et al., 2016a; Björnson et al., 2016b; J. Chen et al., 2016; Do et al., 2018). However, implementing massive MIMO in practice remains challenging due to issues such as pilot contamination, hardware impairments, complex precoding algorithms and accurate channel estimation (Elijah et al., 2016; Larsson et al., 2014; Zaib et al., 2016).

Another pressing concern in HSR systems is handover management. The extremely high speeds result in frequent and rapid transitions between base stations, making the handover process prone to failure and service degradation (Ke et al., 2019). Numerous studies have addressed the problem of hard handovers in HSR environments, proposing various enhancements to improve handover continuity and latency performance (Cheng et al., 2012; Z. Liu & Fan, 2014; Y. Lu et al., 2016; Qian et al., 2013; Tian et al., 2012).

In the HSR context, the communication system faces three key disruptions: frequent handovers, Doppler frequency shifts and rapidly changing radio environments. These factors place stringent demands on the handover decision-making algorithms and execution mechanisms used in LTE-R and beyond. Consequently, optimizing handover protocols to ensure seamless connectivity, low packet loss and minimal service interruption is an urgent and ongoing research priority.

3.3.2 Recommended future directions

To better understand how research topics have evolved over time, an overlay visualization was generated to map the temporal progression of key themes in HSR communication systems. Figure 5 presents an overlay visualization of author keywords from 2016 to 2024, generated using VOSviewer, which illustrates the temporal evolution of research themes in HSR. The visualization applies a colour gradient, ranging from blue to yellow to represent the average publication year for each keyword. Blue tones indicate older research topics, while yellow signifies more recent areas of interest. This gradient effectively captures the shifting landscape of scientific inquiry over time.

The progression from blue to yellow indicates a clear research trajectory, shifting from early studies focused on physical-layer aspects (e.g., delay spread, impulse response) to more recent investigations into network-level optimization and intelligent control mechanisms, such as RIS, intelligent reflecting surfaces (IRS) and MEC. Central and consistently studied topics including “HSR”, “HSR communication”, “mmWave”, “massive MIMO” and “handover” appear prominently in the middle of the network, underscoring their foundational role in the field.

Each node represents an author keyword, with the node size indicating the frequency of the keyword appearance in the literature. Thicker links between nodes represent stronger co-occurrence relationships, revealing the thematic interconnections and joint exploration of related concepts.

The primary aim of this visualization is to reveal emerging research directions and pinpoint potential future priorities in the field of HSR communication. Keywords highlighted in yellow represent recent and emerging topics, including: RIS, mmWave communication, MEC, full-duplex communication, HSR scenarios, transmission scheduling, multiple high-speed train coordination, machine learning, neural networks, resource allocation, train-to-train communication, Doppler spread, multi-objective optimization, cognitive radio, interdependent networks, channel state information (CSI) and OTFS. These themes exemplify how the field is moving towards the integration of adaptive, intelligent and high-capacity communication systems to meet the demands of high-speed and high-mobility environments.

Furthermore, the increasing focus on AI and spectrum innovation including technologies such as visible light communication (VLC), mmWave and IRS marks a paradigm shift towards future-ready railway communication networks that are fully connected, context-aware and energy-efficient (Puspitasari et al., 2023). Emphasis on real-time communication paradigms, such as train-to-train connectivity and decentralized computing through MEC, supports the emergence of smart railway infrastructures capable of enabling mission-critical services with ultra-low latency and high reliability.

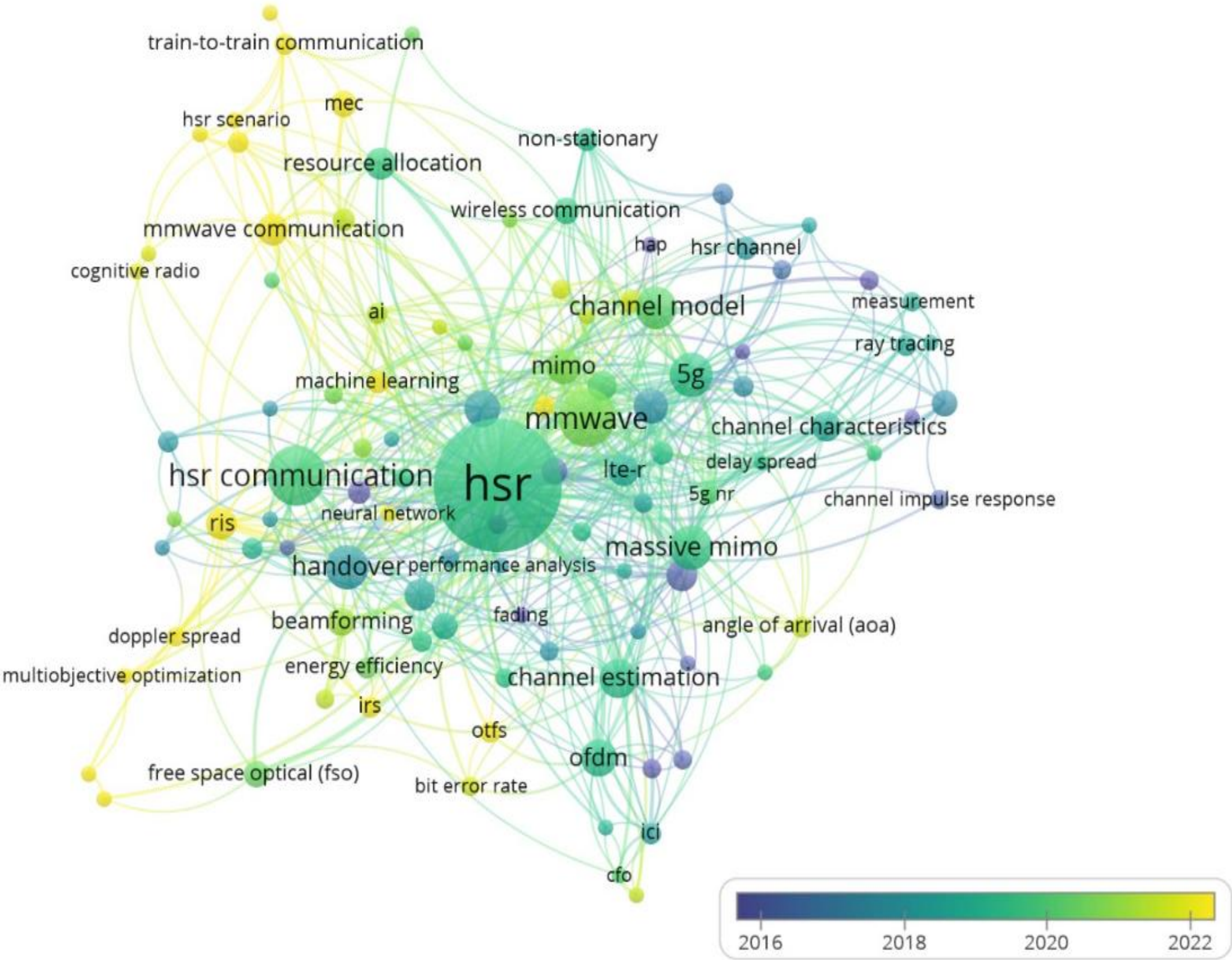

Figure 5. *Overlay visualization of author keywords in HSR communication (2016–2024).*

In summary, the overlay visualization highlights both evolving research trends and frontier technologies driving the transformation of HSR communication systems. Future research should focus on integrating AI-driven optimization, spectrum innovation (mmWave, VLC, RIS) and MEC to achieve ultra-reliable, low-latency communication in HSR environments. Such integration can bridge physical-layer technologies with network-level intelligence, leading to more robust, adaptive and sustainable communication systems for high-mobility scenarios.

4 DISCUSSION

The evolution, thematic structure and technological advancements in HSR communication systems were examined on a sample of 352 scientific articles published between 2005 and 2024. The evolution of scientific publications on HSR communication systems (RQ 1) demonstrates a notable surge in research activity after 2016, with the highest output recorded between 2021 and 2022. This increase aligns with the global momentum to integrate 5G and emerging 6G technologies into high-mobility infrastructure. The geographical distribution reveals that China, Europe and South Korea are leading contributors, while high-impact journals such as IEEE Access, Sensors, and Wireless Communications and Mobile Computing dominate the publication landscape. This trend reflects both governmental investment in transportation modernization and the growing need for advanced communication technologies in next-generation railway systems.

Addressing RQ 2, the keyword co-occurrence analysis revealed four prominent thematic clusters: (1) AI and adaptive communication technologies, focusing on reinforcement learning, resource allocation and reconfigurable intelligent surfaces; (2) 5G network architecture and mobility solutions, covering massive MIMO, network slicing, URLLC and handover mechanisms; (3) signal processing and QoS optimization, addressing channel estimation, OFDM, beamforming and power allocation strategies; and (4) channel modelling and propagation characteristics, encompassing measurement campaigns, ray tracing and geometry-based stochastic models for complex HSR environments. These clusters indicate a clear thematic progression in the literature from traditional physical-layer signal processing techniques towards intelligent, adaptive network-level solutions. This shift is largely driven by the increasing complexity of HSR communications environments, characterized by high mobility, frequent handovers, and strict latency requirements. The results suggest that future research will increasingly rely on cross-layer optimization and distributed intelligence to support high-speed, low-latency and mission-critical applications.

In response to RQ 3, the analysis identifies critical technical challenges that delay the realization of robust HSR communication systems. These challenges are not isolated: dense mmWave deployments increase handover frequency, while massive MIMO requires accurate CSI estimation, which becomes more difficult under fast mobility. The interplay between these technical constraints underscores the need for integrated and cross-layer solutions, rather than isolated optimization of individual components. Table 2 summarizes the shared challenges across these core technologies.

Table 2. *Challenges across core technologies in HSR communication.*

Technology	Key benefits	Shared challenges
mmWave	High data rate, large bandwidth	Susceptible to blockage, path loss, requires dense cells
Massive MIMO	Spatial multiplexing, spectral gain	Pilot contamination, high complexity, hardware costs
Handover	Connectivity continuity	High failure rate at speed, latency, Doppler shift

Despite progress, multiple technical challenges remain unresolved. For instance, handover failures at high speeds continue to hinder service continuity, while hardware complexity and computational load limit the practicality of mmWave and massive MIMO. These issues are further complicated by the harsh and dynamic HSR environment, which introduces Doppler shifts and frequent topology changes.

Overall, the results underline the importance of integrating high-capacity, low-latency communication with intelligent control to enable the future of autonomous and safe high-speed rail systems. The proposed technological directions suggest that future HSR communication architectures must combine advanced physical-layer technologies with network-level intelligence, supported by edge computing and AI-driven decision-making.

5 CONCLUSION

This study provides a comprehensive bibliometric analysis of HSR communication research published between 2005 and 2024. The results demonstrate a steadily increasing academic focus, particularly after 2015, driven by the global expansion of HSR networks and the demand for reliable onboard connectivity. Four key thematic clusters were identified: (1) AI and adaptive communication technologies, (2) 5G network architecture and mobility solutions, (3) signal processing and QoS optimization and (4) channel modelling and propagation characteristics.

The research trajectory shows a shift from conventional wireless technologies to advanced, intelligent systems, with enabling technologies such as mmWave, massive MIMO and handover management emerging as critical to ensuring ultra-reliable, low-latency communication in high-mobility contexts. Emerging trends, including RIS, machine learning and MEC, further highlight the transition towards smart, adaptive and energy-efficient communication solutions. Overall, the findings offer strategic insights for both scholars and policymakers, emphasizing the need for integrated, interdisciplinary approaches to develop robust, intelligent and sustainable communication systems for future HSR environments.

ADDITIONAL INFORMATION AND DECLARATIONS

Conflict of Interests: The authors declare no conflict of interest.

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Data Availability: The materials associated with this study have been deposited in an external repository. The dataset and relevant documentation can be accessed on the Zenodo repository: 10.5281/zenodo.17730825.

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