ISSN 2277-2685
IJESR/June. 2025/ Vol-15/Issue-3s/463-476
Mohammed Arif *et. al.,* / International Journal of Engineering & Science Research

Analysis Of High-Speed Railway Communication Using Relays

Mohammed Arif, Mohammed Waheeduddin, Mohammed Ashraf Hussain, Mrs. Syeda Nousheen Hashmi
[1,2,3]B.E Students, Department Of ECE, Deccan College of Engineering and Technology, India.
[4]Assistant Professor, Department Of ECE, Deccan College of Engineering and Technology, India.
540mohammedarif@gmail.com, md.waheeduddin27@gmail.com, ashrafhussainmohd98@gmail.com, syedanousheenhashmi@deccancollege.ac.in

ABSTRACT

The rapid growth in railway infrastructure and increased travel demands over the past two decades have led to significant advancements in rail systems, particularly in the areas of travel speed and transport capacity. These developments have simultaneously increased the requirements for reliable and efficient railway communication and signaling (C&S) systems. As a critical component of the railway network, the C&S system ensures safe train operations, efficient passenger communication, and overall operational reliability. However, the inherent challenges posed by high-speed rail networks—such as the frequent need for seamless handoffs due to high train mobility—make meeting these requirements particularly challenging.

This project presents an approach to address the handoff issue by implementing a group handoff strategy, which leverages relays based on Multi-Input Multi-Output Orthogonal Frequency-Division Multiplexing (MIMO-OFDM) transmission technology. This group handoff approach, as opposed to the traditional individual handoff process, aims to reduce the complexity and increase the efficiency of handoff procedures by managing handoff events collectively. By integrating MIMO-OFDM transmission with relay nodes, this strategy improves connectivity and communication stability, even at high speeds. Various configurations, including the number of relays and transmission antennas, were tested to evaluate the system's adaptability and performance under different conditions.

In addition to proposing the group handoff technique, this research also explores the performance of non-cooperative versus cooperative communication in a multi-tier heterogeneous network environment.

The performance of the proposed system is assessed using key metrics such as handoff probability, outage probability, coverage probability, and transmission capacity. The results demonstrate improvements in communication reliability and efficiency, offering valuable insights for enhancing modern railway C&S systems. The simulation results are carried out using MATLAB

1-INTRODUCTION

The continuous development and modernization of railway infrastructure over the past two decades have transformed the global rail industry, characterized by significant increases in transport capacity and traveling speed. As the demands for efficient and high-speed railway services grow, the need for robust communication and signaling (C&S) systems becomes increasingly critical. These systems ensure the safe operation of trains, enable efficient communication with passengers, and enhance overall network reliability. However, the complex challenges inherent to railway communication, such as high train mobility and frequent handoff requirements between communicating devices, complicate the provision of seamless, uninterrupted connectivity.

Addressing these challenges is crucial for ensuring the efficiency and safety of high- speed railway (HSR) operations. Frequent handoffs, caused by the rapid movement of trains, can lead to communication interruptions and decreased reliability, Traditional individual handoff mechanisms are often insufficient to meet the needs of modern railway systems. Therefore, innovative solutions are needed to enhance the handoff process, improve communication stability, and optimize the performance of the entire C&S system.

This project proposes a group handoff strategy using relays in a Multi-Input Multi-Output Orthogonal Frequency-Division Multiplexing (MIMO-OFDM) transmission framework as a solution to this pressing issue. By managing handoffs collectively through relays, the approach aims to reduce handoff complexity and enhance connectivity, even at high speeds. Various configurations involving different numbers of relays and transmission antennas were evaluated to determine the optimal setup for robust performance. Furthermore, this study compares cooperative and non-cooperative communication within a multi-tier heterogeneous network, offering insights into the benefits of collaborative data exchange in complex railway environments. The proposed system model is analyzed through key performance indicators, including handoff probability, outage probability, coverage probability, and transmission capacity.

The results presented in this research, including metrics like handoff probability, outage probability, coverage probability, and transmission capacity, would have benefited from MATLAB's powerful graphical capabilities. MATLAB is particularly effective for creating plots, comparing datasets, and highlighting the impact of various configurations (such as the number of relays and antennas) on system performance.

In the context of this study, graphical representation of the results can help illustrate the improvements in communication reliability and efficiency brought by the proposed group handoff strategy. Plots can showcase comparisons between non-cooperative and cooperative communication modes. By visualizing trends and relationships between performance metrics, these graphs provide deeper insights into the system’s behavior and the benefits of the proposed approach, making the research findings more comprehensible and impactful.

2-LITERATURE SURVEY

Various existing literature works in the areas concerned with this project have been reviewed to get a clear and better understanding of the different aspects involved in the project. The titles of these literature works have been listed in the reference section in the thesis. This chapter presents a brief overview of all the literature works that were reviewed.

Synopsis of the Previous Work

This literature survey synthesizes the contributions of each paper in the context of advancing communication technologies for high-speed railway scenarios, emphasizing the role of mobile relay nodes, cooperative strategies, and MIMO systems in addressing the challenges of high-speed mobility and data transmission.

1. In paper [1] This study investigates the challenges of maintaining reliable communication within high-speed railway (HSR) systems due to high mobility and frequent handoffs. The authors propose a novel solution involving moving relays (MR) and cooperative communication. By utilizing group handoff via moving relays instead of individual handoffs, the system aims to reduce outage and handoff probabilities while increasing coverage and transmission capacity. The paper presents a model

analyzing both cooperative and non-cooperative communications in multi-tier heterogeneous networks, accounting for interference, noise, and power control. Through Monte Carlo simulations, it highlighting the effectiveness of using moving relays for reducing communication disruptions due to the Doppler effect and vehicle penetration loss (VPL) within HSR environments ([1]).

2. This paper [2] focuses on enhancing cellular coverage for passengers onboard high-speed trains (HSTs) using a system of cooperative moving relay nodes (MRNs). Modern HSTs face significant challenges such as vehicle penetration loss (VPL) and rapid mobility, which complicates communication with macro networks. The study models an eight- MRN system, with MRNs deployed on train carriages, using external and internal antenna arrays to facilitate efficient data transmission and mitigate VPL. Simulation results demonstrate improvements in achievable throughput for onboard users and positive effects on users in surrounding cells. The cooperative backhaul link architecture offers increased network capacity and reliable coverage, making MRN deployment a viable solution for HST scenarios ([2]).

3. In this paper [3], the research addresses efficient power management and base station planning for high-speed railway networks equipped with moving relay stations. By leveraging orthogonal frequency-division multiple access (OFDMA), the study aims to minimize total downlink power consumption while adhering to quality-of-service (QoS) constraints. Optimal resource allocation algorithms, including a dual decomposition method and a low-complexity suboptimal solution, are proposed to enhance resource efficiency. The paper emphasizes the benefits of employing multiple relays over single- relay scenarios in terms of improving network coverage, minimizing power consumption, and facilitating seamless handover in high-speed environments [3].

4. This paper [4] "Vehicular Communications for 5G Cooperative Small Cell Networks" addresses the challenges of integrating high-mobility vehicular communications within dense 5G small cell networks. It focuses on cooperative transmission strategies between small cells distributed as Poisson point processes, evaluating their impact on vehicular handoff rates and communication capacity. By deriving cooperative and coverage probabilities, the study demonstrates how optimized thresholds can balance network performance and handoff disruptions. Numerical results reveal the influence of cooperative thresholds, antenna configurations, and small cell radii on coverage and mobility. This work offers insights into enhancing vehicular communication efficiency in 5G small cell networks while managing mobility-related challenges.

5. The paper [5] examines a 5G mobile relay system designed to overcome the challenges of providing high data rates for high-speed trains. It adopts an asymmetric architecture where sub-6GHz frequencies are used for base station-relay links, and millimeter-wave (mm Wave) frequencies are employed for relay-user equipment (UE) links. The study analyzes the impact of channel aging and fading conditions on end-to-end signal-to-noise ratios and derives key performance metrics, such as outage probability and average bit- error rates. Results highlight the potential of mobile relay systems to deliver high data rates to HST passengers by mitigating severe penetration loss and other mobility-related communication bottlenecks ([5]).

6. This paper [6] talks about the theoretical potential of multiuser MIMO (multiple-input, multiple-output) systems with a large number of base station antennas serving multiple users in cellular networks. The

approach leverages time-division duplexing and reverse- link pilots to estimate forward and reverse channels, applying linear precoding for data transmission. The study suggests that increasing the number of base station antennas leads to reduced noise and fading effects, ultimately improving system performance. However, challenges such as pilot contamination and inter-cell interference remain critical concerns for further optimization ([6]).

7. This document reviews the performance and capacity metrics of different wireless communication architectures, including single-input single-output (SISO), single-input multiple-output (SIMO), multiple-input single-output (MISO), and multiple-input multiple-output (MIMO) systems. The comparison emphasizes how MIMO systems achieve superior spectral efficiency and capacity due to spatial multiplexing and diversity. The findings illustrate the advantages of using MIMO technology in environments with high data rate demands and mobility, as is often required for advanced railway communication systems ([7]).
8. In this paper [8], it discusses the evolution of wireless communication systems for railways, highlighting the limitations of the existing GSM-R technology, such as low data rates and high latency. It explores the potential of alternative technologies like LTE and 5G to meet the increasing communication demands of modern railway systems. The study presents a methodology for measuring communication channel performance in various railway environments, such as tunnels and rural areas, and emphasizes the need for low- delay, high-reliability networks to support safety-critical applications in railways.
9. This paper [9] presents an improving communication for vehicular users through the use of moving relays, particularly for those traveling on public transport. The study develops a system model that integrates moving relays into a heterogeneous cellular network, analyzing their impact on macro and vehicular user coverage. Results show that moving relays enhance signal quality by mitigating vehicle penetration loss and improving overall network coverage through cooperative communication. The use of moving relays also helps reduce the energy consumption of mobile devices, providing a more robust and efficient network experience for users ([9]).
10. In this work [10], the paper evaluates the effectiveness of mobile relay nodes (MRNs) in enhancing LTE uplink performance for high-speed railway scenarios. It highlights the challenges posed by high-speed environments, such as rapid signal fading, Doppler effects, and frequent handovers. By placing MRNs atop train carriages, the study demonstrates improved communication quality through efficient backhaul and access links. The authors discuss various relay configurations and their impact on network load and resource allocation, emphasizing the importance of robust MRN deployment for seamless communication in high-speed contexts ([10]).

3-MULTIPLE INPUT MULTIPLE OUTPUT SYSTEMS AND ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING SYSTEM

MIMO formats

The different MIMO formats - SISO, SIMO, MISO and MIMO require different numbers of antennas as well as having different levels of complexity. Also dependent upon the format, processing may be needed at one end of the link or the other - this can have an impact on any decisions made.

The different forms of antenna technology refer to single or multiple inputs and outputs. These are related to the radio link. In this way the input is the transmitter as it transmits into the link or signal path, and the output is the receiver. It is at the output of the wireless link.

Therefore, the different forms of single / multiple antenna links are defined as below:

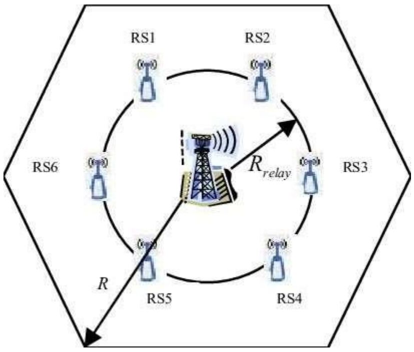
1. SISO - Single Input Single Output
2. SIMO - Single Input multiple output
3. MISO - Multiple Input Single Output
4. MIMO - Multiple Input multiple Output

Cooperative And Non-Cooperative Communication Using Relays

Relays are crucial components in wireless communication systems, enhancing network performance by improving signal quality, coverage, and reliability. Depending on their functionality, placement, and mode of operation, relays can be categorized into several types, each serving a unique purpose in network architecture. Here is a detailed discussion of the different types of relays used in modern wireless networks:

Fixed Relays

Fixed relays are stationary nodes that are strategically placed within a network to improve coverage, especially in areas with weak signal strength or high interference. Their primary role is to extend the reach of base stations by relaying signals between users and network access points. Fixed relays are commonly used in urban environments, where buildings and other obstacles may cause signal attenuation. By deploying fixed relays, network operators can enhance connectivity in dense or challenging locations, used in urban areas, network edges, or areas with high physical obstructions.



Fixed relay-based network

These are Cost-effective for enhancing coverage; typically, less complex to manage compared to mobile relays but they lack mobility that may make them less effective in dynamically changing environments.

Moving Relays (MRs)

Moving relays (MRs) are designed to be mounted on vehicles such as buses, trains, or cars. These relays move with their host, providing continuous connectivity to users within or around the vehicle as it moves through the network. Moving relays are particularly beneficial in high-speed scenarios, such as high-speed trains, where frequent handoffs between base stations can lead to connection drops. By maintaining a stable link with the network, MRs enable seamless communication for onboard users.

These are used in High-speed trains, buses, vehicles in motion. These provide huge help to Reduce handoff frequency for users; provide a consistent connection for high-mobility environments. But Mobility introduces additional challenges related to maintaining a stable link with base stations and managing interference.

Amplify-and-Forward (AF) Relays

In the amplify-and-forward (AF) relaying protocol, the relay node simply amplifies the received signal and retransmits it to the next node or destination. This method is relatively simple and does not require complex signal processing at the relay.

However, the relay also amplifies noise along with the signal, which can degrade the overall signal quality. Simple relay deployments where cost and complexity must be minimized. Low processing complexity; suitable for scenarios where rapid signal forwarding is necessary. The limitation of these relay type is it amplifies noise and interference along with the signal, potentially reducing end-to-end signal quality.

Decode-and-Forward (DF) Relays

Decode-and-forward (DF) relays differ from AF relays in that they decode the received signal, perform error correction, and then re-encode and retransmit the signal to the next node. This process helps reduce noise and improve the quality of the transmitted signal. While DF relays offer improved performance over AF relays, they require more processing power and may introduce additional delays due to the decoding and re-encoding process. High-reliability applications where signal integrity is crucial. Reduces noise propagation and enhances signal quality; effective for improving reliability in multi-hop communication but has higher processing complexity and potential delays compared to AF relays.

Cooperative Relays

Cooperative relaying involves multiple relays working together to transmit data to a destination. This approach leverages diversity techniques to mitigate channel fading and interference, improving overall network reliability and throughput. Cooperative relays can transmit the same data simultaneously or collaborate to enhance signal strength and quality at the destination. This approach is particularly useful in challenging environments where signal fading and interference can degrade communication quality. High-density networks, areas with significant fading or interference. Provides spatial diversity; reduces fading effects and improves network performance. They increases network complexity due to coordination requirements; potential for higher signaling overhead.

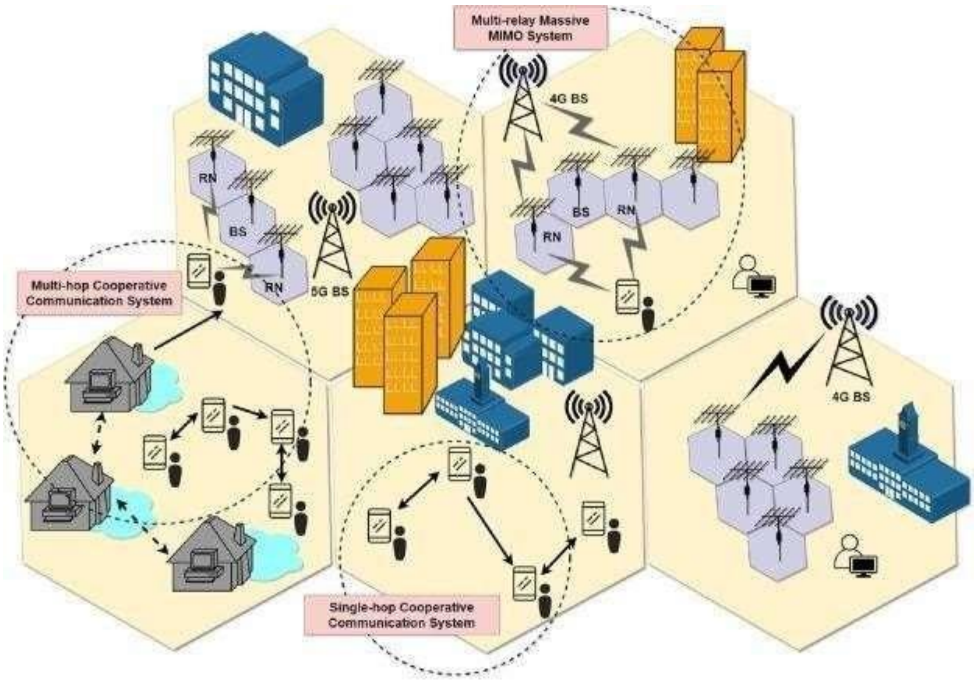
Challenges and Considerations in Relay Deployment

Despite their advantages, deploying relays in wireless networks presents several challenges:

- **Interference Management**: Relays can introduce additional interference into the network, which must be carefully managed to prevent performance degradation.
- **Complexity and Cost**: Implementing relay-based solutions can increase network complexity and incur additional costs for installation and maintenance.
- **Mobility and Reliability**: In high-speed scenarios, maintaining a stable connection between the relay and base stations or user equipment can be challenging due to rapid changes in channel conditions.
- **Power Consumption**: Relays, particularly mobile ones, may require significant power, posing challenges for energy efficiency.

Classification of cooperative communication networks

Cooperative communication has emerged as a pivotal technology in modern wireless networks, addressing challenges such as coverage limitations, reliability, and spectrum efficiency. By leveraging the collaborative efforts of multiple nodes, this approach significantly enhances the performance and robustness of communication systems. The diverse nature of cooperative communication systems has led to the need for systematic classification, enabling researchers and engineers to design solutions tailored to specific network demands. The classification of cooperative communication networks is essential for understanding their structure and operation. This categorization typically considers aspects such as the number of relay nodes involved, the methods employed for forwarding signals, and the types of diversity gains achieved. Each classification criterion sheds light on a unique characteristic of cooperative communication, providing insights into its capabilities and limitations. In this context, cooperative communication can be broadly categorized based on factors such as the network topology, the functionality of relay nodes, and the techniques used to optimize transmission. This classification framework helps streamline the design and implementation of cooperative networks,



5G Cooperative Communication System.

ensuring their adaptability to the dynamic requirements of modern wireless communication systems.

Based On Number of Relays

Cooperative communication networks can be classified based on the number of relay nodes into two main types: **single-relay cooperative communication networks** and **multi- relay cooperative communication networks**. This classification provides insights into the network's complexity, functionality, and performance in various communication scenarios.

4-SIMULATION RESULTS

Bit Error Rate and SNR for different antenna systems: The graph shows the Bit Error Rate (BER) plotted against the Signal-to-Noise Ratio (SNR) for Single-Input Single-Output (SISO), Single-Input Multiple-Output (SIMO/MISO), and Multiple-Input Multiple-Output (MIMO) system

ISSN 2277-2685
IJESR/June. 2025/ Vol-15/Issue-3s/463-476
Mohammed Arif *et. al.,* / International Journal of Engineering & Science Research

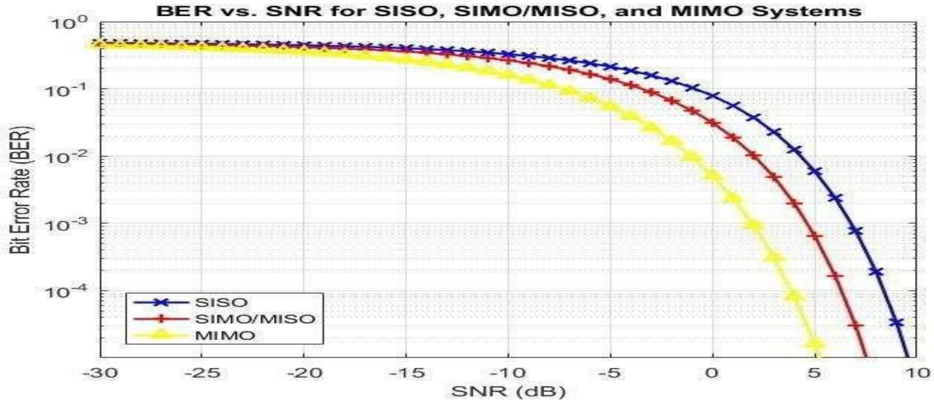


Figure 1 BER vs SNR curve for SISO, SIMO, MISO,MIMO

As the SNR increases, the BER decreases for all systems, indicating improved performance with higher SNR. At an **SNR of -5 dB**, the BER values for different systems show varying performance. **SISO** has the highest BER of **0.16**, indicating poor performance with a single antenna. **SIMO** and **MISO** both have a BER of **0.1**, showing improvement with multiple antennas for reception or transmission. The best performance is seen in **MIMO**, with a BER of **0.03**, highlighting the significant advantage of using multiple antennas for both transmission and reception in combating noise. Overall, **MIMO** outperforms all other configurations at this low SNR.

Table 5.1 BER and SNR values for different systems

SNR in dB		**BER**
-5	**SISO**	0.16
	SIMO	0.1
	MISO	0.1
	MIMO	0.03

SNR for SISO, SIMO, MISO, MIMO

This plot shows the capacity (in bits per second per Hertz, b/s/Hz) as a function of the Signal-to- Noise Ratio (SNR) for different system configurations, including SISO, SIMO, MISO, and MIMO.

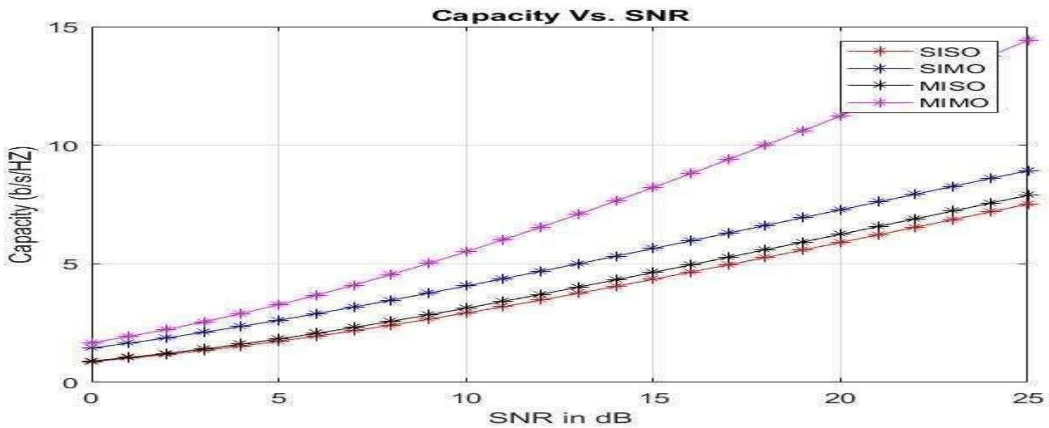


Figure 2 Capacity vs SNR for SISO, SIMO, MISO, MIMO

At an SNR of 15 dB, the data capacity of different communication systems varies. SISO achieves 4.37 bits/Hz, SIMO improves slightly with 4.73 bits/Hz, and MISO further increases the capacity to 5.67 bits/Hz. The best performance is seen in MIMO, with a capacity of 8.25 bits/Hz, due to the use of multiple antennas at both the transmitter and receiver. Overall, MIMO provides the highest capacity, outperforming SISO, SIMO, and MISO at this higher SNR.

Table 5.2 Capacity and SNR values for different systems

		Capacity(bits/Hz)
SNR in dB **15**	**SISO**	4.37
	SIMO	4.73
	MISO	5.67
	MIMO	8.25

Outage Probability of train user versus SINR

This plot illustrates the outage probability as a function of threshold levels for different configurations through simulations.

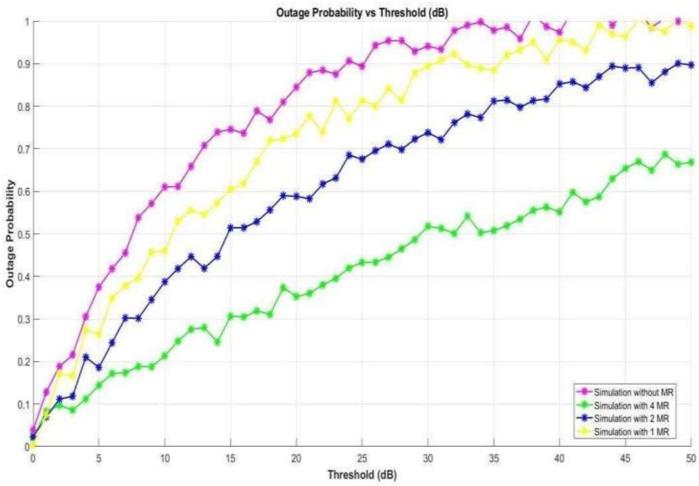


Figure 3 Outage Probability vs Threshold

At an SNR threshold of 20 dB, the Simulation Outage Probability decreases as the number of Maximum Ratio Combining (MR) antennas increases.

Without MR, the outage probability is **0.83**, indicating high susceptibility to outages. With **1 MR**, the probability drops to **0.72**, showing some improvement. Using **2 MR** further reduces the outage probability to **0.581**, and with **4 MR**, it improves significantly to **0.373**, indicating the best performance. In summary, increasing the number of MR antennas enhances system reliability by reducing the outage probability.

Table 5.3 Outage Probability and SNR Threshold values

Simulation Outage Probability				
SNR Threshold	ithout MR	1MR	2MR	4MR
20 dB	0.83	0.72	0.581	0.373

Higher thresholds lead to increased outage probabilities across all configurations.

Coverage Probability of train user versus SINR threshold

The plot compares coverage probability across different thresholds simulation-based results, with and without multiple relay (MR) configurations.

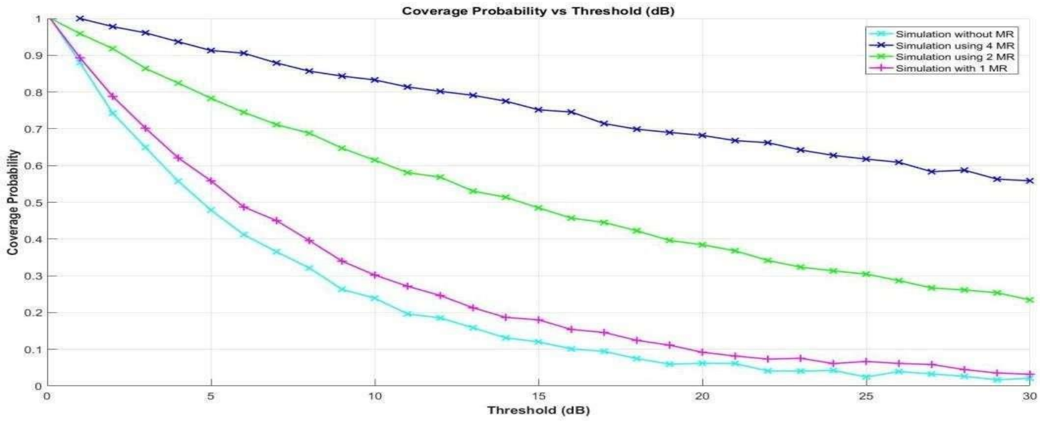


Figure 4 Coverage Probability vs Threshold

Table 5.4 Coverage Probability and SNR Threshold

Simulation coverage Probability				
SNR Threshold	ithout MR	1MR	2MR	4MR
15 dB	0.12	0.179	0.492	0.74

At an SNR threshold of 15, the simulation coverage probability improves significantly with the use of multiple receivers (MR). Without MR, the coverage probability is 0.12. Adding 1 MR increases it to 0.179, while 2 MR boosts it further to 0.492. With 4 MR, the probability reaches 0.74, demonstrating a substantial improvement in coverage as the number of receiver's increases.

Transmission capacity

The graph you provided displays the **Transmission Capacity vs. Threshold (dB)** for various configurations, simulation-based approaches with different numbers of Multiple Relays (MR).

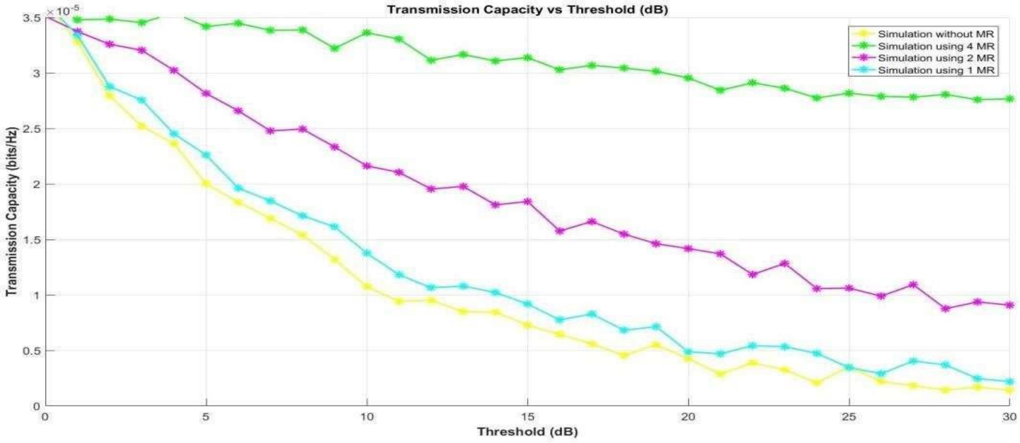


Figure 5 Transmission Capacity vs Threshold

All configurations achieve the highest transmission capacity at lower thresholds, with capacity declining as the threshold increases. Systems with more relays consistently outperform those with fewer or no relays, indicating the strong benefits of using relay-assisted configurations

Table 5.5 Transmission capacity and SNR Threshold

Transmission capacity(bits/Hz)				
SNR Threshold	**ithout MR**	**1MR**	**2MR**	**4MR**
10 dB	1.24	1.39	2.22	3.3

At an SNR threshold of 10, the transmission capacity improves with the use of multiple receivers (MR). Without MR, the capacity is 1.24. Adding 1 MR increases it to 1.39, while 2 MR raises it further to 2.22. With 4 MR, the capacity reaches 3.3, showing a notable enhancement in transmission performance as the number of receiver's increases.

Handoff Probability for base stations

This graph shows the handoff probability as a function of the distance between two base stations.

Handoff probability increases with distance from one BS to another, with systems using multiple relays (1 MR, 2 MR, 4 MR) achieving smoother and more predictable handoff transitions.

Systems without MR show a steeper increase in handoff probability, indicating less reliable handoff behavior over larger distances.

The results suggest that using relays can enhance seamless mobility support in wireless networks.

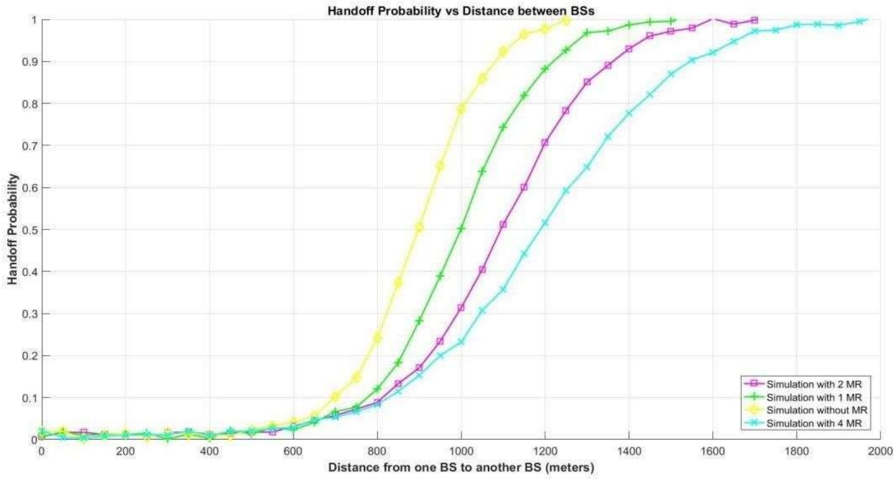


Figure 6 Handoff Probability

The table presents the handoff probability at a fixed distance of 1000 meters for different configurations involving multi-relays (MRs). The readings indicate that without any relay, the handoff probability is high at 0.763, suggesting frequent interruptions in connectivity as users move between base stations. Introducing a single relay reduces this probability significantly to 0.5, indicating an improvement in network continuity. Adding two relays further decreases the handoff probability to 0.306, demonstrating enhanced coverage and fewer handoff events.

Finally, with four relays, the probability is minimized to 0.24, showcasing the best performance in maintaining seamless connectivity.

5-CONCLUSION

This project presents a simulation-based evaluation of wireless communication systems, focusing on SISO, SIMO, MISO, and MIMO configurations. Key performance metrics analyzed include Bit Error Rate (BER), capacity, throughput, coverage probability, outage probability, and handoff probability. Among all systems, MIMO consistently outperformed others due to spatial multiplexing and diversity gains. At -5 dB, MIMO achieved a BER of 0.03, compared to 0.16 (SISO), 0.1 (SIMO), and 0.1 (MISO). At 15 dB, MIMO reached the highest capacity of 8.25 bits/Hz, outperforming SISO (4.37), SIMO (4.73), and MISO (5.67).

Increasing the number of receivers also enhanced performance. At 10 dB, capacity rose from 1.24 (no MR) to 3.3 (with 4 MR), and coverage probability at 15 dB increased from 0.12 to 0.74. At 20 dB, outage probability dropped from 0.83 (no MR) to 0.373 (4 MR). Cooperative relaying further boosted performance, improving coverage, throughput, and reducing outages. The handoff probability at 1000 meters decreased from 0.763 (no relays) to 0.24 (4 relays), ensuring smoother connectivity. Overall, MIMO and relay-based systems significantly enhance wireless communication performance in terms of reliability, efficiency, and coverage

REFRENCES

1. Munjal, Meenakshi & Singh, N.. (2019). Group mobility by cooperative communication for high speed railway. Wireless Networks. 25. 10.1007/s11276-018-01923-2.
2. S. Scott, J. Leinonen, P. Pirinen, J. Vihriala, V. Van Phan and M. Latva-aho, "A Cooperative Moving Relay Node System Deployment in a High Speed

Train," 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), Dresden, Germany, 2013, pp. 1-5, doi: 10.1109/VTCSpring.2013.6691818.

3. H. Ghazzai, T. Bouchoucha, A. Alsharoa, E. Yaacoub, M. -S. Alouini and T. Y. Al-Naffouri, "Transmit Power Minimization and Base Station Planning for High-Speed Trains With Multiple Moving Relays in OFDMA Systems," in IEEE Transactions on Vehicular Technology, vol. 66, no. 1, pp. 175-187, Jan. 2017, doi: 10.1109/TVT.2016.2542344.

4. X. Ge, H. Cheng, G. Mao, Y. Yang and S. Tu, "Vehicular Communications for 5G Cooperative Small-Cell Networks," in IEEE Transactions on Vehicular Technology, vol. 65, no. 10, pp. 7882-7894, Oct. 2016, doi: 10.1109/TVT.2016.2539285.

5. J. Zhang, H. Du, P. Zhang, J. Cheng and L. Yang, "Performance Analysis of 5G Mobile Relay Systems for High-Speed Trains," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 12, pp. 2760-2772, Dec. 2020, doi: 10.1109/JSAC.2020.3005492.

6. T. L. Marzetta, "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas," in IEEE Transactions on Wireless Communications, vol. 9, no. 11, pp. 3590-3600, November 2010, doi: 10.1109/TWC.2010.092810.091092.

7. Bala, Diponkor & Waliullah, G. M. & Hena, Mst & Abdullah, Md & Hossain, Mohammad. (2020). Study the Performance of Capacity for SISO, SIMO, MISO and MIMO in Wireless Communication. 8. 1-6.

8. Fernández-Berrueta, Nerea & Goya, Jon & Arrizabalaga, Jaione & Moya, Iker & Mendizabal, Jaizki. (2021). Railway Wireless Communications Channel Characterization. Applied Sciences. 12. 345. 10.3390/app12010345.

9. Khan and A. Jamalipour, "Moving Relays in Heterogeneous Cellular Networks—A Coverage Performance Analysis," in IEEE Transactions on Vehicular Technology, vol. 65, no. 8, pp. 6128-6135, Aug. 2016, doi: 10.1109/TVT.2015.2478775.

10. J. Calle-Sanchez, E. Martinez-de-Rioja, M. Molina-Garcia and J. I. Alonso, "Performance of LTE Mobile Relay Node Usage for Uplink Access in High Speed Railway Scenarios," 2015 IEEE 81st Vehicular Technology Conference (VTC Spring), Glasgow, UK, 2015, pp. 1-5, doi: 10.1109/VTCSpring.2015.7146012.

11. R. Knopp and P. A. Humblet, "Information capacity and power control in single-cell multiuser communications," in Proc. IEEE Int. Conf. Commun., Seattle, WA, Jun. 1995, pp. 331– 335, 1995.

12. R. U. Nabar, H. B¨olcskei, and F.W. Kneub¨uhler, "Fading relay channels: performance limits and space-time signal design," IEEE J. Sel. Areas Commun., vol. 22, no. 6, pp. 1099–1109,Aug. 2004

13. E.-H. Shin and D. Kim, "On the capacity growth of opportunistic single-relay selection using quality-based feedback in fixed-gain amplify-and-forward relaying," IEEE Commun. Lett., vol. 13, no. 11, pp. 835–837, Nov. 2009.

14. X. Zhang, A. Ghrayeb, and M. Hasna, "Network coding and relay assignment schemes for systems with multiple two-way relay channels," in Proc. 2010 IEEE ICC.

15. B. Rankov and A. Wittneben, "Spectral efficient protocols for halfduplex fading relay channels," IEEE J. Sel. Areas Commun., vol. 25, no. 2, pp. 379–389, Feb. 2007.

16. F. Hu, Z. Ling, T. Liu, H. Li and B. Ai, "Wireless Perception of High-Speed Railway Communication: Challenges, Framework, and Future Directions," in IEEE Wireless Communications, vol. 31, no. 4, pp. 284-292, August 2024, doi: 10.1109/MWC.022.2200630.

17. Y. Sun, C. -Y. Lee, J. -m. Jo, J. -h. Lee and Y. -J. Han, "Study on the effectiveness of high- speed railway communication and signaling system based on 4G LTE technology," 2013 13th International Conference on Control, Automation and Systems (ICCAS 2013), Gwangju, Korea (South), 2013, pp. 402-406, doi: 10.1109/ICCAS.2013.6703988.

18. Atsushi Kanno, Pham Tien Dat, Naokatsu Yamamoto, Tetsuya Kawanishi, Nagateru Iwasawa, Nariya Iwaki, Kazuki Nakamura, Kunihiro Kawasaki, Naoki Kanada, Naruto Yonemoto, Yosuke Sato, Masato Fujii, Katsuya Yanatori, Nobuhiko Shibagaki, and Kenichi Kashima, "High-Speed Railway Communication System Using Linear- Cell-Based Radio-Over-Fiber Network and Its Field Trial in 90-GHz Bands," J. Lightwave Technol. 38, 112-122 (2020)

19. Xuying Chen, Wei Chen, Xiao Gong, Bo Ai, Ian Wassell, Wireless channel estimation for high-speed rail communications: Challenges, solutions and future directions,High-speed Railway,Volume 1, Issue 1,2023.

20. Guo, W., Qureshi, N. M. F., Siddiqui, I. F., & Shin, D. R. (2022). Cooperative Communication Resource Allocation Strategies for 5G and Beyond Networks: A Review of Architecture, Challenges and Opportunities. Joural of King Saud University - Computer and Information Sciences, 34(10), 8054-8078.

21. Jiayi Zhang, Hongyang Du, Peng Zhang, Julian Cheng, and Liang Yang(2020) “Performance Analysis of 5G Mobile Relay Systems for High-Speed .

22. Jingjing Yan1, Dapeng Li1, Youyun Xu1 and Jianping Chen3(2019) “Performance Evaluation of LTE-R System with Mobile Relay for Differentiated Services”.

23. Bharathy R, Vannilavan P, Rajasekar K, Vignesh R, Vasantha Kumar S(2018)“Network Coding as a Performance Booster for Multi-hop Transfer of Data” in IJSIET volume 3 issue 3.

24. Ana Gonzalez-Plaza , Juan Moreno Iñaki Val , Aitor Arriola , Pedro M Rodriguez (2017). “5G communications in high speed and metropolitan railways”.

Li-Wen Chen and Yu-Lun Huang (2018) “An Enhanced Handover Scheme adopting Mobile Relays in a LTE-A Network for High-Speed Movements”.