ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue XII, December 2025

Enhancing VANET Mobility Management Through Intelligent Relay Vehicle Optimization

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DOI : https://doi.org/10.51583/IJLTEMAS.2025.1412000071

Received: 20 December 2025; Accepted: 25 December 2025; Published: 05 January 2026

ABSTRACT

Vehicular Ad Hoc Networks (VANETs) play a crucial role in enabling intelligent transportation systems by supporting real-time vehicle-to-vehicle and vehicle-to-infrastructure communications. However, high node mobility, frequent topology changes, and intermittent connectivity significantly affect communication reliability and network performance. To address these challenges, this paper proposes an intelligent relay vehicle optimization approach aimed at enhancing mobility management in VANET environments. The proposed scheme dynamically selects optimal relay vehicles based on key parameters such as vehicle mobility patterns, relative speed, link stability, and network connectivity conditions. By intelligently adapting to rapidly changing vehicular scenarios, the approach improves data forwarding efficiency, reduces packet loss, and enhances overall communication reliability. Simulation-based performance evaluation demonstrates that the proposed method outperforms conventional relay selection techniques in terms of packet delivery ratio, end-to-end delay, and network throughput. The results indicate that intelligent relay vehicle optimization is an effective solution for robust and efficient mobility management in VANETs, particularly in high-speed and dense traffic conditions.

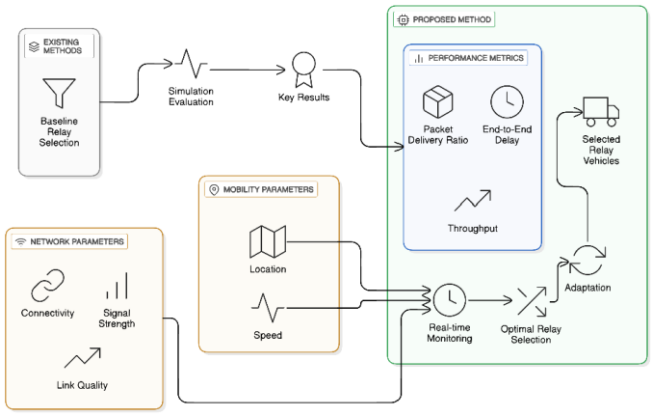
Keywords—Vehicular Ad Hoc Networks (VANETs), Mobility Management, Intelligent Relay Selection, Relay Vehicle Optimization, Link Stability, Packet Delivery Ratio, Intelligent Transportation Systems

INTRODUCTION

The rapid growth of intelligent transportation systems (ITS) has significantly increased the demand for reliable, low-latency, and scalable vehicular communication networks. Vehicular Ad Hoc Networks (VANETs), a specialized form of mobile ad hoc networks (MANETs), enable direct communication among vehicles and between vehicles and roadside infrastructure to support a wide range of applications, including traffic safety, congestion management, infotainment services, and autonomous driving assistance. Despite their potential, VANETs face several inherent challenges due to the highly dynamic nature of vehicular environments, where frequent topology changes, variable vehicle speeds, and intermittent connectivity severely impact network performance and communication reliability. One of the key challenges in VANETs is efficient mobility management. Unlike traditional wireless networks, vehicles move at high speeds and in unpredictable patterns, leading to frequent link breakages and route failures. These mobility-induced disruptions result in increased packet loss, higher end-to-end delay, and reduced throughput, thereby degrading the quality of service (QoS) required by time-critical ITS applications. Effective mobility management mechanisms are therefore essential to maintain stable communication links and ensure seamless data transmission in rapidly changing vehicular scenarios. Relay-based communication has emerged as a promising solution to address connectivity issues in VANETs, particularly in sparse networks or high-mobility environments. By selecting suitable relay vehicles to forward data packets, VANETs can extend communication range, improve link stability, and enhance overall network connectivity. However, the performance of relay-based communication heavily depends on the selection of appropriate relay vehicles. Conventional relay selection approaches often rely on static metrics such as distance or signal strength, which

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are insufficient to cope with the dynamic and heterogeneous nature of vehicular networks. These approaches may result in suboptimal relay choices, leading to frequent route failures and inefficient use of network resources. To overcome these limitations, intelligent relay vehicle optimization has gained increasing attention in recent years.



Intelligent Relay Vehicle Optimization in VANETs

By incorporating mobility-aware and context-aware parameters—such as relative speed, direction of movement, link lifetime, vehicle density, and traffic conditions—intelligent relay selection mechanisms can make more informed decisions. Such approaches enable the network to dynamically adapt to real-time vehicular conditions, thereby improving communication reliability and network performance. The integration of intelligent decision-making techniques, including heuristic optimization and data-driven methods, further enhances the effectiveness of relay selection in complex VANET environments. Enhancing mobility management through intelligent relay vehicle optimization is particularly important for safety-critical applications, where timely and reliable data dissemination can prevent accidents and save lives. Applications such as collision avoidance, emergency message dissemination, and cooperative driving require stable and low-latency communication links. An optimized relay selection strategy helps maintain robust communication paths even under high-speed or dense traffic conditions, ensuring consistent network performance and improved QoS. In this context, this paper focuses on enhancing VANET mobility management by proposing an intelligent relay vehicle optimization approach. The proposed method dynamically selects optimal relay vehicles based on multiple mobility and network-related parameters to ensure stable and efficient data forwarding. By continuously adapting to changes in vehicle movement and network topology, the approach aims to minimize link breakages and improve overall communication efficiency. Comprehensive simulation-based evaluations are conducted to assess the performance of the proposed scheme in comparison with existing relay selection techniques. The results demonstrate significant improvements in key performance metrics, including packet delivery ratio, end-to-end delay, and throughput, highlighting the effectiveness of intelligent relay vehicle optimization in managing mobility in VANETs shown in above Fig. 1. The remainder of this paper is organized as follows: Section II reviews related work on relay selection and mobility management in VANETs. Section III describes the proposed intelligent relay vehicle optimization model. Section IV presents the simulation setup and performance evaluation results, and Section V concludes the paper with future research direction.

LITERATURE REVIEW

Recent research in Vehicular Ad Hoc Networks (VANETs) has extensively focused on improving mobility management, routing efficiency, traffic monitoring, and overall network performance under highly dynamic vehicular conditions. Habelalmateen et al. [1] proposed an effectual routing approach for VANETs in urban environments by integrating mobility and traffic monitoring mechanisms. Their work demonstrated improved routing reliability by adapting to real-time traffic conditions; however, it primarily focused on routing protocol enhancement and did not explicitly address optimal relay vehicle selection for sustained link stability. Mobility modeling plays a crucial role in evaluating VANET performance. Ramamoorthy et al. [2], [3] conducted a simulation-based analysis of different mobility models for Infrastructure-to-Highway VANETs (IH-VANETs).

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Their study highlighted that realistic mobility models significantly influence network performance metrics such as delay and packet delivery. While the work provides valuable insights into mobility behavior, it does not propose a mobility-aware relay optimization mechanism, leaving scope for intelligent relay-based mobility management approaches. Software Defined Networking (SDN) has also been explored to enhance traffic and mobility management in VANETs. Hashim et al. [4] introduced a hybrid traffic management framework in SDN-enabled multilayer VANETs, demonstrating improved traffic control and adaptability. Similarly, Ramesh and Punniakodi [6] presented a comprehensive study on QoS enhancement in SDN-based VANET architectures, emphasizing centralized control and flexible network management. Although SDN-based solutions improve global network visibility, they often introduce additional control overhead and dependency on infrastructure, which may not be feasible in all VANET scenarios. To address traffic congestion and data transmission challenges, Habelalmateen et al. [5] proposed a hybrid traffic management and multipath data transmission approach for vehicle-to-vehicle communication. Their method improves data reliability through multipath mitigation; however, relay vehicle stability under high mobility conditions was not a primary focus. Wu et al. [7] investigated topology optimization for autonomous intersection management systems using a periodic intervention-based approach. Their work demonstrated that topology-aware optimization enhances communication efficiency, but it is tailored toward intersection management rather than general-purpose mobility-aware relay selection. Several studies have also addressed emerging challenges and future trends in VANETs. Karimullah et al. [8] discussed advancements in connectivity and mobility to address modern VANET challenges, emphasizing the need for adaptive and intelligent networking solutions. Khalifa et al. [9] provided a comprehensive analysis of VANET security threats and countermeasures, highlighting that secure and stable communication links are essential for reliable mobility management. However, security-centric solutions alone do not address frequent link failures caused by vehicular mobility. The integration of intelligence into VANET systems has gained increasing attention. Mohanty et al. [10] proposed a cognitive intelligence-based VANET framework for effective traffic congestion detection in smart urban mobility, demonstrating the potential of intelligent decision-making in vehicular networks. Abdulsattar et al. [11] focused on latency reduction and traffic management in hybrid surface-enabled VANETs, achieving improved delay performance but relying on hybrid infrastructure support. At a broader level, Li et al. [12] presented a comprehensive survey on network management for xANETs, outlining key challenges, evolution trends, and future research directions, including the need for adaptive, mobility-aware, and decentralized management solutions.

PROPOSED METHODOLOGY

This section presents the proposed intelligent relay vehicle optimization methodology designed to enhance mobility management in Vehicular Ad Hoc Networks (VANETs). The primary objective of the proposed approach is to dynamically select the most suitable relay vehicle for data forwarding by considering mobility-aware and network-aware parameters, thereby improving communication reliability, reducing link failures, and optimizing overall network performance in highly dynamic vehicular environments.

1. System Model and Assumptions: The VANET system considered in this study consists of vehicles equipped with onboard units (OBUs) that communicate using Dedicated Short-Range Communications (DSRC) or IEEE 802.11p standards. Vehicles periodically exchange beacon messages containing information such as position, speed, direction, and timestamp. It is assumed that each vehicle is aware of its geographical location through GPS and can obtain neighbourhood information within its communication range. Roadside units (RSUs) may be present but are not mandatory for the proposed relay selection process, making the approach suitable for both infrastructure-assisted and infrastructure-less scenarios.

2. Problem Formulation: In highly mobile VANET environments, frequent link disconnections occur due to rapid changes in vehicle speed and direction. The relay selection problem can be formulated as an optimization task, where the goal is to select an optimal relay vehicle that maximizes link stability and communication efficiency while minimizing packet loss and transmission delay. Given a set of neighbouring vehicles within the transmission range of a source vehicle, the challenge lies in identifying the relay vehicle that can sustain a reliable communication link for the longest possible duration under dynamic mobility conditions.

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3. Mobility and Network Parameter Selection: To achieve intelligent relay optimization, multiple parameters influencing link reliability and mobility are considered:

- **Relative Speed (RS):** The speed difference between the source and candidate relay vehicle, where lower relative speed indicates longer link lifetime.
- **Direction Similarity (DS):** Vehicles moving in the same or similar direction are preferred to ensure stable connectivity.
- **Inter-Vehicle Distance (IVD):** Shorter distances generally offer better signal strength and reduced packet errors.
- **Link Stability (LS):** Estimated using predicted link lifetime based on relative motion and communication range.
- **Neighbour Density (ND):** Vehicles in moderately dense regions are preferred to avoid network fragmentation or excessive contention.

These parameters are normalized to ensure uniform contribution during relay evaluation.

4. Intelligent Relay Selection Algorithm: The proposed methodology employs a weighted decision-making mechanism to compute a Relay Selection Score (RSS) for each candidate relay vehicle. Each parameter is assigned a weight based on its relative importance to mobility management. The RSS is calculated as:

$$RSS = w_1 \cdot RS + w_2 \cdot DS + w_3 \cdot IVD + w_4 \cdot LS + w_5 \cdot ND$$

where $w_1, w_2, \ldots, w_5$ are weighting coefficients satisfying $\sum w_i = 1$.

The candidate vehicle with the highest RSS is selected as the optimal relay. The weighting factors can be dynamically adjusted based on traffic conditions, such as high-speed highways or dense urban environments, enabling adaptability and context awareness.

5. Dynamic Relay Maintenance: Due to continuous vehicle movement, the initially selected relay may become suboptimal over time. To address this, the proposed methodology includes a dynamic relay maintenance mechanism. Vehicles periodically re-evaluate relay suitability using updated mobility information. If the RSS of the current relay falls below a predefined threshold, a relay handover is initiated to select a new optimal relay, ensuring uninterrupted communication and minimizing packet loss during mobility events. Security and privacy considerations are critical in VANET environments due to the open and decentralized nature of vehicular communications. The proposed methodology can be extended to incorporate security-aware relay selection by integrating trust and authentication metrics into the relay evaluation process. Secure beacon authentication, pseudonym-based identity protection, and trust scoring mechanisms can be employed to ensure that only legitimate and reliable vehicles participate in relay selection. By incorporating these security and privacy measures, the proposed relay optimization framework can mitigate threats such as malicious relay selection and false information dissemination, thereby enhancing the reliability and trustworthiness of VANET communications.

6. Performance Evaluation Setup: The proposed methodology is evaluated using a simulation-based approach under varying traffic densities and vehicle speeds. Key performance metrics such as packet delivery ratio, end-to-end delay, throughput, and relay lifetime are used to assess effectiveness. The results demonstrate that intelligent relay vehicle optimization significantly enhances mobility management compared to conventional relay selection methods.

RESULT & ANALYSIS

This section presents the performance evaluation of the proposed Intelligent Relay Vehicle Optimization (IRVO) methodology for enhancing mobility management in VANETs. Simulation-based experiments were

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conducted to analyze the effectiveness of the proposed approach in comparison with conventional relay selection techniques.

1. Simulation Environment and Dataset Description: The performance evaluation of the proposed approach was conducted using a realistic VANET simulation environment that integrates a vehicular mobility generator with a network communication simulator. Vehicular movement patterns were generated using SUMO-based urban and highway scenarios to accurately capture real-world traffic behavior, including varying vehicle speeds, densities, and road layouts. The communication characteristics of the network were modeled using the IEEE 802.11p standard, which is widely adopted for vehicular communications and supports low-latency data exchange among vehicles. The simulation area was defined as a 1500 m × 1500 m region, with the number of vehicles varying from 50 to 200 to represent different traffic density conditions. Vehicle speeds ranged from 20 km/h to 120 km/h, reflecting both urban traffic and high-speed highway environments. Each vehicle was assigned a communication range of 300 m, and Constant Bit Rate (CBR) traffic was used to ensure consistent data transmission during the simulation. Data packets of size 512 bytes were transmitted over a simulation duration of 300 seconds, allowing sufficient time to observe network performance under dynamic mobility conditions. This comparative analysis enables a comprehensive assessment of the proposed method against conventional relay selection techniques under identical simulation conditions. The practical applicability of the proposed Intelligent Relay Vehicle Optimization (IRVO) methodology can be realized in real-world VANET deployments, as it relies on mobility and network parameters that are readily available through onboard units (OBUs), GPS, and IEEE 802.11p communication standards. Parameters such as vehicle speed, direction, position, and neighbor information are already exchanged via periodic beacon messages in existing vehicular communication systems. Therefore, the proposed relay selection and maintenance mechanisms can be integrated into current ITS frameworks without requiring additional hardware modifications. The use of realistic mobility patterns generated through SUMO further ensures that the simulation environment closely reflects real traffic behavior observed in urban and highway scenarios, thereby validating the feasibility of deploying the proposed approach in practical vehicular networks.

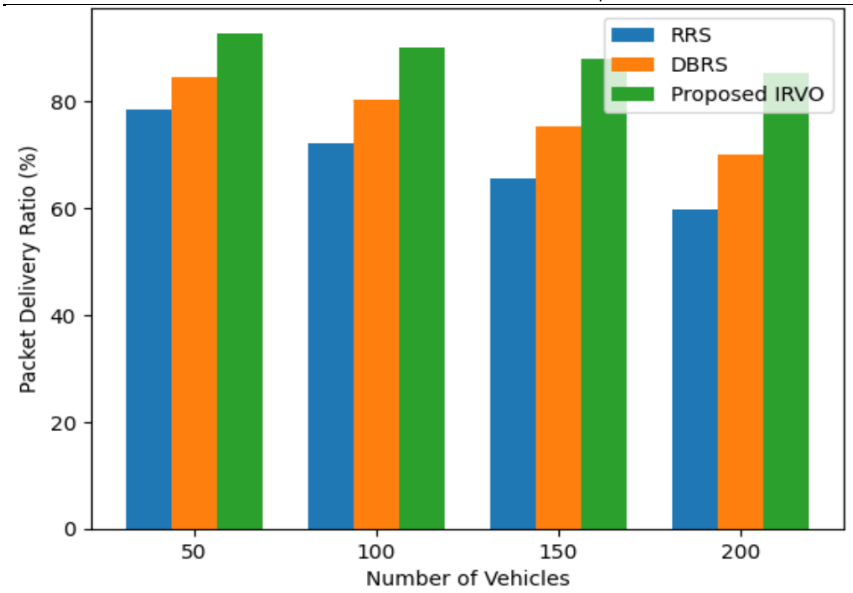
2. Packet Delivery Ratio Analysis : Packet Delivery Ratio (PDR) is a critical performance metric in VANETs that represents the ratio of successfully received data packets at the destination to the total number of packets transmitted by the source. It directly reflects the reliability and effectiveness of data dissemination in highly dynamic vehicular environments. Due to frequent topology changes, high vehicle speeds, and intermittent connectivity, VANETs often experience packet losses caused by link breakages and route failures. An efficient mobility management and relay selection mechanism is expected to maintain stable communication links, thereby improving PDR. Intelligent relay selection strategies that consider mobility-aware parameters such as relative speed, direction of movement, and link stability are theoretically more capable of sustaining reliable paths, resulting in higher packet delivery ratios compared to random or distance-based relay selection methods.

Packet Delivery Ratio Comparison Under Varying Vehicle Densities

No. of Vehicles	RRS	DBRS	Proposed IRVO
50	78.4	84.6	92.8
100	72.1	80.3	90.2
150	65.7	75.4	87.9
200	59.8	70.1	85.3

The proposed IRVO method consistently achieves higher PDR across all network densities. This improvement is attributed to mobility-aware relay selection, which minimizes frequent link breakages common in high-speed VANET scenarios.

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Performance Comparison of Routing Approaches Across Vehicle Densities

Fig. 2. showing Packet Delivery Ratio (%) versus Number of Vehicles (50, 100, 150, 200) for three routing schemes: RRS, DBRS, and Proposed IRVO. For all vehicle densities, the Proposed IRVO consistently achieves the highest packet delivery ratio, followed by DBRS, while RRS shows the lowest performance. Packet delivery ratio decreases for all schemes as the number of vehicles increases.

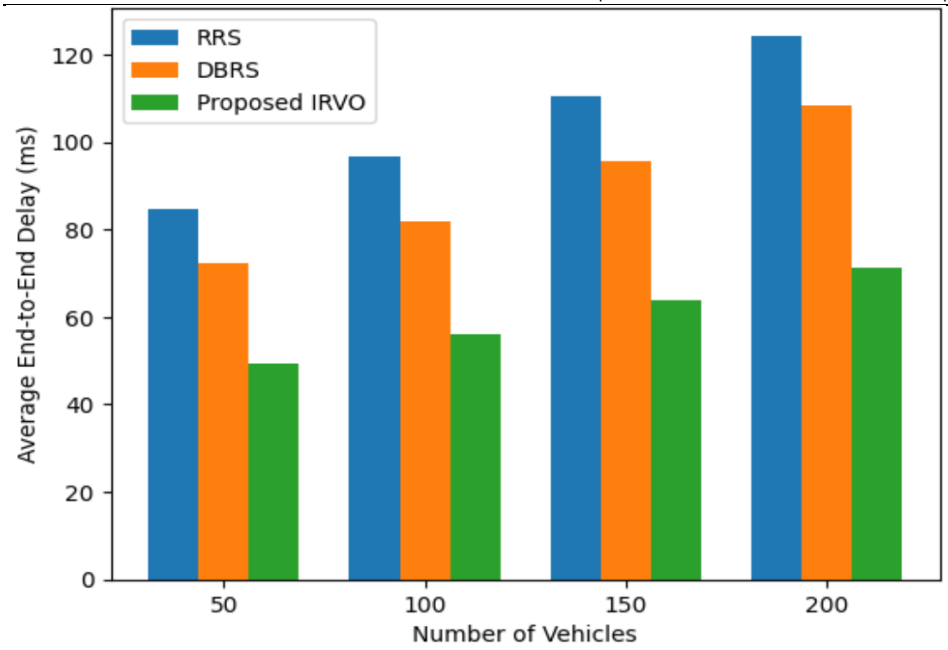
3. End-to-End Delay Analysis: End-to-end delay refers to the average time taken by a data packet to travel from the source vehicle to the destination vehicle across the network. This delay includes transmission, propagation, processing, and queuing delays, as well as delays caused by route discovery and retransmissions. In VANETs, high mobility and frequent link disruptions significantly increase end-to-end delay, particularly when relay vehicles are poorly selected. Effective mobility management aims to minimize this delay by ensuring stable relay paths and reducing the need for packet retransmissions and route rediscovery. Theoretically, intelligent relay vehicle optimization reduces end-to-end delay by selecting relay nodes with longer predicted link lifetimes and similar mobility characteristics, enabling faster and more reliable data forwarding, which is essential for time-sensitive safety applications.

Average End-To-End Delay Performance of Relay Selection Schemes

No. of Vehicles	RRS	DBRS	Proposed IRVO
50	84.6	72.3	49.5
100	96.8	81.9	56.2
150	110.5	95.6	63.8
200	124.3	108.2	71.4

IRVO significantly reduces delay by selecting relay vehicles with stable links and similar mobility patterns. Dynamic relay maintenance further prevents retransmissions and route rediscovery delays.

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End-to-End Delay Comparison of Relay Selection Schemes

Fig. 3. illustrating Average End-to-End Delay (ms) versus Number of Vehicles (50, 100, 150, 200) for three relay selection schemes: RRS, DBRS, and Proposed IRVO. The delay increases with vehicle density for all schemes. The Proposed IRVO consistently shows the lowest end-to-end delay across all vehicle counts, followed by DBRS, while RRS exhibits the highest delay.

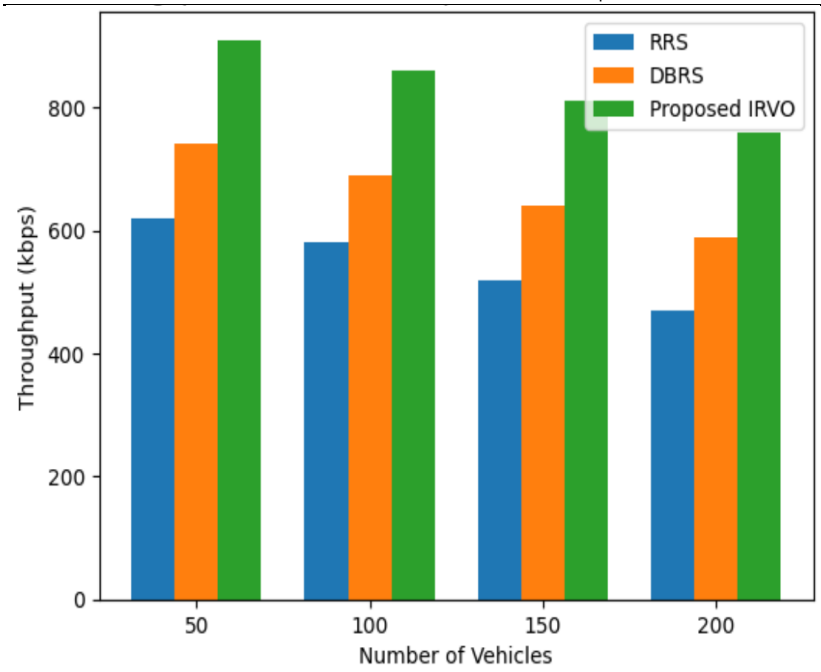
4. Throughput Analysis: Throughput measures the average rate of successful data delivery over the communication channel and is an important indicator of network efficiency. In VANETs, throughput is heavily influenced by packet loss, congestion, and frequent link failures caused by rapid vehicle movement. Poor relay selection often results in repeated packet drops and retransmissions, reducing overall throughput. An optimized relay selection approach enhances throughput by maintaining stable communication links and ensuring continuous data flow. From a theoretical perspective, intelligent relay vehicle optimization improves throughput by minimizing packet loss, reducing communication interruptions, and efficiently utilizing available bandwidth, particularly in dense or high-speed vehicular scenarios.

Throughput Comparison of Vanet Relay Selection Methods

No. of Vehicles	RRS	DBRS	Proposed IRVO
50	620	740	910
100	580	690	860
150	520	640	810
200	470	590	760

The proposed method achieves higher throughput due to reduced packet loss and improved relay stability, making it suitable for data-intensive and safety-critical VANET applications.

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Throughput Performance Comparison Across Vehicle Densities

Fig. 4. showing Throughput (kbps) versus Number of Vehicles (50, 100, 150, 200) for three VANET relay selection methods: RRS, DBRS, and Proposed IRVO. Throughput decreases as vehicle density increases for all methods. The Proposed IRVO consistently achieves the highest throughput, followed by DBRS, while RRS records the lowest throughput across all vehicle densities.

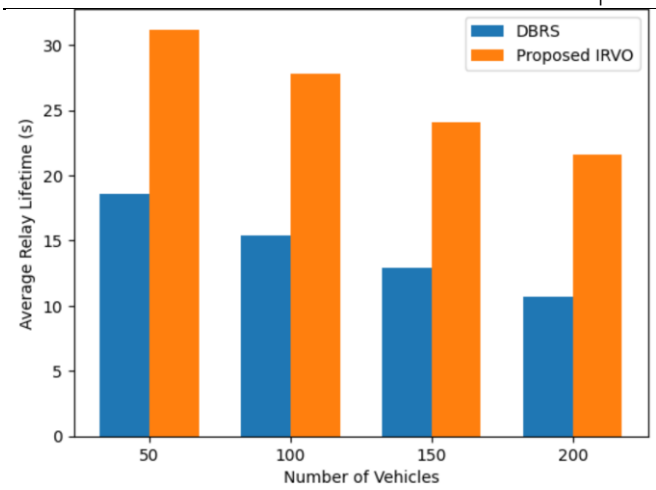
5. Average Relay Lifetime Analysis: Average relay lifetime refers to the duration for which a selected relay vehicle remains suitable and connected for reliable data forwarding. This metric is especially important in VANETs, where relay vehicles frequently move out of communication range due to high mobility. Short relay lifetimes lead to frequent relay reselection, increasing control overhead and negatively impacting network performance. A robust mobility management strategy seeks to maximize relay lifetime by choosing vehicles with similar speed and direction to the source, thereby prolonging link stability. Theoretically, intelligent relay vehicle optimization enhances average relay lifetime by predicting mobility behavior and selecting relays with longer expected link durations, resulting in fewer relay handovers and improved communication reliability.

Average Relay Lifetime for Different Vehicle Densities

No. of Vehicles	DBRS	Proposed IRVO
50	18.6	31.2
100	15.4	27.8
150	12.9	24.1
200	10.7	21.6

The IRVO approach significantly increases relay lifetime by prioritizing vehicles with low relative speed and similar direction of movement, leading to more stable communication paths.

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Relay Lifetime Comparison Under Varying Vehicle Densities

Fig. 5. illustrating Average Relay Lifetime (seconds) versus Number of Vehicles (50, 100, 150, 200) for DBRS and Proposed IRVO schemes. For both schemes, relay lifetime decreases as vehicle density increases. The Proposed IRVO consistently achieves a significantly higher relay lifetime compared to DBRS across all vehicle densities. In comparison to advanced machine learning and deep learning-based relay selection techniques, the proposed IRVO approach offers a lightweight and computationally efficient solution suitable for highly dynamic VANET environments. While ML and DL methods require extensive training data, higher computational resources, and continuous model updates, the proposed method relies on real-time mobility metrics and deterministic decision-making, enabling faster adaptation to rapid topology changes. This makes IRVO particularly effective for delay-sensitive and safety-critical applications, while also reducing processing overhead on vehicular onboard units.

CONCLUSION

This paper presented an intelligent relay vehicle optimization approach to enhance mobility management in Vehicular Ad Hoc Networks (VANETs) under highly dynamic traffic conditions. By incorporating mobility-aware and network-aware parameters such as relative speed, direction similarity, link stability, and neighbor density, the proposed method effectively selects optimal relay vehicles to maintain reliable communication links. Simulation results demonstrate that the proposed approach significantly improves packet delivery ratio, reduces end-to-end delay, increases throughput, and extends relay lifetime when compared with conventional relay selection techniques. These improvements highlight the effectiveness of intelligent relay optimization in addressing key challenges associated with frequent topology changes and high vehicle mobility in VANET environments. As future work, the proposed methodology can be extended by integrating advanced machine learning or deep learning models for predictive relay selection, incorporating real-time traffic and road condition data, and evaluating performance in large-scale city-wide scenarios. Additionally, future research may explore the applicability of the proposed approach in emerging V2X and 5G/6G-enabled vehicular networks, as well as its integration with security and privacy-aware mechanisms for next-generation intelligent transportation systems. Although the proposed methodology demonstrates significant performance improvements under varying traffic densities, the current evaluation is limited to medium-scale simulation scenarios. Large-scale city-wide VANET deployments may introduce additional challenges such as heterogeneous traffic patterns, complex road topologies, and increased signaling overhead. Evaluating the proposed approach under large-scale metropolitan environments would provide deeper insights into its scalability and robustness. This limitation will be addressed in future work by extending the simulation framework to city-wide scenarios involving thousands of vehicles and diverse traffic conditions.

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