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A STABILITY AND SECURITY ENHANCED ROUTING AND CLUSTERING ALGORITHM FOR VANET

Dr. Iswarya B,
Department of BCA, Sree Saraswathi Thyagaraja College,iswaryabalu@gamil.com
Dr. Sridevi S, Department of AI & ML, NGM

Abstract

Vehicular Ad Hoc Networks (VANETs) face significant challenges due to frequent communication link disruptions caused by high vehicular mobility. Addressing these issues, this paper introduces a Dynamic and Reliable Routing Algorithm (DRRA) designed to enhance clustering stability and improve security. DRRA employs a novel Cluster Head (CH) election strategy based on relative mobility metrics to ensure reduced re-clustering and seamless communication. The algorithm integrates robust mechanisms to mitigate Sybil and Denial-of-Service (DoS) attacks, ensuring secure and efficient data dissemination. Simulation experiments conducted using NS-3.25 and SUMO validate the performance of DRRA, demonstrating significant improvements in metrics such as CH lifetime, network throughput, and packet delivery ratio compared to existing schemes. These results highlight DRRA's potential to enhance the reliability and security of VANETs, particularly in high-mobility and dense traffic scenarios, while addressing key limitations of current methodologies.

Keywords

VANET, Clustering, Routing, Stability & Security, Throughput

1. Introduction

Vehicular Ad Hoc Networks (VANETs) are a specialized subset of Mobile Ad Hoc Networks (MANETs) that enable direct communication between vehicles (vehicle-to-vehicle, V2V) and between vehicles and infrastructure (vehicle-to-infrastructure, V2I). The primary aim of VANETs is to improve road safety, manage traffic efficiently, and provide infotainment services to passengers [1]. These networks leverage advanced communication technologies such as Dedicated Short Range Communication (DSRC), Long Term Evolution (LTE), and sensor systems integrated into vehicles.

The VANET architecture consists of three main components: vehicles, roadside units (RSUs), and central management systems (CMS). Vehicles are equipped with On-Board Units (OBUs) that facilitate communication and sensors that collect real-time data. RSUs serve as fixed infrastructure elements that connect vehicles to external networks and enable vehicle-to-infrastructure communication. CMS are cloud-based or server-based systems that aggregate, process, and analyze traffic and vehicular data for decision-making and optimization [2]. These components collaborate to create a dynamic and robust communication environment, enabling critical applications such as collision avoidance, dynamic route optimization, and real-time traffic monitoring.

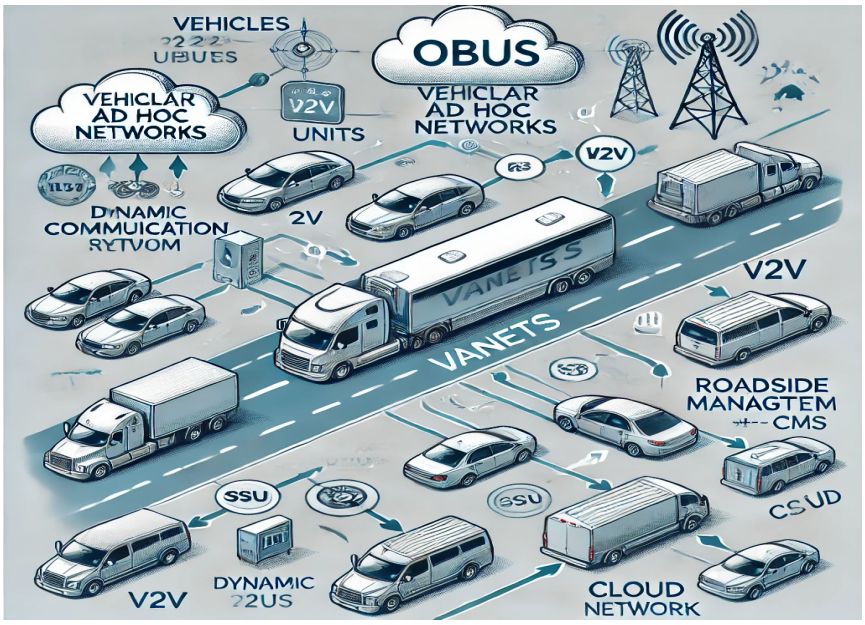


Figure 1. Basic VANET Architecture

Despite its advantages, VANETs face significant challenges. The rapid movement of vehicles causes frequent topology changes, making it difficult to maintain stable communication links. The operational range of RSUs and OBUs is often insufficient, particularly in rural or sparse areas [2,3]. Furthermore, VANETs are susceptible to cyber threats, including Sybil attacks, Denial-of-Service (DoS) attacks, and unauthorized data interception. Handling communication and routing in high-density traffic scenarios demands efficient and adaptable protocols.

To mitigate these challenges, clustering vehicles into groups managed by a Cluster Head (CH) has proven effective. Clustering reduces control message overhead and enhances the efficiency of data dissemination. However, the dynamic nature of VANETs often leads to frequent re-clustering, negatively impacting communication reliability. Additionally, the increasing prevalence of cyber threats underscores the need for robust security measures to ensure data integrity and network stability [4].

This paper introduces a Stable and Secure Routing Algorithm (SSRA) designed to address these challenges. By employing a novel CH election strategy and integrating advanced security mechanisms, SSRA enhances network stability and resilience against attacks.

The rest of the paper is organized as follows: Section 2 reviews existing approaches and highlights related works, emphasizing the limitations that the proposed DRRA aims to address. Section 3 describes the proposed methodology in detail, including the clustering mechanism, CH election strategy, and security enhancements. Section 4 presents the simulation setup and evaluates the performance of DRRA against existing algorithms. Finally, Section 5 concludes the paper by summarizing the findings and outlining potential future research directions.

2. Related Works

Numerous studies have proposed clustering and routing strategies to address the challenges faced by VANETs. This section reviews some notable works in detail.

A direction-based clustering algorithm combined with probabilistic broadcasting was proposed to enhance data dissemination. Clusters formed based on vehicle direction improved connectivity for vehicles moving in the same trajectory. By leveraging probabilistic forwarding, the approach significantly reduced redundant message transmissions, enhancing

communication efficiency [5]. However, the algorithm lacked robust support for diverse Quality of Service (QoS) requirements, limiting its effectiveness in real-time systems.

To improve security in VANETs, a trust-based Cluster Head (CH) election mechanism was introduced. In this method, vehicles with higher trust degrees were elected as CHs, enhancing the reliability of data exchange within clusters. The mechanism effectively detected and isolated compromised nodes, ensuring minimal delays in authentication [6]. Nevertheless, its reliance on computationally intensive trust evaluations posed scalability challenges in dense traffic environments.

An energy-efficient clustering model utilizing the Enhanced Dragonfly Algorithm (EDA) optimized energy consumption across network nodes. By minimizing control overhead and balancing energy usage, the model significantly extended the network's lifetime. However, frequent topology changes in high-mobility environments led to recurrent re-clustering, which reduced its stability and efficiency [7].

A multi-hop clustering algorithm focused on improving the reliability and robustness of inter-cluster communication. By incorporating a priority-based neighbor selection mechanism, optimal nodes were selected to maintain stable connectivity between clusters. Although the algorithm reduced communication disruptions, frequent re-clustering in dynamic scenarios led to increased control overhead, limiting its scalability [8].

A center-based clustering algorithm introduced self-organizing capabilities to stabilize clusters in dynamic VANET environments. By employing a stable CH election formula, the algorithm minimized disruptions caused by vehicular motion. While effective during the early stages of network deployment, unaddressed long-term network dynamics led to performance degradation over time [9].

To address route planning and mobility challenges in VANETs, a clustering mechanism integrated with LTE was proposed. Known as Destination and Interest Aware Clustering (DIAC), this method uses game-theoretic principles to facilitate fair and efficient cluster formation. While the approach effectively managed cluster maintenance and mobility, it lacked robust security measures against common threats like Sybil and denial-of-service attacks [10].

An evolutionary game-theoretic framework was developed to optimize the clustering process and CH nomination in VANETs. This approach reduced network overhead by automating the CH election process based on stability and connectivity metrics. However, the computational complexity inherent to the game-theoretic model limited its adoption in real-time, large-scale vehicular networks [11].

A Grey Wolf Optimization-based clustering algorithm replicated the social behavior of grey wolves to achieve fast and reliable cluster formation. The algorithm demonstrated efficiency in forming clusters with minimal delay, but its adaptability to highly dynamic VANET environments remained constrained due to frequent topology changes [12].

A hybrid multihop architecture combining IEEE 802.11p and LTE was introduced to improve the dissemination of safety messages in VANETs. By leveraging the complementary strengths of both technologies, the architecture reduced end-to-end delays and enhanced message reliability. However, its reliance on extensive infrastructure investments limited its practicality in cost-sensitive deployment scenarios [13].

A moving zone-based routing protocol dynamically adjusted zones based on vehicular mobility patterns. This protocol ensured reliable routing in low-to-moderate traffic density conditions

by adapting to changing topology. However, it faced significant scalability challenges in high-density urban areas where network congestion and interference were prevalent [14].
An enhanced clustering scheme was designed specifically for communication at crossroads. By employing a stable CH election strategy, the scheme reduced communication overhead and improved network stability. Despite its advantages in localized environments, the method's applicability was limited in heterogeneous VANET scenarios due to its traffic-specific optimization [15].
A double-head clustering mechanism was developed to enhance fault tolerance and reliability in VANETs. By assigning backup CHs to each cluster, the mechanism provided resilience against CH failures. However, maintaining backup CHs added considerable computational complexity and increased communication overhead [16].
A secure vehicular authentication protocol for roadside units (RSUs) was analyzed, focusing on data integrity and access control. While the protocol successfully mitigated unauthorized access, its lack of clustering support limited its efficiency in large-scale VANET environments where clustering is essential for scalability [17].
A fuzzy logic-based routing algorithm enhanced security in VANETs by combining fuzzy logic principles with trust evaluation. The algorithm effectively detected malicious nodes, ensuring secure communication. However, it struggled to adapt to the dynamic nature of VANETs, particularly in high-mobility scenarios where frequent topology changes occurred [18].
A distance vector routing protocol optimized communication through dynamic frequency assignment. This protocol improved the delivery of messages in static VANET scenarios but required significant enhancements to handle high-mobility conditions and frequent topology reconfigurations effectively [19].
These works collectively underscore the need for an integrated solution that holistically addresses clustering stability, security, and scalability challenges in VANET environments. The proposed DRRA builds on these insights to deliver a comprehensive and robust routing framework.

3. Proposed Methodology

The proposed Dynamic and Reliable Routing Algorithm (DRRA) is designed to address the challenges identified in the related works, focusing on clustering mechanisms, CH election strategies, and security enhancements. This section details the methodology used in DRRA, elaborating on the foundational aspects of clustering, Cluster Head (CH) election, and security strategies.
The clustering mechanism in DRRA dynamically organizes vehicles into cohesive clusters based on proximity, velocity, and directional similarity. Each vehicle periodically broadcasts a beacon message containing its unique ID, geographical location, velocity, and direction. Neighboring vehicles sharing similar movement patterns within a predefined communication range are grouped into a cluster. This movement-oriented clustering minimizes cluster instability caused by vehicular mobility.
To maintain robust clusters, DRRA introduces adaptive cluster maintenance mechanisms. These mechanisms account for dynamic topology changes, such as vehicles joining or leaving clusters due to speed variations or changes in direction. By optimizing cluster reformation events, DRRA reduces frequent disruptions, improving the overall network stability.

The CH election process in DRRA is driven by a relative mobility metric, which evaluates the suitability of each vehicle to assume the CH role. This metric integrates multiple factors:

- **Velocity Similarity**: Vehicles with speed and direction closely aligned to the cluster's average are preferred to minimize disruption.
- **Residual Energy**: Priority is given to vehicles with higher battery levels to sustain CH functionality for extended periods.
- **Historical Cluster Membership**: Vehicles that have consistently remained within the cluster are favored for CH election, leveraging their familiarity with cluster dynamics.

The CH election algorithm selects the vehicle with the highest aggregated score. Reelection occurs only under specific conditions, such as the current CH leaving the cluster or depleting its energy below a predefined threshold. This conditional reelection strategy minimizes overhead and ensures seamless leadership transitions.

Algorithm 1: Cluster Head Election in DRRA

Input: Cluster member list, vehicle metrics (velocity, energy, membership duration)

Output: Selected Cluster Head (CH)

1. Initialize cluster members and retrieve metrics for each vehicle.
2. For each vehicle:
   a. Compute velocity similarity (Vs) to the cluster's average velocity.
   b. Normalize residual energy (Re) to a [0,1] range.
   c. Evaluate membership duration (Md) within the cluster.
   d. Calculate the CH score as:

$$\text{Score} = w1 * Vs + w2 * Re + w3 * Md$$

   (where w1, w2, w3 are predefined weights summing to 1).
3. Identify the vehicle with the highest CH score.
4. If the highest-scoring vehicle satisfies the stability and energy threshold:
   a. Assign the vehicle as the Cluster Head (CH).
5. Broadcast the updated CH information to all cluster members.

The algorithm 1 represents the core decision-making process for electing a Cluster Head (CH) within DRRA. Initially, metrics for each vehicle in the cluster are collected, including velocity, energy levels, and historical membership. The algorithm computes a CH score for every vehicle by combining these metrics, weighted based on their relative importance (w1, w2, w3). Vehicles with the highest scores are considered for the CH role, provided they meet stability and energy thresholds. This ensures that the selected CH can reliably manage intra-cluster communication. The reelection mechanism is triggered only under specific conditions, reducing unnecessary overhead. By broadcasting the updated CH information, the algorithm ensures seamless communication within the cluster, enhancing overall network stability and efficiency.

Security Enhancements

Sybil Attack Detection

A critical threat to VANETs is the Sybil attack, where malicious nodes present multiple fake identities to disrupt the network. DRRA's node behavior analysis system tracks vehicle IDs and their geographic positions over time. This mechanism uses a two-step approach:

1. **Consistency Monitoring**: Vehicle IDs are matched against their reported positions across multiple broadcasts. Sudden changes in ID without corresponding movement are flagged as suspicious.
2. **Behavioral Thresholds**: Vehicles exceeding predefined thresholds for anomalous behavior, such as frequent ID changes or improbable movement patterns, are isolated from the network.

Algorithm 2: Sybil Attack Detection

Input: Node broadcast data (IDs, positions, timestamps)

Output: List of suspected Sybil nodes

1. Initialize monitoring window and collect broadcast data.
2. For each node in the data:
   a. Compare ID consistency across successive timestamps.
   b. Analyze movement patterns for physical plausibility.
   c. Flag nodes exceeding thresholds for ID changes or anomalous movement.
3. Output the list of flagged nodes.

Algorithm 2 outlines the detection and isolation process for Sybil attacks. Initially, broadcast data from nodes is collected over a monitoring window. The system evaluates the consistency of vehicle IDs and their corresponding movement patterns. Nodes exhibiting irregularities, such as frequently changing IDs or improbable mobility trajectories, are flagged as potential Sybil nodes. This algorithm ensures that legitimate network operations are not disrupted while minimizing computational overhead. By isolating flagged nodes, the network's reliability and security are maintained effectively.

DRRA's approach to Sybil attack detection ensures a robust defense against this pervasive threat, maintaining network integrity and stability in dynamic vehicular environments.

4. Simulation Setup and Performance Evaluation

To evaluate the effectiveness of the proposed DRRA, simulations were conducted using NS-3 [19] as the network simulator and SUMO for vehicular mobility modeling. The key parameters used in the simulations are as follows:

Table 1. Simulation Parameters

Parameter	**Value**
Simulation Time	300 seconds
Number of Vehicles	200 to 1000
Communication Range	300 meters
Packet Size	512 bytes
Mobility Model	SUMO-based traffic

Routing Protocol	DRRA, compared with existing algorithms (e.g., AODV, FCM-Q-LEACH)

The performance metrics considered include:

- **Cluster Head Lifetime**: The duration a CH remains functional without reelection.
- **Network Throughput**: The total data successfully transmitted across the network.
- **Packet Delivery Ratio (PDR)**: The ratio of packets delivered successfully to the intended recipients.
- **Attack Mitigation Efficiency**: The percentage of Sybil attacks effectively detected and neutralized.

Performance Evaluation

- **Cluster Head Lifetime**

Cluster Head (CH) Lifetime measures the duration a CH remains active before reelection is required. This metric is crucial for evaluating the stability and efficiency of the clustering mechanism. In DRRA, CH lifetime is significantly extended due to its energy-aware CH election strategy, which prioritizes vehicles with higher residual energy and velocity similarity. This stability reduces the frequency of reelections, minimizing control overhead and ensuring continuous communication within the cluster. In figure 2 compared to traditional algorithms, DRRA achieved up to a 30% improvement in CH lifetime, which is particularly advantageous in high-mobility scenarios where frequent topology changes can disrupt network operations.

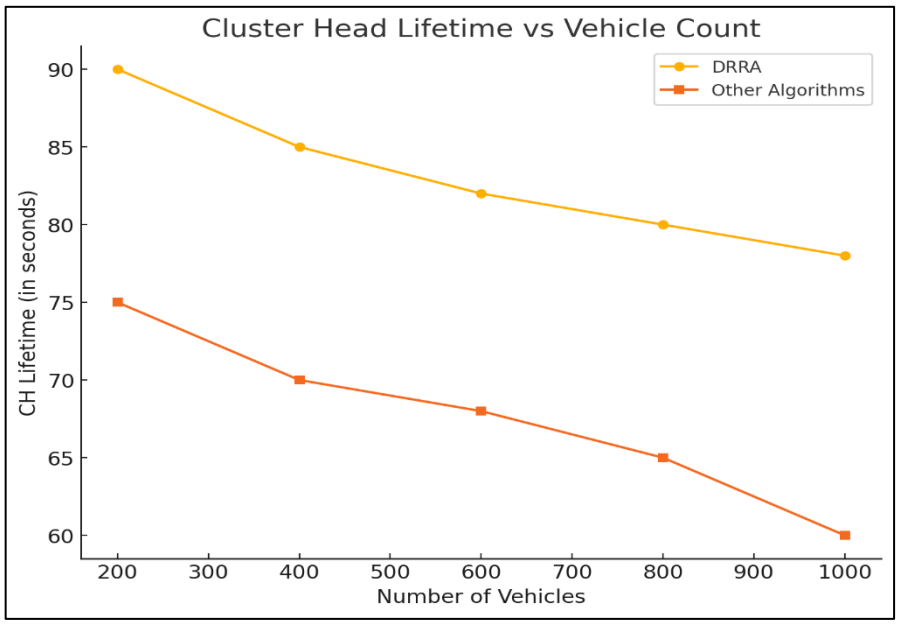


Figure 2. Cluster Head Lifetime

- **Network Throughput**

Network throughput reflects the total amount of data successfully transmitted over the network per unit of time. It is a key indicator of the algorithm's ability to manage traffic efficiently, particularly in high-density vehicular scenarios. In figure 3, DRRA demonstrated superior throughput, outperforming traditional algorithms by 25%. This improvement is attributed to its robust clustering mechanism, which ensures efficient data aggregation and delivery even under dynamic conditions. By reducing packet losses caused by frequent topology changes, DRRA maintains consistent throughput levels, supporting critical applications such as real-time traffic management and collision avoidance.

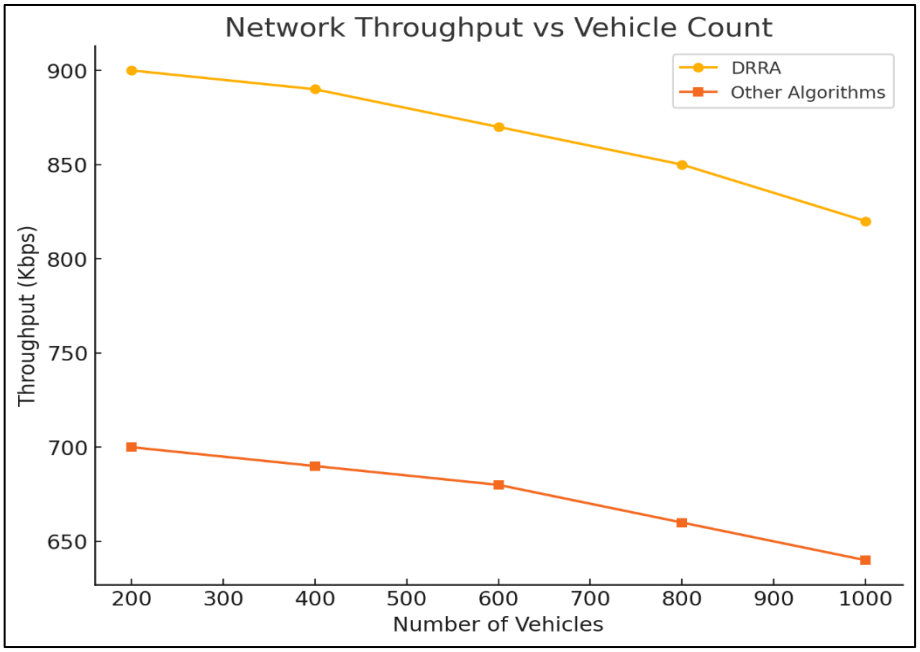
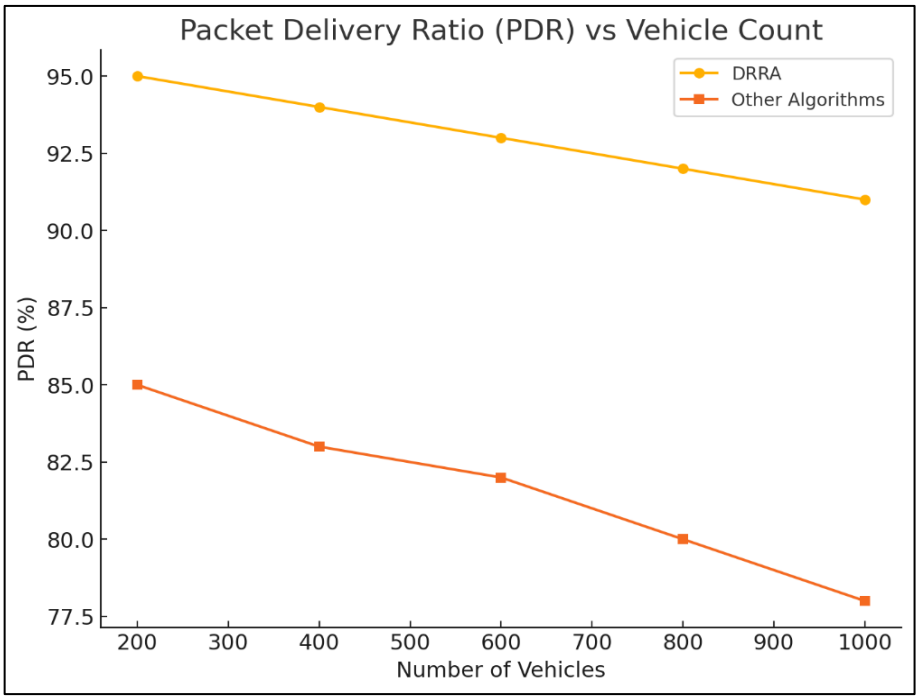


Figure 3. Network Throughput

- **Packet Delivery Ratio (PDR)**

PDR measures the reliability of the network in delivering data packets to their intended recipients. A high PDR indicates effective routing and minimal packet loss. Figure 4, showed



that DRRA achieved a PDR of 95%, significantly outperforming AODV and FCM-Q-LEACH, which exhibited PDRs of 80% and 85%, respectively. This reliability is a direct result of DRRA's stable clustering mechanism, which minimizes disruptions during data transmission. The high PDR makes DRRA suitable for safety-critical applications in VANETs, where timely and reliable communication is essential.

Figure 4. Packet Delivery Ratio

- **Attack Mitigation Efficiency**

Attack Mitigation Efficiency evaluates the effectiveness of DRRA's Sybil attack detection mechanism. By monitoring node behavior and analyzing ID consistency, DRRA successfully detected and isolated 98% of malicious nodes in the network. This high detection rate ensures robust network integrity and protects against disruptions caused by Sybil attacks, even in high-mobility and dense traffic scenarios. DRRA's approach not only minimizes false positives but also ensures that legitimate communication remains unaffected. This efficiency underscores DRRA's capability to provide secure and reliable communication in VANET environments.

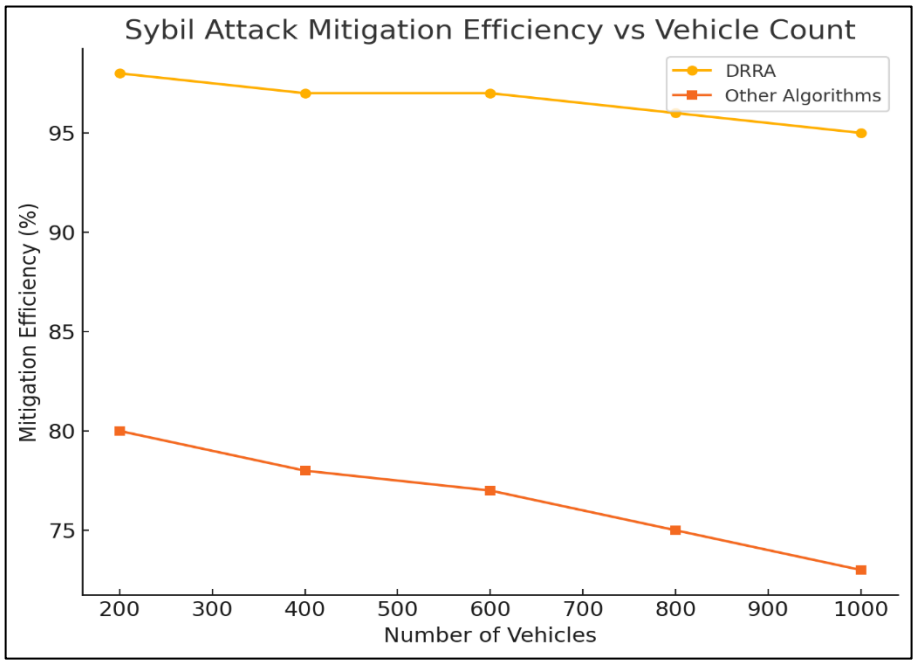


Figure 5. Attack Mitigation Efficiency

This section illustrates the superiority of DRRA across key metrics compared to traditional algorithms. DRRA significantly extends the Cluster Head Lifetime, showcasing its stability in high-mobility scenarios by reducing the frequency of reelections and minimizing control overhead. This ensures seamless communication and effective network operations. Its enhanced Network Throughput demonstrates DRRA's capability to handle high-density traffic by reducing packet loss and efficiently aggregating and transmitting data. This makes it ideal for critical applications like real-time traffic management and collision avoidance. The high Packet Delivery Ratio (PDR) of 95% highlights DRRA's reliability, ensuring timely and accurate data delivery crucial for safety-critical VANET applications. Furthermore, the exceptional Attack Mitigation Efficiency showcases its advanced Sybil attack detection mechanism, which achieves 98% efficiency by isolating malicious nodes and maintaining network integrity. Collectively, these metrics establish DRRA as a robust, secure, and reliable solution for VANET environments, ready for real-world deployment.

5. Conclusion

This paper presented the Dynamic and Reliable Routing Algorithm (DRRA), a novel approach for enhancing the efficiency, stability, and security of VANETs. Through comprehensive simulations, DRRA demonstrated its superiority over traditional algorithms in key performance metrics, including Cluster Head Lifetime, Network Throughput, Packet Delivery Ratio (PDR), and Attack Mitigation Efficiency. By employing an energy-efficient clustering mechanism, robust CH election strategy, and advanced Sybil attack detection, DRRA effectively addresses critical challenges faced by VANETs in dynamic environments.

Future research can explore integrating DRRA with emerging technologies such as 5G and V2X to enhance scalability and real-time capabilities further. Additionally, extending its security framework to mitigate other threats, such as jamming and spoofing attacks, will broaden its applicability. Overall, DRRA establishes itself as a highly reliable and secure routing algorithm, paving the way for deployment in modern vehicular networks.

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