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Mobility Estimation-Based Clustering for Energy-Efficient Routing in IoT-Enabled VANETs

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ABSTRACT: Combining Internet of Things (IoT) devices with Vehicular Ad hoc Networks (VANETs) offers substantial benefits for traffic management, transportation efficiency, and road safety. However, challenges related to energy consumption, routing efficiency, and stability remain significant obstacles, particularly as modern VANETs increasingly rely on Electric Vehicles (EVs) and Solar-Powered Roadside Units (SP-RSUs), which have limited energy budgets. Existing routing protocols often fail due to the impact of high vehicular mobility and restricted energy resources. This affects periodic rerouting, unstable communication, and decreases network lifetime. This paper suggests a Mobility Estimation-Based Clustering Routing (MEBCR) protocol to treat these issues. In a united framework, the proposed MEBCR merges a hybrid mobility estimation module, including the Kalman Filter and Gauss-Markov approaches, together with cluster formation and energy-aware routing strategies. This design is essential for sustaining the processes in energy-restricted environments, guaranteeing reliable communication and a prolonged network. By comparing with existing protocols, simulation outcomes show that MEBCR preserves 10-28% extra energy and 13-42% node survival. Additionally, it reduces cluster variations by approximately 48-60%. These outcomes confirm the efficiency and robustness of the proposed protocol, making it a suitable solution for green and intelligent transportation systems in next-generation networks.

Keywords: Internet of Things, Vehicular Ad hoc Networks, Energy Consumption, Routing Efficiency, Mobility Estimation.

1. INTRODUCTION

The Internet of Things (IoT) has made breakthroughs in developing intelligent transportation systems through the connectivity between heterogeneous devices, such as vehicles and infrastructure [1-3]. Through real-time data sensing, processing, and exchange, IoT plays an essential function in promoting traffic management, road safety, and energy-efficient mobility services [4-6].

One of the primary factors in IoT-based intelligent transportation is the use of Vehicular Ad Hoc Networks (VANETs), which lets vehicles communicate directly with one another through Vehicle-to-Vehicle (V2V) and with roadside infrastructure via Vehicle-to-Infrastructure (V2I) communication. By integrating IoT devices into VANETs, vehicles and Roadside Units (RSUs) can share information, expose traffic conditions, and uphold intelligent mobility services [7-9].

Routing protocols play a prime part in ensuring reliable data communication and efficient resource utilization [10-13]. Traditional routing protocols in VANETs have focused on providing connectivity, reliability, and latency reduction. Those were suitable when vehicles relied on conventional fuel and RSUs were powered by the electrical network. Under these situations, energy efficiency was not a priority [14-17]. However, these restrictions prevent the deployment of scalable and sustainable VANET solutions in IoT environments. Moreover, the dynamic mobility of vehicles complicates routing management. The frequent topology changes lead to uneasy communication links and superfluous overhead. While existing mobility estimation techniques can provide accurate estimations, they typically require resource-heavy computations. This makes them unsuitable for resource-constrained IoT-enabled VANETs [18-22].

However, energy efficiency has become a substantial challenge in VANETs due to the move toward Electric Vehicles (EVs) and the growing deployment of Solar-Powered RSUs (SP-RSUs). Unlike classical fuel-based vehicles, EVs operate on limited battery capacity, and frequent data transmission or processing tasks can accelerate energy depletion, directly affecting vehicular services. Similarly, SP-RSUs rely on harvested solar energy, which is inherently variable and constrained by environmental conditions. This highlights the need for routing protocols that equate connectivity and latency with energy-awareness. To ensure sustainable communication in IoT-enabled transportation networks [23-25].

This creates a gap for the evolution of routing protocols that involve EV-based and SP-powered vehicular networks. Therefore, protocols that integrate mobility estimation, lightweight clustering, and energy-aware communication mechanisms are necessary. To guarantee reliable, efficient, and sustainable working in next-generation IoT-enabled VANETs [26-28].

This paper proposes a Mobility Estimation-Based Clustering Routing (MEBCR) protocol. The motivation behind this study is the urgent requirement for scalable and sustainable vehicular communication structures. It can hold high mobility dynamics and operate under stringent energy restrictions, especially in networks controlled by EVs and SP-RSUs. The primary objective of this study is to propose a routing protocol that minimizes energy consumption, prolongs network lifetime, and promotes routing stability with minimal computational and communication overhead. To achieve this, MEBCR benefits from Kalman Filter and Gauss-Markov approaches for estimating vehicle mobility, along with cluster formation and energy-aware routing strategies, all within a unified framework. The MEBCR ensures the sustainable operations in energy-constrained environments, efficient data delivery, and a sustainable process in IoT-enabled VANETs. The main contributions of this paper are as follows:

1- Propose a hybrid mobility estimation module that integrates the estimation abilities of the Kalman Filter and Gauss-Markov to forecast vehicle trajectories in VANET environments. This minimizes the breakage of the link and promotes route stability.
2- Introduce a clustering approach that groups vehicles and chooses Cluster Heads (CHs) utilizing a weight function. This minimizes control overhead and ensures stable intra-cluster communication.
3- Design an energy-aware routing mechanism where CHs form a communication backbone, and an end-to-end route between source and destination is chosen utilizing a cost function. This includes efficient route choice, balanced energy use, and keeps communication in energy-restricted environments such as EV and SP-RSUs.
4- Implement the proposed protocol in MATLAB and conduct comprehensive simulations under different traffic densities and mobility speeds. The outcomes are compared against routing protocols, demonstrating improvements in packet delivery ratio, end-to-end delay, routing overhead, energy efficiency, network lifetime, and cluster stability.

The remainder of this paper is organized as follows: Section 2 surveys the related work on VANET routings. Section 3 provides a detailed description of the proposed routing protocol. Section 4 outlines the simulation setup and discusses the evaluation results. Finally, Section 5 concludes the paper and outlines potential directions for future research.

2. RELATED WORKS

Although numerous protocol improvements have been made in VANET, it still faces challenges regarding mobility, energy efficiency, and clustering [29, 30]. These matters become more critical in modern VANETs, which are powered by EVs and supported by SP-RSUs. In this section, we summarize some protocols to highlight their contributions and limitations. To provide the basis for enhancing our proposed protocol.

EELAR (Energy-Efficient Location-Aided Routing) was proposed in [31] as an enhancement of the LAR protocol with energy-awareness. The protocol limits route discovery to a smaller, targeted area depending on the estimated location of the destination node. Specifically, the network's circular area is centered at the base station, which is divided into six equal sub-areas. Route control packets are forwarded only within the sub-area that contains the target node, rather than being flooded through the whole network. The base station preserves a position table with node locations. This smooths selective flooding and minimizes route discovery overhead. The primary advantage of EELAR is that it reduces the number of control packets by restricting route discovery to a minimal zone, resulting in energy savings. The focused discovery mechanism promotes the efficiency of route setup and increases delivery success rates. However, the limitations of EELAR require a central station to maintain node positions. This is not practical in ad hoc environments without fixed infrastructure. Moreover, the EELAR relies on the accuracy of the node location data, and incorrect information could lead to suboptimal routing decisions and failed packets. Finally, the division of the network into six sub-areas is inefficient in dynamically changing network topologies. As the network grows, updating the position table from the base station becomes resource-intensive and heavy communication.

Q-EER (QoS-aware Energy-Efficient Routing) is proposed in [32] to supply both energy efficiency and Quality of Service (QoS) guarantees. QEER combines residual energy, link quality, hop count, and delay limits when choosing routes. This includes not only a prolonged network lifetime but also reliable and timely data delivery. This protocol is applicable in applications where both energy saving and QoS performance are crucial. Its strengths are averted early depletion by distributing energy consumption across nodes. It is appropriate for real-time applications due to its delay, reliability, and throughput. It enhances communication more reliably by utilizing energy and QoS as criteria for decision-making. However, the limitation is that multi-metric route selection raises complications for resource-limited nodes. Performance backs as the network size and traffic load grow. Additionally, minimal efficiency in highly dynamic networks, such as VANETs. Ensuring QoS can lead to rapid energy consumption.

MA-AODV (Mobility Aware-Ad hoc On Demand Distance Vector) is proposed in [33], which modifies the traditional AODV protocol. It is designed to improve routing by combining mobility awareness. MA-AODV promotes route discovery and maintenance by including node mobility metrics, such as relative speed and link expiration time, when choosing and maintaining routes. This produces a route that is more stable and minimizes frequent re-routing. The strengths of MA-AODV lie in its respect for node movement patterns, which leads to highly stable routes, decreased route breakages, and improved reliability in high-mobility environments. Moreover, it reduces routing overhead because fewer route discoveries are required, resulting in enhanced packet delivery ratio and lower end-to-end delay under high mobility scenarios. However, the limitations of MA-AODV are that it focuses on mobility rather than protecting battery power, which is a drawback for IoT-based VANETs. Additional computation due to mobility estimation, such as link expiration time calculations, results in gathering processing overhead. It operates entirely in small to medium-sized networks but may fight in extensive networks due to control overhead.

P-GEDIR (Peripheral Node-Based Geographic Distance Routing) is proposed in [34] as a refinement of the traditional GEDIR. P-GEDIR addresses challenges in urban environments due to frequent obstacles and complex road structures by integrating peripheral nodes, which are existing at the edges of the transmission range, to help in routing decisions. This protocol is designed to enhance packet delivery activity and minimize communication overhead in dense urban traffic scenarios. Its strengths promote routing efficiency by using peripheral nodes, which leads to enhanced packet delivery ratios, decreases unnecessary retransmissions and control message overhead, and optimizes network resources. P-GEDIR is designed for urban environments and effectively navigates complex road networks and traffic situations. Additionally, it scales with rising network size and vehicle density. However, the Limitations of P-GEDIR depend on node density, which may not improve as much as the sparse networks. The protocol relies on peripheral node identification and routing calculations, which incur computational overhead. Furthermore, P-GEDIR firstly concentrates on locative parts and does not wholly account for the dynamic nature of vehicle mobility.

LEACH-V (Low-Energy Adaptive Clustering Hierarchy-Vector Quantization) is proposed in [35] as an improvement of the traditional LEACH protocol, designed to enhance intra-cluster communication efficiency. To find the shortest energy-efficient routes between cluster heads to reduce total energy consumption, LEACH-V adds vector quantization techniques. LEACH-V utilizes the data transmission that occurs along the most energy-efficient routes by calculating the Euclidean distance between cluster heads. The force of LEACH-V includes minimizing energy consumption through intra-cluster communication, which expands network lifetime. LEACH-V's design is practical with increasing network size and preserves performance across several deployments. It is suitable for real-world applications because the protocol depends on vector quantization for route optimization. However, this is not permanently the case in actual scenarios due to the determinations of LEACH-V assume an equal distribution of sensor nodes. The integration of vector quantization adds computational overhead, which could be affront for resource-limited nodes. The effectiveness of vector quantization in path optimization depends on accurate distance measurements, which are influenced by environmental factors. Additionally, the protocol may not perform optimally in highly dynamic environments.

ECHS (Efficient Cluster Head Selection) is proposed in [36] as a lightweight and scalable clustering scheme for VANETs. It utilizes a simple cluster head chosen mechanism, which prioritizes stability depending on vehicle mobility, connectivity, and position. The focus is on minimizing the frequency of cluster reformation and maintaining cluster uniformity in dense, high-mobility networks. The strengths of ECHS are that it decreases cluster head switching and frequent re-clustering. This improves total network performance. It proceeds entirely under fast-changing VANET topologies, avoiding metrics and heavy computations, making it suitable for real-time VANET applications. However, the limitations of ECHS are that it doesn’t integrate energy-awareness. Focuses on stability and scalability but does not immediately optimize for QoS metrics, such as delay and packet delivery ratio. Additionally, it does not employ mobility estimation to promote cluster longevity.

Despite the significant gaps that remain in routing, mobility estimation, clustering, and energy efficiency in VANETs, existing protocols have made notable contributions to these areas. However, some protocols progress energy employment but overlook mobility dynamics. This leads to unstable routes in high-speed situations. Others promote adaptability but ignore the importance of energy restriction. This reduces network lifetime. Similarly, several protocols supply scalability and load balancing but fail to combine accurate mobility estimation. This results in frequent cluster reformation. In the modern VANETs, which are increasingly powered by EVs and supported by SP-RSUs, these limitations become more critical, as energy resources are constrained and network sustainability is primary. Hence, the need for a protocol such as the proposed MEBCR, within a unified framework, is to combine mobility estimation, cluster formation, and energy-aware routing strategies. It estimates node movement, maintains stable communication links, and minimizes route failures through hybrid mobility estimation. Provides scalable communication, minimizes routing overhead, and promotes stability in high-mobility environments through its clustering strategy. Additionally, the energy-aware proposal assures reliable delivery and expands network lifetime. This is profitable for EVs and SP-RSUs, which have bound energy. Resulting in stable cluster formation, efficient energy employment, and sustainable communication, the MEBCR protocol is warranted. That is appropriate for the next generation of VANETs. Table 1 displays a comparison of the MEBCR protocol vs. existing protocols.

Table 1. Comparison of the MEBCR protocol vs. existing protocols

Protocol	Mobility Estimation	Energy Efficiency	Cluster-Based	Stability	Scalability
EELAR	No	Yes	No	Medium	Medium
Q-EER	No	Yes	No	High	Medium
MA-AODV	Yes	No	No	Medium	Low
P-GEDIR	No	No	No	Medium	Low
LEACH-V	No	Yes	Yes	Medium	Medium
ECHS	No	No	Yes	High	High
Proposed MEBCR	Yes	Yes	Yes	High	High

3. PROPOSED ROUTING PROTOCOL

The proposed MEBCR protocol comprises three modules: mobility estimation, clustering, and energy-aware routing, which are detailed in this section. In the hybrid mobility estimation module, to forecast vehicle activity, the Kalman Filter and Gauss-Markov approaches are applied. The clustering module groups vehicles and chosen CHs. While CHs are used to form a communication backbone, the end-to-end route between source and destination is determined by the energy-aware routing module. Clustering and energy-aware routing supplement each other in this design, with clustering working at the local level and energy-aware routing working at the global level. This makes it appropriate for modern VANETs with EVs and SP-RSUs, where keeping energy resources is primary to prolong network lifetime. Table 2 shows the pseudocode of the proposed MEBCR protocol.

3.1. Mobility Estimation Module

Frequent changes in a vehicle's speed, direction, and position result in rapid variations in the network topology of vehicular environments. Therefore, mobility estimation is a key part of VANETs. To minimize packet loss, promote routing stability, and support real-time traffic management for applications. Mobility estimation uses protocols to estimate node movement, reduce route defeats, and preserve stable communication links. Routing protocols may depend only on instant node positions without mobility estimation. This can speedily become outdated, leading to inactive route decisions [37, 38]. We use a hybrid estimation module by combining the Kalman Filter and Gauss-Markov approaches to treat these challenges.

The Kalman Filter approach is a repetitive mathematical method that estimates the state of a dynamic system by filtering out noise from measurements [39, 40]. It can estimate vehicle positions and velocities in VANETs by integrating current notices with past estimates. Several advantages of the Kalman Filter include the provision of real-time and repetitive updates, which make it lightweight for employment in highly dynamic environments. Furthermore, it decreases the action of measurement noise from sensors and GPS to promote estimation reliability for short-term mobility behaviors. This happens through the standard estimate update equations, such as in Equations (1-5) [41]:

$$\hat{x}_{n|n-1} = A.\hat{x}_{n-1|n-1} + B.u_n \tag{1}$$

$$Y_{n|n-1} = A.Y_{n-1|n-1}.A^T + M \tag{2}$$

$$K_n = Y_{n|n-1}.H^T.(H.Y_{n|n-1}.H^T + R)^{-1} \tag{3}$$

$$\hat{x}_{n|n} = \hat{x}_{n|n-1} + K_n.(z_n - H.\hat{x}_{n|n-1}) \tag{4}$$

$$Y_{n|n} = (I - K_n.H).Y_{n|n-1} \tag{5}$$

Where $\hat{x}_{n|n}$: estimated state vector for position and velocity, z_n: observed position, Y: covariance matrix, K_n:Kalman gain, A, B, H: system matrices, and M, R: process and measurement noise.

The Gauss-Markov approach is a stochastic mobility model [42, 43]. For realistic vehicular movement, it is extensively employed in wireless networks. The Gauss-Markov approach has temporal, a vehicle's future velocity and direction rely on its past cases. Compared to other models, this approach makes mobility manners softer and realistic. In VANETs, these are bases for precisely modeling vehicle movement. Finally, the Gauss-Markov approach aids in estimating the medium and long-term mobility. To hold realistic vehicle mobility behavior, the velocity and direction of each vehicle are updated utilizing Equations (6-7) [44]:

$$v(t) = \alpha.v(t-1) + (1-\alpha).v^{-} + \sqrt{1-\alpha^2}.w(t) \quad (6)$$

$$\theta(t) = \alpha.\theta(t-1) + (1-\alpha).\theta^{-} + \sqrt{1-\alpha^2}.w^{-}(t) \quad (7)$$

Where $v(t), \theta(t)$: present velocity and direction, v^{-}, θ^{-}: mean velocity and direction, α: tuning parameter ($0 \leq \alpha \leq 1$), $w(t), w^{-}(t)$: Gaussian random variables.

Mobility Estimation begins with each vehicle periodically gathering mobility factors, such as position, velocity, and direction. The Kalman Filter is applied to smooth short-term estimates and mitigate GPS noise. At the same time, the Gauss-Markov is used to estimate long-term mobility manners, such as velocity and direction. The estimated mobility information is broadcast to 1-hop neighbors. A hybrid module enhances link reliability, minimizes route breakages, and promotes total routing performance in VANETs.

3.2 Clustering Module

Clustering is a widely accepted technique in VANETs for organizing vehicles into structured groups. This reduces routing overhead and promotes communication efficiency [45, 46]. Clusters in the proposed protocol rely on estimated vehicle positions to maintain stability and reduce unnecessary energy consumption. Each cluster is managed by a Cluster Head (CH), which is chosen to utilize a composite weight function that focuses on residual energy, relative mobility, and node degree, as shown in Equation (8) [47]:

$$W_i = p_1.\frac{E_i}{E_{max}} + p_2.\frac{1}{\Delta M_i} p_3.\frac{D_i}{D_{max}} \quad (8)$$

Where E_i: residual energy of the node i, ΔM_i: relative mobility with respect to neighboring nodes, D_i : node degree (number of neighbors), $p_1 + p_2 + p_3 = 1$: weight parameters. By gathering these factors, the chosen process ensures that the CHs are both energy-efficient and stable. Moreover, maintaining robust connectivity with neighboring nodes is crucial. Each vehicle calculates its W_i and interacts with this value with the neighboring nodes. The node with the highest W_i in a neighborhood is the CH, while other nodes combine with the nearest CH as cluster members. If CH energy reduces below a threshold, reclustering is triggered. This form guarantees that nodes with higher residual energy, lower relative mobility, and greater connectivity are more likely to become CHs. This improves cluster stability and prolongs network lifetime.

3.3 Energy-Aware Routing Module

In the proposed MEBCR protocol, routing decisions are navigable by an energy-aware cost function that establishes each selected route based on three critical factors: hop count, energy consumption, and link stability. The cost function is expressed as Equation (9) [48]:

$$C_{route} = \sum_{i=1}^{n}(a.\frac{1}{L_i} + b.\frac{1}{E_i} + c.H_i) \quad (9)$$

Where L_i: estimated link lifetime between nodes i and $i+1$, E_i: residual energy of node i, H_i: hop penalty (usually 1), a, b, c: adjustable weight parameters. By regarding energy and link quality, this routing method prolongs network lifetime, improves route stability, and includes reliable data delivery in the highly dynamic VANET environment. When a source node wants to send data, it first sends a route request to its CH. The CH then forwards the route request to the next CHs until it arrives at the destination CH. Each selected route is evaluated employing the C_{route}. The destination CH chooses the route with the lowest C_{route}. The source starts data transmission along the chosen route. If a potential link disconnect is estimated, the protocol dynamically rechooses an alternative route to maintain reliable communication.

Table 2. Pseudocode of the proposed MEBCR protocol

```
Input: vehicle positions, velocities, directions, residual energy, and communication range
Output: stable clusters with elected CHs and energy-efficient, stable routing
Step 1: Mobility Estimation
        For each vehicle:
            Gather position, velocity, and direction
            Apply the Kalman Filter approach to smooth short-term estimates
            Apply the Gauss-Markov approach to estimate long-term mobility
            Broadcast estimated mobility to 1-hop neighbors
        End For
Step 2: Clustering
        For each vehicle:
            Calculate W_i
            Exchange W_i with neighboring nodes
            If W_i is the highest among neighbors Then
               Assign node as CH
            Else
               Join the nearest CH as a cluster member
            End If
            If CH energy < threshold or CH moves out of range Then
               Trigger reclustering
            End If
        End For
Step 3: Energy-Aware Routing
        When the source wants to send data:
            Send route request to CH
            CH forwards the request to the next CHs until the destination CH
            For each candidate route:
               Compute C_route
            End For
            Destination selects the route with the lowest C_route
            Source transmits data along a selected route
            If an estimated link failure occurs Then
               Dynamically select an alternative route
            End If
Step 4: Maintenance and Updates
        Periodically:
            Update mobility estimates
            CH monitors members' energy
            If CH or member energy < threshold or link unstable Then
               Trigger reclustering
            End If
End
```

4. SIMULATION PARAMETERS AND RESULTS

This section presents the simulation details and parameters utilized to assess the performance of the proposed MEBCR protocol. The evaluation includes comparing its performance against existing routing protocols, namely Q-EER, P-GEDIR, and LEACH-V. All protocols were executed and tested in the MATLAB simulator under similar conditions and simulation parameters, ensuring the fairness and reliability of the outcomes.

4.1 Sumulation Parameters

Comprehensive simulations were performed to evaluate the performance of the proposed MEBCR protocol. The simulation framework was designed to hold various traffic and mobility conditions by varying node density, speed, and clustering intervals [49]. Criterian VANET communication settings were dependent. Moreover, IEEE 802.11p for vehicular links and a first-order radio energy model are included to measure energy consumption. A node speed (10-60 km/h) and number of nodes (50-150) were tested within a 1000 m×1000 m simulation area. Each scenario was conducted multiple times to guarantee fairness and accuracy, and the average results were analyzed. The key simulation parameters are summarized in Table 3:

Table 3. Key simulation parameters

Parameter	Value
Area of Simulation	1000 m × 1000 m
Time of Simulation	300 seconds
Number of Nodes	50 to 150
Speed of Node	10-60 km/h
Time of Pause	0 seconds (continuous mobility)
Transmission Range	250 meters
MAC Protocol	IEEE 802.11p
Type of Traffic	Constant Bit Rate
Size of Packet	512 bytes
Rate of Packet	4 packets/sec
Initial Energy per Node	2 Joules
Energy Model	First-order radio energy model
Cluster Maintenance Interval	10 seconds
Number of Runs per Scenario	10

4.2 Results and Discussions

This study compares the performance of Q-EER, P-GEDIR, LEACH-V, and the proposed MEBCR protocol across key metrics, including packet delivery ratio, end-to-end delay, routing overhead, energy efficiency, network lifetime, and cluster stability. The outcomes are analyzed to confirm the effectiveness of MEBCR and explain the improvements it introduces over existing approaches.

A. Packet Delivery Ratio

Packet delivery ratio (PDR) is one of the most stringent metrics in VANETs. It appears as the ratio of the number of data packets received at the destination successfully to the number of packets sent by the source. A high PDR considers the accuracy and robustness of the routing protocol under different situations. As node speed grows, the network topology becomes more dynamic and less estimable. This leads to frequent route breakages and packet loss. As shown in Figure 1, the proposed MEBCR has the highest PDR at all speeds, indicating prime packet accuracy under dynamic vehicular conditions. This performance is primarily for mobility estimation, which accounts for link breaks and decreases packet loss due to stable clustering and frequent route variation. At 60 km/h, MEBCR achieves an efficiency of 85.4%, which is 20.4% higher than Q-EER (65%), 23.6% higher than P-GEDIR (61.8%), and 12.4% higher than LEACH-V (73%). Q-EER displays a significant drop in PDR as speed grows. Its reactive nature leads to frequent route breakages and delayed repairs, resulting in a rise in packet loss. Without a mobility estimation and clustering mechanism, accuracy suffers in highly dynamic VANET environments. P-GEDIR registers the lowest PDR at all speeds. It is derived from greedy forwarding voids, which become more popular at high mobility. Its high dependence on positional accuracy and no redundancy make it prone to packet drops during unexpected topology alterations. LEACH-V implements well at low speeds due to stable cluster-based forwarding. However, its PDR drops as speed rises because the cluster head chosen is not mobility-aware, which leads to frequent cluster re-formation and packet loss.

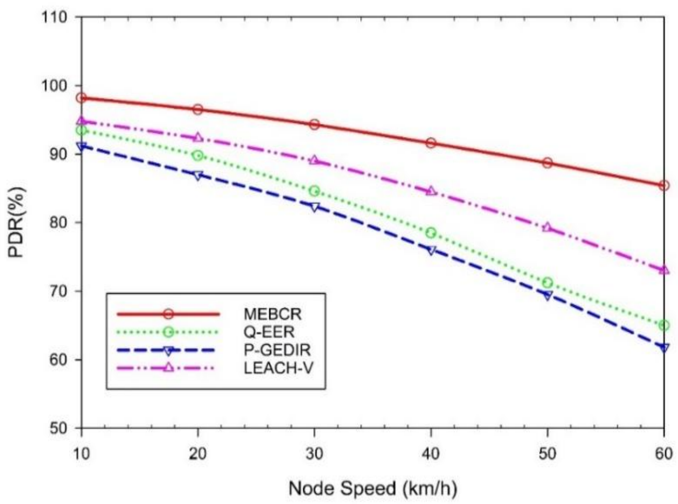

Figure 1. Packet Delivery Ratio

B. End-to-End Delay

End-to-end delay refers to the time it takes for a data packet to travel from the source to the destination. It considers the routing protocol's efficiency in treating transmission and maintaining route stability. As shown in Figure 2, the proposed MEBCR has the lowest end-to-end delay across all node densities. Its mobility estimation mechanism can proactively form stable routes and minimize route breaks, while stable cluster heads reduce unnecessary control communication and decrease the time required for route setup. Furthermore, packet forwarding is more deterministic due to stable routing decisions, which deny delay spikes even as density grows. At 150 nodes, MEBCR achieves an average delay of 55 ms, which is 36% lower than Q-EER (86 ms), 39% lower than P-GEDIR (90 ms), and 20% lower than LEACH-V (69 ms). Q-EER experiences high delays due to frequent route finds in dynamic topologies. As node density increases, delays rise pointedly due to queue buildup and routing table maintenance overhead. Without clustering or mobility estimation, Q-EER leads to route setup delays under higher loads. P-GEDIR is more delay-prone under high density due to greedy forwarding void and reactive backtracking, which trigger excessive and control messaging resulting in extended delivery times. An acute rise beyond 100 nodes indicates contention and collision elevation. LEACH-V outperforms Q-EER and P-GEDIR at low to medium node densities due to its cluster-based forwarding. However, as density increases, delays grow since random cluster-head rotation leads to instability. This is causing intermittent routing gaps and temporary route disturbance.

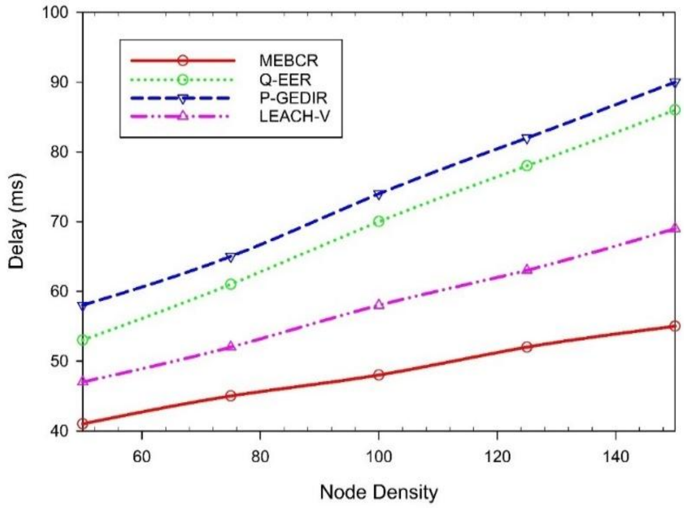

Figure 2. End-to-End Delay

C. Routing Overhead

Routing overhead is the ratio of control packets to the total number of transmitted packets. A minimal overhead mentions a more efficient protocol, since fewer resources are wasted on maintaining routes. As shown in Figure 3, the proposed MEBCR has low overhead across all time intervals. Its use of mobility estimation and clustering decreases needless rerouting and control signaling. CHs are chosen based on node stability and residual energy, which reduces the frequency of cluster reformation. Furthermore, MEBCR restricts broadcast traffic by depending on stable routes, thus decreasing the size of control packets. At 300s, MEBCR has only 1090 control packets, which is 22% fewer than LEACH-V (1390), 27% fewer than Q-EER (1500), and 31% fewer than P-GEDIR (1580). Q-EER utilizes queue-aware metrics but lacks mobility estimation and clustering mechanisms, resulting in a reactive response to topology alterations with frequent control packet floods. A higher control overhead due to persistent route maintenance contributes. P-GEDIR is greedy and reactive, which depends on frequent position updates. It also suffers from void handling and backtracking, which lead to frequent re-routing and additional control signaling, making it the protocol with the highest control overhead at all simulation times. LEACH-V utilizes a round-based clustering mechanism, which results in the transmission of scheduled control messages regardless of need. Although its overhead rises over time, it remains more predictable than Q-EER and P-GEDIR. The MEBCR reduces routing overhead by integrating mobility estimation with energy-aware clustering, minimizing route discoveries, and efficiently managing control messages. This balance includes both scalability and communication efficiency in VANETs.

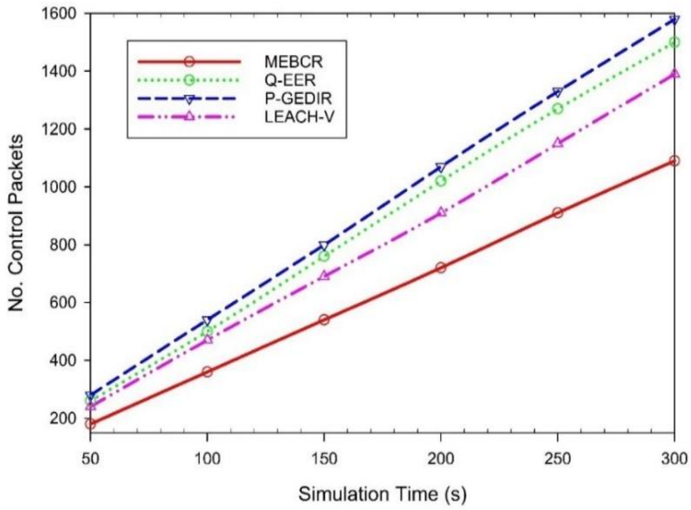

Figure 3. Routing Overhead

D. Energy Efficiency

Energy efficiency refers to the optimal utilization of energy resources by network nodes to maximize operational lifetime and preserve network integrity. It measures how effectively a routing protocol reduces energy consumption during communication tasks such as data transmission, reception, processing, and routing while ensuring reliable and timely data delivery. As shown in Figure 4, the proposed MEBCR exhibits higher energy efficiency compared to the other protocols. By estimating node mobility, MEBCR reduces needless communications, including frequent route repairs and cluster reformations. These are significant reasons for energy depletion. CHs are chosen depending on stability, velocity, and residual energy. This ensures that minimum-energy nodes are not tired with overhead jobs. At 300s, MEBCR holds approximately 75.1 Joules, which is 7-16 Joules more than other protocols (67 Joules for Q-EER, 58.9 Joules for P-GEDIR, and 68 Joules for LEACH-V). This corresponds to a 10-28% improvement in energy preservation. This indicates that MEBCR extends network lifetime and maintains sustainable operations under mobility. In contrast, Q-EER's reactive nature leads to repeated route rediscovery, and nodes can be overused unevenly due to a lack of mobility estimation and energy awareness. Its energy curve shows a steady but descending curve, albeit sharper than that of MEBCR. Due to frequent location broadcasts, reactive forwarding, and void handling, P-GEDIR assumes heavy energy loss. This produces high control traffic and speeds battery depletion. Despite its routing efficiency, the communication overhead exceeds its advantages. LEACH-V firstly performs better than Q-EER and P-GEDIR due to its clustering mechanism. Still, depending on random CH rotation, it sometimes gives overhead jobs to droopy nodes, creating an energy imbalance. As mobility rises, its performance deteriorates.

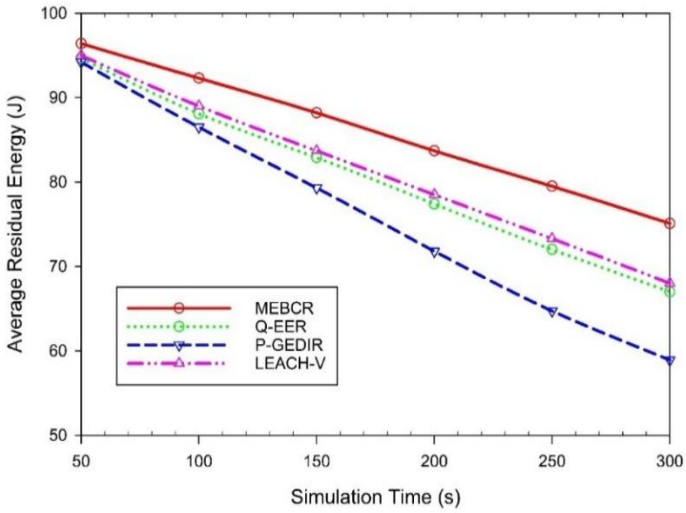

Figure 4. Energy Efficiency

E. Network Lifetime

Network lifetime refers to the duration of time a network remains operational and connected from the moment the network becomes active until a specific, stringent condition is met. As shown in Figure 5, the proposed MEBCR has the longest extended network lifetime among all compared protocols. At 300s, 91 out of 100 nodes are still alive, significantly outperforming the alternatives. This improvement enables MEBCR to utilize mobility estimation, energy-aware, and balanced load distribution to avert overburdening specific nodes. By minimizing retransmissions and limiting rerouting, MEBCR conserves energy while preserving stable clusters and averting packet flooding. In contrast, Q-EER nodes fail at 100s due to repeated route breaks and energy-inefficient rerouting. By the 300s, only 63 nodes remained alive, resulting in a 37% node death rate, which highlights the lack of load-balancing mechanisms. P-GEDIR has a short lifetime, with only 53 surviving nodes at 300s. It depends on high control overhead, frequent location broadcasts, and void handling, which results in high energy exhaustion and bad scalability. LEACH-V initially shows better performance through clustering; however, its random CH rotation ignores residual energy, which leads to early node failures. At 300s, 79 nodes survive, superior to Q-EER and P-GEDIR but still 12 minimum than MEBCR. This corresponds to a 13-42% improvement in node survival under MEBCR.

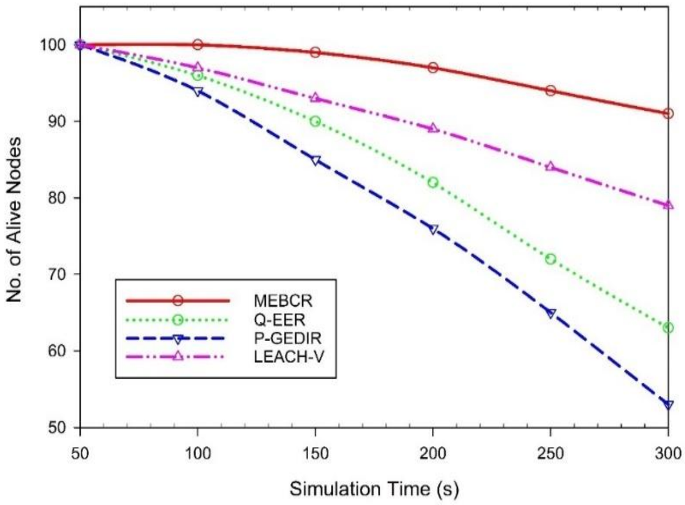

Figure 5. Network Lifetime

F. Cluster Stability

Cluster stability refers to a state in which the CH and its member nodes remain linked with each other for an extended period despite mobility or topology variations. As shown in Figure 6, the proposed MEBCR is the most stable across all mobility levels and exhibits the fewest cluster variations in high-speed environments. MEBCR achieved robustness by combining mobility estimation, which utilizes historical movement and direction estimation, with the choice of stable, slow-moving nodes as CHs. As node speed rises, MEBCR scales gracefully, preserving a minimum rate of reclustering. At 60 km/h, MEBCR has 15 cluster variations, which is fewer than 60% compared to Q-EER (38 clusters), 53% compared to P-GEDIR (32 clusters), and 48% compared to LEACH-V (29 clusters). By contrast, Q-EER lacks clustering and mobility awareness. As speed rises, frequent route repairs and implicit, unstable groupings lead to high instability. At 60 km/h, Q-EER exhibits 38 cluster variations, the worst among the protocols. P-GEDIR is directional but uses reduction cluster management. At higher speeds, the forwarding regions vary, triggering virtual cluster reorganizations. It's more stable than Q-EER but still less than MEBCR. LEACH-V employs frequent clustering but is not speed-adaptive. It's random CH chosen removes mobility factors, which causes early cluster degeneration as speed rises; stability decreases significantly above 30 km/h.

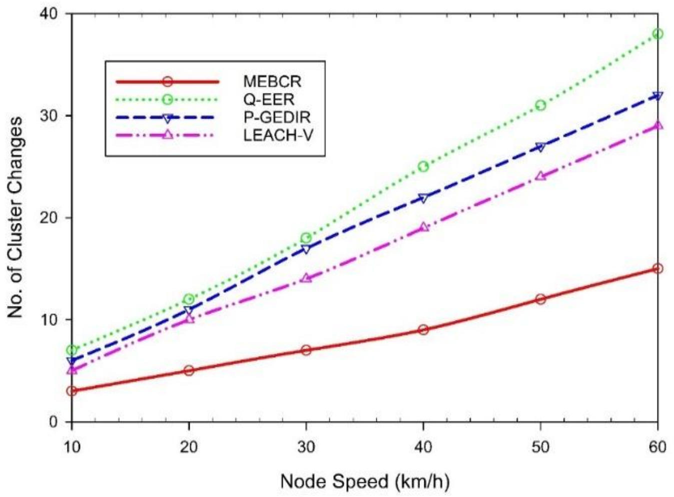

Figure 6. Cluster Stability

5. CONCLUSION

Many routing protocols fail to address the impact of high vehicular mobility and limited energy resources, especially in modern VANETs, which increasingly rely on EVs and SP-RSUs, which face persistent challenges related to energy consumption, routing efficiency, and stability. These limitations often result in unstable communication, frequent rerouting, and minimized network lifetime. To address these challenges, this paper introduced the MEBCR protocol, which leverages stable cluster formation, energy awareness, and mobility estimation to ensure reliable communication and extended network sustainability. The outcome of our proposal demonstrates that outstanding performance is achieved by preserving more energy and maintaining node survival. Moreover, it exhibits fewer cluster varians under high-speed mobility. These results assure the robustness, scalability, and adaptability of MEBCR. The significance of these findings lies in MEBCR's capability to balance between energy consumption, minimize control overhead, and prolong operational lifetime. This makes it fully-suited for VANETs and IoT-enabled mobility systems. MEBCR provides a practical foundation for next-generation intelligent transportation and communication networks, ensuring high packet delivery and low latency even in high-speed scenarios. While MEBCR demonstrates considerable improvements, certain limitations exist. The protocol has been evaluated fundamentally through simulations, which may not provide a thorough explanation of real-world VANETs with various traffic, environmental conditions, and hardware restrictions. Furthermore, network slicing, edge computing, and ultra-reliable low-latency communication are needed to develop to support 5G/6G lineaments operation. Future work can address these restrictions, leading to intelligent transportation systems in the next generation, which would raise their applicability.

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