IAES International Journal of Artificial Intelligence (IJ-AI)
Vol. 15, No. 1, February 2026, pp. 229~236
ISSN: 2252-8938, DOI: 10.11591/ijai.v15.i1.pp229-236

Efficient data streaming in dynamic vehicular networks: a hybrid controller for seamless connectivity

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Article Info

Article history:

Received May 15, 2025
Revised Dec 24, 2025
Accepted Jan 10, 2026

Keywords:

Artificial intelligence
Controller
Data transmission
Internet-of-vehicle
Routing
Vehicular network

ABSTRACT

The demand for highly efficient data transmission is being increasingly demanded for dynamic vehicular networks progressively especially in the case of internet-of-vehicle (IoV). The current data transmission methods are known to encounter inefficiencies in terms of unreliable routing and restricted scalability. Evolving studies have found artificial intelligence (AI)-based schemes more suitable to address these issues; however, there are no significant innovations towards developing a potential framework that can not only increase data transmission performance but also minimize the analytical overheads of AI. Hence, this paper presents a novel baseline framework by introducing an optimized controller structure at anchor points with the inclusion of novel ideologies of orientation degree and selection of mediating node. The proposed model witnesses 32.3 dB of signal quality, 857 kbps throughput, 81 ms delay, and 171 ms of response time, exhibiting much better performance in contrast to the frequently used data transmission method. The proposed model contributes to a solid foundation for any futuristic AI model for efficient and reliable data transmission in IoV.

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1. INTRODUCTION

Internet-of-vehicles (IoV) permits a large network of vehicles using satellites, Wi-Fi, and cellular networks, along with the usage of artificial intelligence (AI) and big data to offer predictive maintenance, smart traffic management, and autonomous driving [1]. However, IoV differs from vehicular adhoc network (VANET) in various perspectives. Here, the former deals with AI-based decision-making or using big data analytics, then the latter is found to use real-time coordination primarily [2]. Further, the range of connections and device inclusion in IoV is far higher and more complex than in contrast of VANET. At present, there are various studies claiming for evolved routing strategies in IoV [3]–[5]; however, there are wide-open set of challenges in current times.

There are various types of shortcomings when it comes to performing data transmission in the vehicular network of IoV, which are frequent alterations in topology, intermittent connectivity, and issues of local maxima in geographic routing, [6]. Scaling the data transmission scheme to millions of vehicles in IoV is another practical challenge, which also leads to extensive overhead towards maintaining frequent updates of routes that adversely affect routing performance [7]. Apart from this, there is also a frequent exchange of control messages, which is mainly used either for route maintenance or for route discovery operations. Such a task not only uses excessive channel capacity but also consumes processing overhead. From the perspective of delay-sensitive applications in vehicular networks, it is noted that the majority of the applications towards collision avoidance demand a minimal score of end-to-end delay, while conventional data transmission schemes may not actually cater to the demands and constraints of real-time applications in IoV [8], [9]. Because of all the above-mentioned issues, it is very challenging to practically maintain stable routes yielding to unreliable communication.

In all these contexts, AI has a potential scope in addressing these issues [10]. Basically, AI models are capable of learning optimal decisions of routing that further facilitate context-awareness to be incorporated during data transmission, even in a complex environment. Machine learning algorithms are known to contribute to prediction towards trajectories of vehicular nodes, which can definitely contribute towards route stability. Apart from this, AI incorporation can also contribute towards route optimization for minimizing energy consumption, which is highly helpful when dealing with resource-constrained devices in IoV.

There is no denying the fact that AI is a better solution; however, there is not much attempt to create a suitable baseline architecture for supporting advanced AI for effective data transmission in IoV. In the majority of existing studies [11], the model acquires a dataset from a publicly available resource, subjects it to standard normalization, and directly feeds it to different variants of AI. By adopting such a strategy, the extent of innovation is solely dependent on the AI model, whereas there are good chances to reframe the baseline model and incorporate much of logical operations, which could further minimize the operational and computational load on the AI module and yield better optimized results at the same time. Unfortunately, there are few such ideologies being incorporated in the existing system, working towards this direction.

The related work associated with various data transmission schemes for advanced vehicular networks has been studied. It is noted that there is frequent work carried out using a type of scheme which uses data transmission based on position, where the node residing near to destination node receives the data packet. In the absence of such a greedy forwarding scheme, such methods use perimeter forwarding. Considering naming this method as CMet1, there are various works carried out in [12]–[15]. Another frequently used data-transmission method is found to jointly use topology-based data integrated with position-based routing. Considering naming this method as CMet2, such approaches often evaluate anchor points using street graphs where data packets are transmitted from one anchor to another (anchors are typically the intersection points). This method is witnessed in work carried out in [16]–[19]. There are also various existing studies emphasizing towards formulation of data transmission during an emergency. Considering the name of such approaches as CMet3, various authors in [20]–[25] have presented solutions to perform message dissemination during distress conditions.

The research problems identified are as follows. First, the majority of the existing CMet1 schemes lack consideration of bandwidth, reliability, and delay, even if they offer better scalability and minimal overhead. Second, a maximum of CMet2 methods suffer from carrying outdated information of the path, even if they have better performance on urban scenarios with enhanced routing decisions. Third, CMet3 methods induce computational expenses, especially in terms of higher bandwidth usage, and hence they are not resource efficient, especially in the case of dynamic street topology. All these are actually open-ended research challenges that need to be addressed immediately.

The aim of the proposed study is to develop a novel computational model towards managing larger streams of traffic data, along with leveraging interactive services among vehicles using a newly optimized controller system for mediating nodes. The proposed system introduces a baseline model that could perform more logical, cost-effective computational operations for leveraging AI operations in IoV. The term mediating nodes refers to those intermediate vehicular nodes that connect two vehicles' communication systems when they are found residing at common sensing-transmission zones of both vehicular nodes. The idea is to bridge the communication when two sensing regions of two vehicles don’t intersect each other, but have a common node called a mediating node between them.

The value-added contribution of proposed study are as follows: i) the proposed study introduces orientation degree for optimizing the decision of data transmission in vehicular networks that can assess signal quality, mobility, and relative position between two nodes; ii) the introduced scheme improves the data transmission efficiency by incorporating a selection mechanism for mediating nodes dynamically based on communication capabilities, mobility, and proximity; iii) the proposed scheme supports vehicle to everything (V2X) where standalone communication capabilities of a vehicle is encouraged as well as vehicle can take assistance of infrastructure-based communication too; and iv) the presented framework is found to offer an improved scalability permitting managing voluminous vehicle for a defined road segment. It is to be noted that the proposed study considers the controller to be a communication device mounted in the middle of an intersection of multiple lane segments. The controller device extracts information from incoming vehicles and generates an outcome of a specific decision of a path to be considered as an exit.

2. METHOD

The prime aim of the proposed study model is to construct a novel software modelling towards streamlining the traffic flow, along with an introduction to an optimized traffic controller system for mediating communication services for the IoV system. The complete framework is designed considering certain essential operational modules, viz., smart processing of on-board unit (OBU), formation of clustering grid, and selection of mediating node. The sole purpose of this adopted methodology is towards ensure scalable facilitation of data streaming with real-time and adaptive performance; much needed for the dynamic environment of vehicular networks. Figure 1 highlights the adopted layout of the proposed study model.

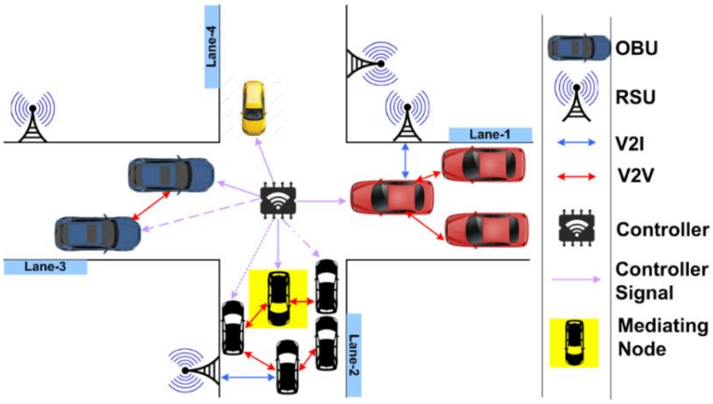

Figure 1. Layout of proposed model

According to Figure 1, it can be noted that there are various operational modules involved in the design structure of the proposed layout. Each operational blocks are meant to execute a specific task and is also interconnected with the other. A simplified mathematical operation is carried out to accomplish this task. The following is the briefing of mathematical modelling within each operational module of the proposed study.

2.1. Smart processing of on-board unit

The aim of this first module is to construct a local unit of communication known as OBU within the vehicle before formulating a routing decision. The study considers that a smart OBU is mounted on each vehicle that performs multiple tasks associated with data packets before actually sensing them, viz., buffering the stream, filtering the flow, and categorizing the packets. The mathematical expression towards the data stream, acting as input feed, is represented as (1).

$$D_{in}(t) = \sum_{i-1}^{N} P_i(t) \tag{1}$$

In (1), it can be noted that quantification of an incoming data stream $D_{in}(t)$ is dependent upon the number of data packets/services N and the i^{th} data packet obtained at t^{th} time i.e., $P_i(t)$. The proposed system also links a priority value π_i, considering a range of [0, 1] with each $P_i(t)$ data packet. Hence, it will mean that if π_i=1 that it will represent services with higher priority, while if π_i=0 will represent services with lower priority (e.g. entertainment-based services). This can be further simplified in the form of a mathematical expression as (2).

$$F_i(t) = \begin{cases} 1, & if\ \pi_i > \delta \\ 0, & otherwise \end{cases} \tag{2}$$

In (2) showcases the variable δ to represent the priority cut-off score defined by a system towards the computation of the filtering function $F_i(t)$ with priority awareness. Hence, the final mathematical expression of the effective data stream will be as (3).

$$D_{ef}(t) = \sum_{i-1}^{N} P_i(t).F_i(t) \tag{3}$$

In (3) represents that all the OBUs interconnect themselves to form a possible network with the vehicular interface, while a priority cut-off score is used for filtering the incoming data packets for assessing their type and urgency. All the buffered data packets are arranged in the form of a queue while they are further forwarded selectively depending on their available signal quality, vehicle direction, and channel capacity. The proposed system differentiates from the existing system by incorporating smart and calculated decision-making, while conventional study models on vehicular networks usually consider OBU as transceivers with usual functionality towards communication. They are also devoid of adaptive capabilities of storing intelligent filtering. On the contrary, the smart OBU in the proposed study model plays the role of a preprocessing computational module that fuses dynamic buffer management with data filtering with priority awareness. This causes drastic minimization of network overhead and hence contributes to improved packet quality during data forwarding operations.

2.2. Formation of clustering grid

The prime aim of this module is to perform a logical partitioning of the IoV environment into multiple controlled communication zones for facilitating local decision-making and minimizing data transmission complexities. The proposed study uses a clustering grid for partitioning the geographic simulation area depending on the deployment of the roadside unit (RSU). Considering A as a simulation area where a square cluster of size lxl is managed by RSU. Hence, cumulative C clusters can be mathematically defined as (4).

$$C = \frac{A}{l^2} \tag{4}$$

In (4) states that the simulation area A is classified into C number of clusters such that A=L×W and c_j∈C with a defined set of operational vehicles $V_j(t)$, consists of multiple number of m vehicles (v_1, v_2, … v_m). The system also uses R_j as a local data transmission protocol towards the topology of adopted clusters. Hence, it will mean that the road network is classified into equal-sized clusters, which are controlled by the RSU. A localized protocol is assumed to be used for enabling communications among the vehicles, giving importance to the density of clusters. The mathematical formation of the density of the local cluster is represented as (5).

$$\rho_j(t) = \frac{|V_j(t)|}{l^2} \tag{5}$$

In (5), it can be noted that the computation of the density of local cluster ρ is very much dependent upon operational vehicular nodes V and the squared size of cluster l^2. Apart from this, the proposed system also maintains a local routing table by all cj clusters, which is mathematically depicted as τ_j ={(v_i, θ_i, QoS_i)}, where the degree of orientation associated with a vi vehicular node is represented as θi while matrix *QoSi* consists of the capacity of buffer information and availability of channel capacity. Hence, each operational vehicular nodes are tracked by the RSU along with monitoring the quality of communication and mobility direction using the degree of orientation and density attributes, respectively. Gateway nodes are assumed to be used to support inter-cluster communication.

However, it is to be noted that conventional hybrid methods usually don't deploy geographic clustering explicitly, and they are found to be highly dependent on generic data transmission schemes that lack any form of localized intelligence inclusion. This leads to maximized overhead in conditions of dense traffic by the existing system. On the contrary, the proposed model introduces a clustering grid for improving stability and scalability in the IoV environment with higher dynamicity. Apart from this, this module also facilitates parallel decision-making of routing that significantly enhances adaptability and minimizes latency in mobility scenarios of IoV.

2.3. Selection of mediating node

The aim of this module is to offer an adaptive and reliable multihop communication base by choosing the best mediating vehicular nodes considering their communication reliability and spatial orientation. For every data packet, the degree of orientation is computed between source nodes, along with the computation of destination and potential mediating nodes. The proposed system uses the degree of orientation in order to control the selection process of mediating nodes for offering efficient transmission of data. This is basically done to accomplish enhanced stability and directional alignment in the IoV environment. The mathematical expression for the degree of orientation angle is as (6).

$$\theta = cos^{-1}\left(\frac{\vec{v}_{sr}.\vec{v}_{rd}}{|\vec{v}_{sr}||\vec{v}_{rd}|}\right) \tag{6}$$

In (6), the variables $\vec{v}_{sr}$ and $\vec{v}_{rd}$ represents the communication vector from the source node to the mediating node and the mediating node to the destination node, respectively. It should be noted that higher alignment is identified in the presence of a reduced score of the θ orientation angle. A new form of empirical function known as the utility function U is determined for assessing the suitability of the mediating node, considering motion direction, signal strength, and buffer status. Further, the proposed system deploys a utility function U with respect to mediating node v_r that is mathematically represented as (7).

$$U(v_r) = \alpha.\left(1 - \frac{\theta}{\pi}\right) + \beta.\left(\frac{B_r}{B_{max}}\right) + \gamma.\frac{S_r}{S_{max}} \quad (7)$$

In (7), the computation of the utility function U is carried out with respect to the orientation angle θ, signal strength S_r existing between transmitting node v_s and mediating node v_r, maximum buffer B_{max}, maximum value of signal S_{max}, and buffer space B_r for mediating node v_r. Apart from this, the (7) also considers entities α, β, and γ to represent multiple weight coefficients that are empirically tuned. Hence, the expression for the optimal mediating node is as (8).

$$v_r^* = arg_{v_r \in N(v_s)}^{max} U(v_r) \quad (8)$$

In (8), the variable $N(v_s)$ represents a single-hop neighboring node of the transmitting vehicular node. Hence, only the node with the maximum score of the utility function is considered as the mediating node. Further, the system instantly constructs multihop paths without any dependencies for discovering a complete end-to-end route. Existing data transmission schemes mainly rely on either a location-based forwarding strategy or perform route discovery at regular intervals. Both conditions are actually static and do not have any inclusion of dynamic orientation involved in modelling. Hence, different from existing schemes, the proposed system uses this module to introduce a selection method of mediating nodes with direction awareness known for adapting mobility patterns in real-time, thereby ensuring robust routes and more stability. It can now be stated that the proposed system offers reliable packet delivery and link longevity by its inherent inclusion of motion-based filtering and orientation attributes.

3. RESULT AND DISCUSSION

The implementation of the proposed study is carried out considering 500 vehicular nodes simulated on a 1,000×1,100 m^2 area with 2-10 m/s of vehicular speed and 2,000 bytes of packets. The proposed logic was scripted in MATLAB and has been compared with three state-of-the-art methods, CMet1, CMet2, and CMet3, considering four performance metrics, e.g. signal quality, response time, delay, and throughput. Table 1 highlights the numerical outcome of the study. The outcome shows the proposed system Prop to excel in better performance in every sense. The numerical outcome in Table 1 exhibits the following facts: the proposed model, Prop, excelled in superior performance mainly due to the inclusion of the clustering grid and selection of mediating node using orientation degree. This inclusion not only minimizes loss of data packets but also enhances link stability. Although CMet2 is found to perform slightly better in the presence of lighter condition of load conditions, the Prop successfully facilitates minimal response time mainly due to its local decision-making with smart OBU under dynamic vehicular traffic conditions.

Table 1. Numerical outcome of study

Performance metric	CMet1	CMet2	CMet3	Prop
Signal quality (PSNR in dB)	24.8	26.1	27.4	32.3
Response time (ms)	284	241	198	171
End-to-end delay (ms)	158	131	108	81
Throughput (kbps)	532	619	718	857

Prop also offers robust connectivity, which is mainly due to the inclusion of a data transmission strategy using the degree of orientation, even in the presence of sophisticated traffic conditions, potentially minimizing end-to-end delay. Further, a better form of utilizing channel capacity is facilitated by Prop due to adaptive load balancing and a mechanism to split the traffic stream. This eventually leads to a significant enhancement in throughput in contrast to all conventional models.

Figure 2 exhibits the graphical outcome of comparative analysis obtained from Table 1 for better interpretation of outcomes from a visibility perspective. Specifically, Figure 2(a) illustrates the signal quality, Figure 2(b) presents the response time, Figure 2(c) depicts the end-to-end delay, and Figure 2(d) shows the throughput performance. The discussion of the outcomes is as follows: the inducement of orientation degree is quite a novel approach in a routing metric for dynamically assessing the communication quality. This scheme contributes to affinity evaluation between the vehicular nodes and all the possibilities analysis for maintaining a reliable connection. Hence, even without using any conventional AI methods, the logical operation involved in Prop serves a similar purpose but with low computational cost and devoid of any resource dependencies of resources. The proposed system Prop also introduces a selection mechanism of a mediating node, which has not been reported in any existing literature. Interestingly, Prop is capable of minimizing unwanted retransmission and enhancing the throughput and response time. Different from conventional models, Prop is capable of adapting to changes, which is highly necessary in IoV operations. Another significant novelty of Prop is its joint operation of fixed access point (RSU) and mobile mediating nodes (vehicular node), which makes it suitable for both urban, rural, and highway traffic systems. Prop offers enhance flexibility and scalability even in the presence of extensive traffic in peak instances in IoV, thereby offering a highly reliable communication solution.

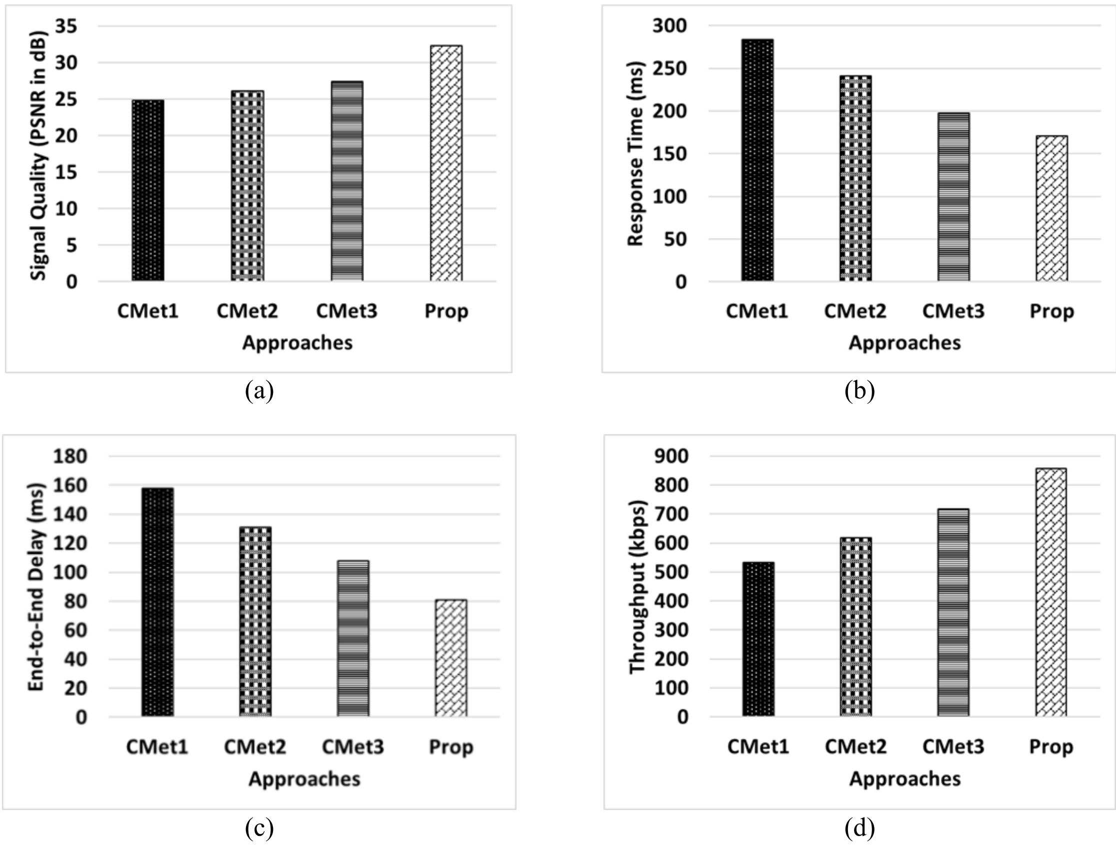

Figure 2. Accomplished study outcome for (a) signal quality, (b) response time, (c) end-to-end delay, and (d) throughput

4. CONCLUSION

This paper presents a novel baseline framework with a controller design that is meant exclusively towards enriching the analytical performance of an AI-based IoV communication system. The contribution of proposed study model are as follows: i) different from frequently adopted data transmission approaches, proposed system is found to offer enhanced signal quality, minimized response time, lower end-to-end delay, and improved throughput; ii) the novel introduction of orientation degree in the form of a routing attribute contributes towards optimal selection of routes; iii) the joint effort of fixed access point and mobile mediating node contributes towards seamless connectivity on multiple environments of vehicular traffic in IoV; and iv) the dependencies towards either fixed-path or single-hop routing in conventional data transmission methods is potentially minimized in proposed model thereby offering more dynamic process of data transmission in vehicular network. The future work will be towards extending the same baseline model for incorporating machine learning models for further witnessing optimized results. The enhanced outcomes of routes obtained from this baseline model will further be optimized in future work on related performance metrics with better and reliable prediction accuracy.

FUNDING INFORMATION

The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Mayuri Kundu		✓		✓		✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [AB], upon reasonable request.

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