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Research Article

Enhancing Routing Efficiency in VANETs by Leveraging 5G to Mitigate Congestion

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Abstract

Transportation networks impact millions of people daily. Their efficiency immediately affects travel time, safety, and environmental sustainability. Unfortunately, various issues hinder the expected performance and efficiency of these networks. Traffic congestion is an up-to-date issue in the urban environment. Fuel consumption is high because travel time has increased, which has a passive environmental impact. Extensive research has been conducted to progress the intelligent transportation systems installed on communication networks and information to treat this congestion. However, there is a significant amount of affront residue in combining real-time data, estimation analytics, and 5G abilities effectively. This paper offers a novel routing algorithm integrating vehicular ad hoc networks with 5G technology to increase routing efficiency and minimize congestion. This routing is named 5G adaptive traffic management (5G-ATM). It collects real-time data from connected vehicles and roadside units to estimate traffic status and congestion. Out of simulations in an urban environment, the proposed 5G-ATM routing significantly progresses over previous routing protocols, such as an ant colony-inspired energy-efficient for optimized link state (AC-OLSR) routing and directional-cache agent-based location-aided (D-CALAR) routing. During rush hours, 5G-ATM shows the lowest traffic congestion events. Moreover, it minimizes average travel times by almost 8% compared to D-CALAR and 21% compared to AC-OLSR. These outcomes suggest that combining vehicular ad hoc networks with 5G technology helps manage traffic more efficiently, providing an efficient pathway and practical transportation systems.

1. INTRODUCTION

From modernistic infrastructures, such as intelligent and sprawling cities, to rural regions, roadways supply everyday mobility for millions of people [1, 2]. In the United States alone, 350 million individuals travel approximately 3.2 trillion vehicle miles on public highways [3-5]. Currently, many roadways are burdened by congestion. In 2024 alone, the average American commuter wasted upwards of 43 hours in traffic, nearly threefold from 1982. During that same span, the miles driven on U.S. roadways skyrocketed from approximately 1.6 to 3.2 trillion [6-8]. The problem is global; one study detailed that in areas from Tokyo to São Paulo, the average commuter wasted between 192 and 500 hours per year on the road [9-11]. In urban areas, travelers face significant difficulties due to increasing traffic congestion [12-14]. Inefficient traffic routing leads to traffic accidents, deaths, and environmental pollution. An essential component in alleviating congestion and ensuring road safety is efficient and dynamic traffic routing. Vehicular Ad Hoc Networks (VANETs) play a necessary part in this status by enabling real-time communication and data sharing between vehicles and infrastructure. This led to the implementation of a smooth adaptive traffic management system that can react to rapidly variable traffic conditions. Great efforts have been made to develop intelligent transportation systems that rely on information and communication networks to address congestion [15-17]. VANETs are an evolution of these networks, which coordinate traffic by sharing real-time data between vehicles and thus improve safety.

The unique characteristics of VANETs generate many restrictions and affect the robust routing performance within the range. [18-20]. Overcoming these complex routing restrictions is urgently needed to establish an intelligent transportation system that relies on convenient mobility and can leverage connected vehicle technology for dynamic and efficient traffic routing [21, 22]. Wireless networks are predominantly ad hoc, leading to many routing challenges. As with ad hoc networks, the

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dynamic nature of vehicular topologies presents its own set of unique routing challenges. Detecting these vehicular traffic-related core issues further highlights the need for research in developing routing optimizations within the vehicular environment [23-25].

Various protocols can be designed to discover the most efficient routes. The main challenge of these protocols is relying on on-demand route discovery without real-time traffic data integration. They don't actively adapt to changing traffic conditions, leading to a delayed response to congestion [26, 27]. Earlier implementations often utilized older communication technologies like 4G, which may introduce latency and limit data transfer rates, impacting the effectiveness of real-time data usage. Moreover, they experience performance degradation in high-density traffic scenarios due to increased overhead and route discovery delays. While some studies have considered environmental factors, they often don't comprehensively address fuel efficiency and emissions in routing decisions [28, 29].

Today, few systems can effectively deal with large amounts of vehicular data in real-time. Fortunately, the arrival of 5G mobile networks benefits networking infrastructure for heterogeneous data transfers across multiple target systems [30-32]. However, there is a distinct lack of a clear and coherent vision linking 5G augmented vehicular communication to breaking the bottlenecks posed by the sheer scope and complexity of the systems needed to leverage this data [33, 34]. The convergence of VANETs with 5G technology has sparked considerable interest in recent years. The high data rates, massive device connectivity, and ultra-low latency in 5G promise to address VANET's longstanding challenges, such as routing inefficiency and network congestion [35-37]. Although 5G has introduced numerous improvements in VANET routing, these recent protocols still face challenges regarding routing efficiency and congestion.

In this paper, we propose a 5G adaptive traffic management (5G-ATM) routing algorithm. The motivation behind our study is to integrate VANETs with 5G in urban environments. It leverages 5G's ultra-low latency and high bandwidth in combination with traffic estimation, sustainability-aware routing to address the previous challenges. The main objective of the proposed 5G-ATM routing algorithm is to ensure stable performance under varying traffic densities, while proactively mitigating congestion before it degrades network service. The significant contributions of this paper are as follows:

1- Use real-time data continuously collected from vehicles and roadside units (RSUs) to make proactive routing decisions, and integrate live traffic information with estimation analytics.

2- Utilize advanced estimation analytics that integrate real-time and historical traffic data to estimate congestion, allowing smoother traffic flow and proactive bottleneck reduction. This surpasses classic reactive routing methods.

3- Leverage 5G technology's ultra-low latency and high bandwidth to achieve faster and reliable communication between vehicles and infrastructure. This involves overcoming the latency and throughput restrictions of previous VANET protocols.

4- Investigate dynamic route adjustments and efficient data treatment for high vehicle density environments. This reduces congestion events such as peak-hour and long intersection delays. That will enhance total traffic management in urban environments more effectively than the present static or minimal adaptive routing protocols.

5- Merge fuel consumption and environmental sustainability metrics immediately into the routing decisions, which reduces travel time and carbon footprint. That provides routing optimization beyond performance to environmental regard, which is little covered in previous works.

The remainder of this paper is divided as follows: Section 2 discusses related works. Section 3 describes the proposed routing algorithm and the case study. Section 4 presents the simulation parameters and the results. Finally, in Section 5, we conclude the research and suggest future directions.

2. RELATED WORKS

Although numerous protocol improvements have been made in VANET, it still faces challenges regarding routing efficiency and network congestion. In this section, we summarize some of these recent router protocols.

An ant colony-inspired energy-efficient OLSR (AC-OLSR) routing protocol is proposed in [38]. The authors utilized mobile factors to assess the pheromone condensation of the native environment cognitively. This data was applied to set apart multipoint relays. Eventually, the cost function was integrated into the optimized link state routing (OLSR) protocol. The advantages of this protocol are energy-efficient routing and leveraging ant colony optimization to reduce energy consumption. Enhanced network longevity by minimizing redundant transmissions. Improved packet delivery ratio due to the adaptive nature of the algorithm. Moderate scalability through optimal link-state routing. Ant colony optimization increases the computational overhead on the contracts, making it less suitable for large-scale VANETs with high mobility. Performance may degrade in high-density networks due to increased routing table size and computational demands. The protocol's efficiency in delay-sensitive applications may be limited, as ant colony mechanisms inherently require iterations for convergence.

A quality of service-inspired zone clustering and grouping (QoS-IZCG) routing protocol is proposed in [39]. The authors develop an existing zone-based routing scheme by optimizing clustering, which depends on considering the nodes' energy-consuming rate. Subsequently, they designed a quality of service (QoS) aware routing cost function to recognize the optimal route. The advantages of this algorithm are increased energy efficiency in zone-based routing protocols and optimized network lifetime by balancing energy consumption across nodes. Effective management of node mobility within zones reduced route discovery overhead and improved execution in terms of throughput and delay. On the other hand, the predefined zones may not adapt to dynamic network topologies in VANETs, which can lead to reduced routing scalability. Moreover, the energy savings may diminish in heterogeneous environments with varying node capabilities.

A greedy traffic light and queue-aware routing (GTLQR) protocol is proposed in [40], which enhances routing efficiency in urban VANETs. The GTLQR routing decisions combine real-time traffic status, vehicle queue lengths, and road connectivity. This protocol can help vehicles select next-hop nodes based on geographic proximity to the destination, in addition to current congestion levels and road availability. Moreover, it leverages periodic messages to collect neighbor and queue information to ensure context-aware routing. The advantage of GTLQR is the capability to minimize packet loss and delay in dense urban scenarios, where intersections and traffic signals affect mobility. However, GTLQR has some limitations, such as it depends on the accuracy and timeliness of queue length and traffic light data. This leads to it not always being available in real-world applications. Furthermore, the use of periodic messages leads to communication overhead. This affects performance in highly dynamic or low environments.

A directional-cache agent-based location-aided (D-CALAR) routing is proposed in [41]. The authors designed context factors for separate context-aware inter-vehicle interactions. This data contains the speed, the vehicle’s identity, and priority. The information is then stored in every vehicle’s cache list for routing. The advantage of this protocol is that it utilizes cache agents to reduce route discovery latency. Direction-based routing improves the accuracy of packet delivery in high-mobility VANET scenarios. Moreover, it reduced communication overhead and enhanced scalability for urban and highway environments. On the other hand, ensuring up-to-date cache information in high-mobility scenarios is challenging, potentially leading to stale route information. Using cache agents introduces extra overhead in maintaining and updating route information. The protocol is tailored for specific scenarios, which may limit its adaptability to diverse VANET environments.

A dynamic energy ad-hoc on-demand distance vector (DE-AODV) routing protocol is proposed in [42]. The authors consider the residual routing cost function, which uses the energy of nodes to recognize the route that consists of nodes with maximized energy. Suppose a node mutation to a lower energy state occurs when transmitting data. The protocol uses an independent mechanism of utilizing external batteries to look after the immediate link. The advantages of this protocol are that it focuses on power-aware routing, prolonging the network’s operational life. Ensures energy-efficient path selection, reducing battery drain on individual nodes. Moreover, it maintains network connectivity through adaptive power control, enhances throughput, and minimizes packet loss. In contrast, relying on energy metrics alone may not account for other crucial factors like link stability or traffic conditions. Performance may degrade in high-mobility environments where energy levels fluctuate rapidly. It may not perform optimally in heterogeneous networks with mixed energy capabilities.

With the advent of 5G, vehicle connectivity is further enriched by improving commercially feasible, robust, efficient, and secure routing protocols.

The salient features of the 5G wireless network that can enhance the VANET are the considerable bandwidth and the use of various spectrum technologies, offering a wider opening and covering multiple ranges of frequency bands, which can surmount the attenuation due to atmospheric absorption and free path loss [43]. This extends the life of the battery, thus reducing the frequency of recharges of infrastructure nodes. Packet routing is executed based on the signal strength received by adjacent forwarders. The delivery of data packets is quicker without interruptions when finding the route over a complex VANET using wireless channels [44, 45]. Deploying 5G in VANETs directly addresses some of the problems in VANETs. It can provide an efficient and robust technique to avoid or mitigate such issues because of the wider bandwidth and low-latency-enabled facilities [46, 47].

Despite many improvements in VANET routing protocols, current routing protocols first depend on reactive or heuristic approaches that do not blend congestion control estimation [48, 49]. Many protocols reduce the integration with real-time data from the emerging 5G infrastructure. This limits their understanding of such dynamic and dense traffic environments. Moreover, present solutions fail to optimize routing efficiency, decrease latency, and improve environmental sustainability within a merged framework. These gaps stand out as the pressing need for routing algorithms such as the proposed 5G-ATM. This leverages estimation analytics, real-time 5G-enabled communication, and eco-friendly metrics. To supply adaptive, low-latency, and sustainable traffic management in urban VANET scenarios. TABLE I shows the comparison of 5G-ATM vs. existing algorithms.

TABLE I. COMPARISON OF 5G-ATM VS. EXISTING ALGORITHMS

Feature	**Proposed 5G-ATM**	**AC-OLSR**	**QoS-IZCG**	**GTLQR**	**D-CALAR**	**DE-AODV**
Objective	Minimize Congestion and Latency, Optimal Real-Time Routing with Estimated Traffic Management, and Eco-Friendliness	Enhance Routing with Energy Efficiency and QoS	Improve QoS in terms of Energy and Latency	Enhance Routing Performance by Combining Real-Time Traffic Status	Enhance Routing with Location-Aided Directional Caching and Agent-Based Logic	Energy-Efficient Routing for Mobile Networks
Approach	Heuristics (Estimation and Dynamic based on Real-Time Data)	Heuristics (Reactive Routing with Ant Colony Optimization)	Clustering (QoS-based Zone Clustering)	Position-based Greedy Forwarding	Location (Directional Caching, Agent-based Logic, and Location-Aided Routing)	Power Control (Energy-Aware and Route Optimization)
Metrics	Traffic Congestion, Travel Time, Fuel Consumption, Energy Efficiency, and Safety	Throughput, Packet Delivery Ratio, Energy Consumption, and Delay	Energy Consumption, Delay, Throughput, and Packet Loss	Queue Length, Traffic State, Relative Distance, Road Connectivity, and Channel Quality	Scalability, Adaptability, and Location-Aided Performance	Energy Consumption, Packet Delivery Ratio, and Routing Overhead
Routing Decision	Based on real-time data and Estimation Models (5G-enabled RSUs)	Based on Network Conditions Observed by Vehicles (Ant Colony Optimization)	Based on Zone Clusters and QoS Metrics	Based on the Congestion Level and Proximity to the Destination	Based on Directional Caching and Real-Time Location Data	Based on Energy Consumption and Routing Updates
Route Adjustment	Dynamic adjustment using Real-Time Traffic and Estimation Data	Dynamic Updates via Ant Colony Optimization, but No Real-Time Estimation Adjustments	Adaptive Adjustment based on Traffic Density and QoS Metrics	Dynamic based on Periodic Messages and Real-Time	Dynamic Updates based on Location, Caching, and Traffic Stats	Static Updates based on Energy Constraints and Node Mobility
Data Collection	5G-enabled RSUs, Vehicle Sensors, V2X Communication	Limited Data Collection (Node-to-Node)	Vehicles Within Zones Exchange Data	Periodic Messages (Queue and Traffic Data)	Rely on Location-Based Data and Directional Caching	Energy-based Data for Power Management
Traffic State Estimation	Detection to assess Congestion and Signal Quality	Limited	Limited	Moderate	Incorporates Real-Time Estimation based on Location and Direction	Limited
Estimation Traffic Management	Yes, using Historical Data and Real-Time Analysis	Non	Yes, It Estimates Congestion Based on QoS Metrics	Non	Yes, It Focuses on Short-Term Adjustments.	Non
Scalability	High (Scalable with 5G Infrastructure and Real-Time Data Collection)	Moderate (depends on Network Size and Mobility)	High (Effective in Large Networks with QoS Clustering)	Moderate (due to Overhead in Dense Networks)	High (due to Location-Aided Design and Efficient Caching)	High (Scalable with AODV's on-Demand Routing)
Energy Efficiency	High (considers Energy Consumption in the Cost Function)	Moderate (Energy-Efficient Routing based on Ant Algorithms)	High (Focuses on Reducing Energy Consumption in Zone-Based Routing)	No Explicitly Addressed	Moderate (Caching Reduces Energy Usage, but Real-Time Updates Increase Load)	High (Energy-Efficient Routing)
Security	Moderate (basic Security Features; Potential for Enhancement with V2X)	No Explicit Security Features	Moderate (Focused on QoS but Lacks Strong Security Measures)	No Explicitly Addressed	Moderate (Requires Additional Measures for VANET Specific Threats)	Low (Primarily Energy-Focused with Minimal Security Features)
Robustness	High (Real-Time Updates, Estimation Models Reduce Failures)	High (Handles Link Failures via Cooperative Mechanisms)	High (Adaptive Clustering Improves Robustness)	Moderate	High (Robust to Failures with Location and Caching Mechanisms)	Moderate (based on AODV, Vulnerable to Node Mobility and Energy Depletion)
Adaptability	High (Dynamic, Adaptable to Varying Traffic Conditions)	Moderate (Adaptation Occurs Reactively)	High (Adaptable to Changes in Traffic and QoS)	High (Adapt Routes based on Current Traffic and Signal Status)	High (Adapts based on Traffic and Location Data)	High (Adapts to Network Changes based on Energy and Mobility)

3. PROPOSED METHODOLOGY AND CASE STUDY

One crucial factor in 5G-ATM is the advantage of 5G's high bandwidth, which achieves low latency for collecting and disseminating real-time traffic data. It also develops a dynamic routing protocol based on traffic and vehicle density and estimates traffic in advance to manage routes. This section discusses the details of the 5G-ATM structure, followed by a case study scenario.

3.1 Proposed 5G-ATM Architecture for VANETs

The proposed 5G-ATM structure is a communication architecture for a vehicular network that integrates software-defined networking (SDN) and 5G technology for traffic management, as shown in Fig. 1. SDN is the central control for managing network traffic, which communicates with the 5G base station for network control. The 5G base station supplies centralized communication management and connects to RSUs wirelessly. The RSUs work as intermediary nodes between vehicles and the SDN controller, simplify vehicle-to-infrastructure (V2I) communication, and authorize handovers between RSUs as vehicles move through the road. Vehicles communicate with nearby RSUs for traffic updates and routing decisions. Vehicle-to-vehicle (V2V) communication is also used for real-time information sharing. TABLE II summarizes the essential mathematical notations used in the 5G-ATM procedure.

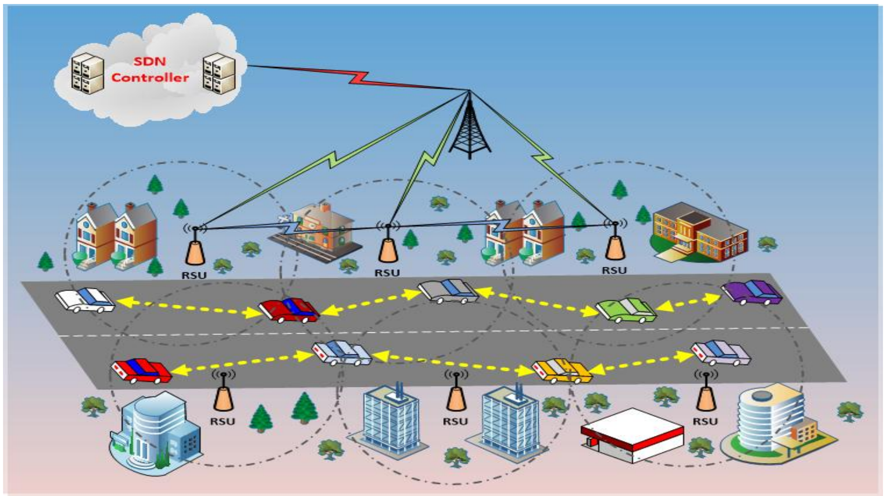

Fig. 1. Proposed 5G-ATM structure

TABLE II. SUMMARY OF THE ESSENTIAL MATHEMATICAL NOTATIONS

Symbol	Description
d	Traffic density levels
f	Traffic flow efficiency
N_A	Number of active vehicles on the road segment
L_{road}	Length of road segment
A	Average speed of vehicles
R	Rate of incoming vehicles
Ps	Probability of smooth flow (derived from historical traffic patterns)
γ	Environmental factors (liters per 100 kilometers)
D	Delay introduced due to current conditions
$C_{fun}(p)$	Cost function
$E_{tra}(p)$	Energy or fuel consumption for route p
$D_{ist}(p)$	Distance to the destination of route p
$R_{fact}(p)$	Risk or safety factor for route p
z_1, z_2, z_3	Dynamic weights are adjusted based on user preferences or real-time conditions
S_{rout}	Optimal route selection
P	Set of all potential routes
$C_{fun}(t)$	Estimated cost function for the future time
$\alpha_0, \alpha_1, \dots \dots \alpha_n$	Model coefficients derived from training

The 5G-ATM procedure starts with each vehicle collecting data on the density of surrounding vehicles, speed, and location (GPS coordinates or derived position). Then, 5G-enabled RSUs collect data from multiple vehicles within their coverage. This enables low-latency, high-bandwidth communication to analyze traffic flow across larger road segments. The central control coordinates RSUs to analyze the current traffic state using mathematical models and metrics. The d is used to identify traffic density levels (e.g., congested vs. free-flowing) and f refers to traffic flow efficiency on the road. They are calculated as equations (1) and (2):

$$d = \frac{N_A}{L_{road}} \tag{1}$$

$$f = \frac{R * Ps * \gamma}{D} \tag{2}$$

Central control is used to manage and coordinate network resources dynamically over traffic flow decisions while preserving flexibility and scalability across the network. This can provide real-time repetition of communication paths, efficient bandwidth, and enhanced performance in response to changing traffic status. To rank potential routes based on predefined metrics such as the cost function, as in equation (3):

$$C_{fun}(p) = z_1 * E_{tra}(p) + z_2 * D_{ist}(p) + z_3 * R_{fact}(p) \tag{3}$$

Optimal route selection by balancing travel time, distance, and safety. Include fuel/energy consumption as a cost metric for eco-friendly routing. Use dynamic weights (z_1, z_2, z_3) based on user preferences or real-time conditions. The cost of all available routes should be calculated to select the optimal route for each vehicle. Then, choose the route with the lowest cost as per the equation (4):

$$S_{rout} = argmin_{p \in P} C_{fun}(p) \tag{4}$$

To anticipate future traffic states from historical data, we employ an Autoregressive (AR) time-series model for estimation analytics, as equation (5):

$$C_{fun}(t) = \alpha_0 + \alpha_1 * C_{fun}(t-1) + \alpha_2 * C_{fun}(t-2) + \cdots + \alpha_n * C_{fun}(t-n) \tag{5}$$

Use this model to adjust routes proactively, avoiding estimated congested areas. Vehicle routes should be updated based on estimations and real-time monitoring, and then vehicles should be notified with selected routes. Traffic conditions are continuously monitored for dynamic route updates via RSUs and vehicle sensors. The updates are sent to vehicles in real-time to maintain optimal flow. Moreover, V2V Communication enables the rapid dissemination of route updates among nearby vehicles. This improves reaction times to changing conditions and reduces latency in route adjustments. Finally, routes are updated with minimal driver input for safety. The system prioritizes automation to minimize distractions for drivers. TABLE III provides pseudocode for 5G-ATM.

TABLE III. PSEUDOCODE FOR 5G-ATM

```
Algorithm: 5G-ATM for Leveraging 5G in VANETs
Input: Real-time vehicle data (location, speed, density)
Output: Optimal route for each vehicle, dynamic updates

1. Initialize RSUs with 5G connectivity
2. Each vehicle sends data to RSUs (density, speed, location)
3. RSUs aggregate data and calculate metrics: traffic density levels and traffic flow efficiency
4. RSUs send collected traffic data to central control to compute the cost function for all routes
5. Select an optimal route
6. Estimate future traffic states using historical data
7. Proactively update routes to avoid congestion
8. Enable V2V communication for faster dissemination of updates
9. Automate route updates with minimal driver intervention
10. Repeat steps 3-9 continuously for real-time traffic management

End Algorithm
```

3.2 Case Study Scenario: Urban Traffic Management in Erbil City

This section explains the scenario used in this paper as the case study. Erbil City is a mid-sized urban area experiencing significant traffic congestion, particularly during rush hours, as shown in Fig. 2. Erbil was chosen as the case study location due to its improving urban infrastructure and growing vehicle density. Moreover, individual traffic patterns are characterized by mixed traffic flows, frequent congestion at intersections, and a reduction of completely automated traffic management systems. These characteristics make Erbil an ideal environment for assessing the proposed 5G-ATM. Moreover, the implementation of an intelligent traffic management system has been raised by the local government to reduce congestion and improve travel efficiency.

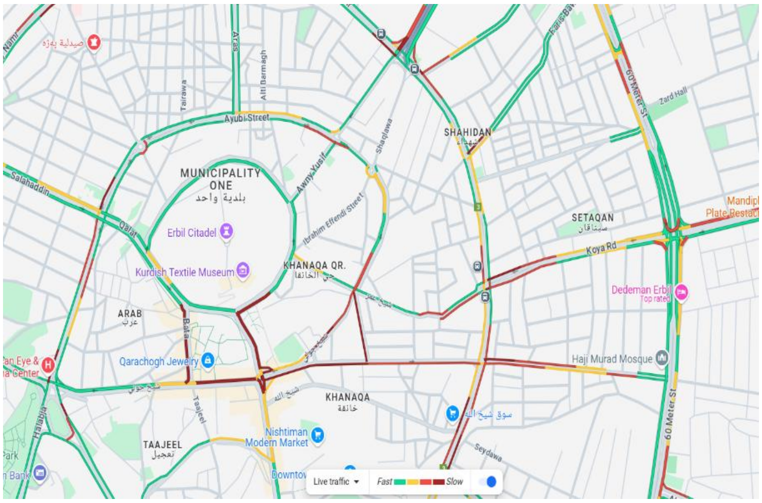

Fig. 2. Road network in Erbil city

The 5G-ATM simulates deploying a VANET routing algorithm using 5G technology under movement scenarios in dynamic smart cities. A historical Manhattan grid model has been selected for the case study. MATLAB and Google Maps resolve the case study and extract the intersection images. The traditional Manhattan model supposes a grid of perpendicular streets. Erbil's Road network includes both a grid, such as the central districts, and unequal external roads. We adapted the model by examining block sizes, intersection densities, and turning chance to identify actual traffic data in Erbil's urban center. The average block length and intersection spacing were fitted depending on satellite maps and local planning data. At the same time, randomization was inserted for fixed road segments to consider the city's non-regular layout. This adaptation lets the simulation realistically reduplicate Erbil's traffic flow dynamics while preserving the computational efficiency of the Manhattan model.

4. SIMULATION PARAMETERS AND RESULTS

This section covers the simulation details and parameters utilized to assess the performance of the proposed 5G-ATM. Then compares its performance against existing routing protocols, such as AC-OLSR and D-CALAR. The proposed protocol is investigated using MATLAB simulator under the same conditions and simulation parameters for all comparative protocols.

4.1 Simulation Parameters

The simulation environment considers realistic urban conditions with parameters chosen to include reproducibility and comparability. The simulation involves mobility models to enable vehicles to accelerate, change direction, and decelerate, enabling realistic scenarios to be carried out. This section of the study utilizes a customary mobility model named the car-following model. The map road segment is divided into two-speed zones utilizing the average speed information gained from the RSUs. If the average vehicle speed on a specific road segment is low, that segment is believed to be congested, while those with rising average speeds are seen as released from congestion. However, due to cumulative historical data, incessantly averaging vehicle speeds is subject to causing faults. The data is historically distinctive regarding the current average speed at a given time. To alleviate this affront, we inspire divisions based on 5-minute time slots, with the total average being computed in any slot, utilizing the data gained from only that slot. TABLE IV summarizes the simulation parameters regarding network configuration, vehicular movement, and communication characteristics.

TABLE IV. SIMULATION PARAMETERS

Parameter	Value
Simulation Area	2km x 2km
Simulation Time	2000 seconds
Number of Vehicles	400 vehicles
Vehicle Speed	(35–70) km/h
Traffic Density	25 to 100 vehicles/km, depending on morning and afternoon rush hours and midday)
MAC protocol	IEEE 802.11p
Transmission Range	1000m
5G Bandwidth:	100 MHz
5G Carrier Frequency	28 GHz
Packet Size	1024 bytes
Latency	5 ms

4.2 Results and Discussion

This study compares AC-OLSR, D-CALAR, and 5G-ATM in the performance metrics (traffic congestion, average travel time, fuel consumption reduction, packet delivery ratio, and average vehicle density) and briefly discusses the results. The outcomes are evaluated to show the validation and refinement presented by the proposed approach.

A. Traffic Congestion

Traffic congestion is a key indicator of a routing algorithm's ability to manage and optimize traffic flow. Congestion arises when the density of vehicles exceeds the road's capacity, leading to delays, increased fuel consumption, and inefficient resource utilization. This evaluation analyzes how the 5G-ATM, AC-OLSR, and D-CALAR mitigate traffic congestion under various vehicle densities, as shown in Fig. 3. The 5G-ATM shows the lowest traffic congestion events (3 and 0 in high and low density, respectively). In high-traffic density, the 5G-ATM significantly outperforms AC-OLSR and D-CALAR. That notability stems from its dynamic routing abilities by 5G-enabled RSUs and estimation traffic management. Analyzing real-time and historical data, 5G-ATM proactively recognizes possible congestion regions and detects routes before bottlenecks happen, leading to minimized delays and sleek traffic flow. Further, combining eco-routing metrics guarantees practical travel and reduces environmental effects. In contrast, depending on mutual agent mechanisms, AC-OLSR gets (10 and 1 events in high and low density, respectively), which effectively manages congestion due to its reactive quality and confined scalability. Elevation latency and inefficiencies in congested networks prevent its performance. The D-CALAR register (7 and 1 events in high and low density, respectively), leveraging location-aware directional caching, is preferable to AC-OLSR in congested scenarios but lacks the same estimation capabilities as 5G-ATM. All three protocols proceed entirely in low-density environments, with lower congestion and efficient routing. However, even in sparse traffic conditions, 5G-ATM preserves a slight edge with lower latency and energy-efficient routing decisions, including smooth traffic flow and optimal resource employment. The 5G-ATM dissects the elevated adaptability and efficiency across varying traffic densities, leveraging its utmost robust settling for modern VANET applications.

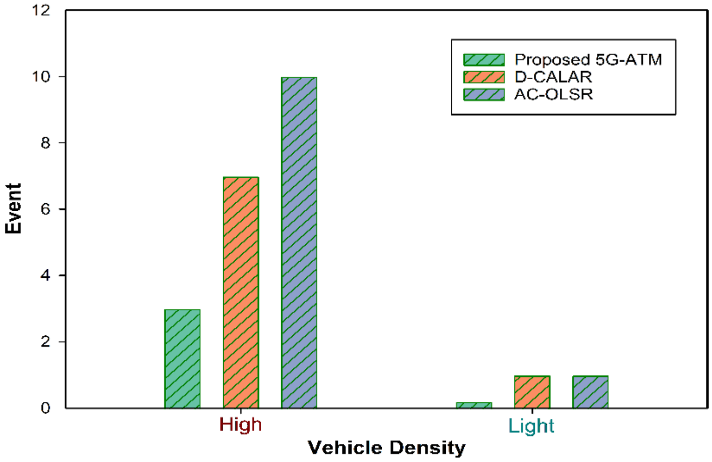

Fig. 3. Traffic congestion events

B. Average Travel Time

Rush hours are described by elevated traffic density and periodic congestion, and laboring average travel time is a stringent metric for assessing the performance of routing algorithms. Efficient algorithms adjust to traffic situations dynamically and reduce delays during rush periods. This evaluation assesses the average travel time of the 5G-ATM, AC-OLSR, and D-CALAR through rush hours (6-8 AM and 2-4 PM) and midday (10 AM-2 PM), as shown in Fig. 4. The 5G-ATM consistently outperforms (20-11 minutes compared to 24-12 and 32-14 minutes in rush and midday hours for D-CALAR and AC-OLSR, respectively). This is due to its proactive route adjustments, driven by estimation traffic models that analyze real-time and historical data. The integration of 5G's ultra-low latency and higher bandwidth results in rapid data swap between RSUs and vehicles. This reduces decision-making delays and speeds up the progress of adaptation. Moreover, the combination of estimation routing and SDN-based centralized control allows for additional timely traffic updates and an optimal path chosen in quite dynamic vehicular environments. The AC-OLSR, a reactive routing protocol based on mutual link state updates, struggles with higher travel times in dense traffic. It adjusts routes only after detecting network revisions, leading to delays as vehicles navigate out of congested zones without any proactive planning. The D-CALAR, while incorporating location-aware routing and directional caching, also faces limitations regarding dynamic route updates. It performs better than AC-OLSR in high density but doesn't have the same estimation capabilities as 5G-ATM, leading to slightly higher travel times than the proposed 5G-ATM. All three protocols show relatively similar performance in low-density areas. However, 5G-ATM still achieves the lowest average travel time due to its ability to fine-tune routes based on real-time data and employee preferences.

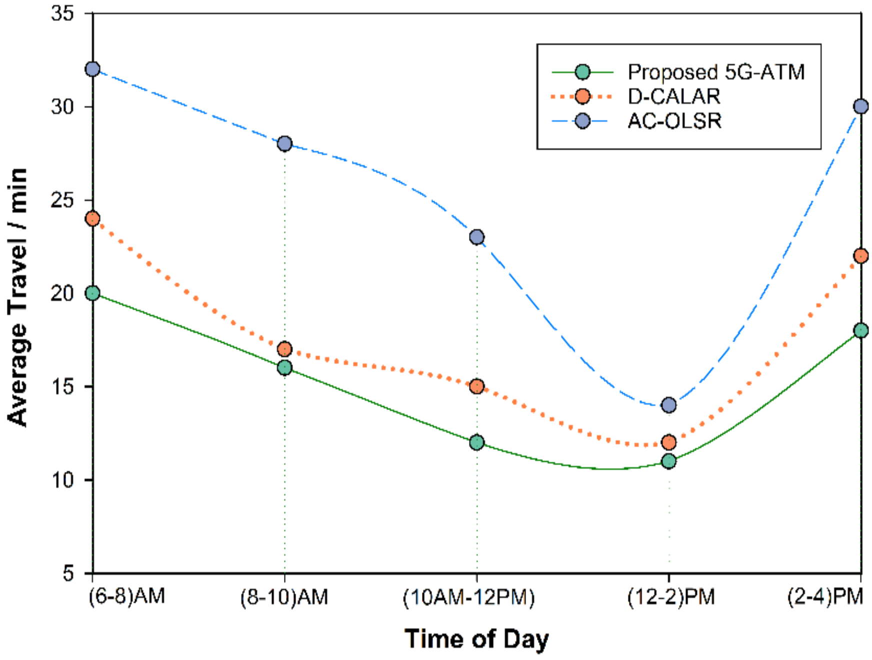

Fig. 4. Average travel time

C. Fuel Consumption Reduction

Fuel consumption is a stringent metric for estimating the eco-friendliness and efficiency of vehicular routing algorithms. Decreasing fuel consumption minimizes drivers' operational costs and contributes to environmental sustainability. This evaluation shows the fuel consumption reduction achieved by 5G-ATM, AC-OLSR, and D-CALAR, as shown in Fig. 5. The outcomes of 5G-ATM are a 35% decrease in fuel consumption in high-density areas, resulting in a provision of 2.8 liters per vehicle per trip. In low-density areas, the 12% decrease means around 0.6 liters saved per vehicle. This results from utilizing the developed algorithm that combines fuel consumption as a parameter in its cost function, ensuring that the elected routes optimize energy efficiency. Real-time adjustments of cost function weights prioritize fuel efficiency during low-vantage traffic, minimizing fuel consumption. By balancing vehicle density across routes, 5G-ATM minimizes stop-and-go traffic, a primary contributor to undue fuel consumption. The algorithm's estimation abilities include vehicles avoiding congested routes where periodic meander and tardy speeds raise fuel consumption. Therefore, its performance in terms of fuel consumption reduction is higher than that of the other AC-OLSR and D-CALAR. The AC-OLSR gets (12% and 9% in high and low density, respectively), which is due to the fact that it does not explicitly factor in fuel consumption when making routing decisions, focusing primarily on link state and network connectivity. As a result, vehicles using AC-OLSR may pass through congested areas or suboptimal routes that increase fuel consumption due to higher travel time and stop-and-go traffic. With location-aware routing and directional caching, the D-CALAR register (20% and 10% in high and low density, respectively), which helps reduce fuel consumption by selecting routes informed by traffic conditions and vehicle locations. However, it lacks the depth of eco-routing metrics and estimation traffic management that 5G-ATM offers, resulting in slightly higher fuel consumption than 5G-ATM. All protocols perform well in fuel efficiency in low-density traffic, with less congestion and delays. However, 5G-ATM still offers the best fuel consumption reduction by optimizing routes for speed and energy efficiency, making it the most fuel-efficient solution.

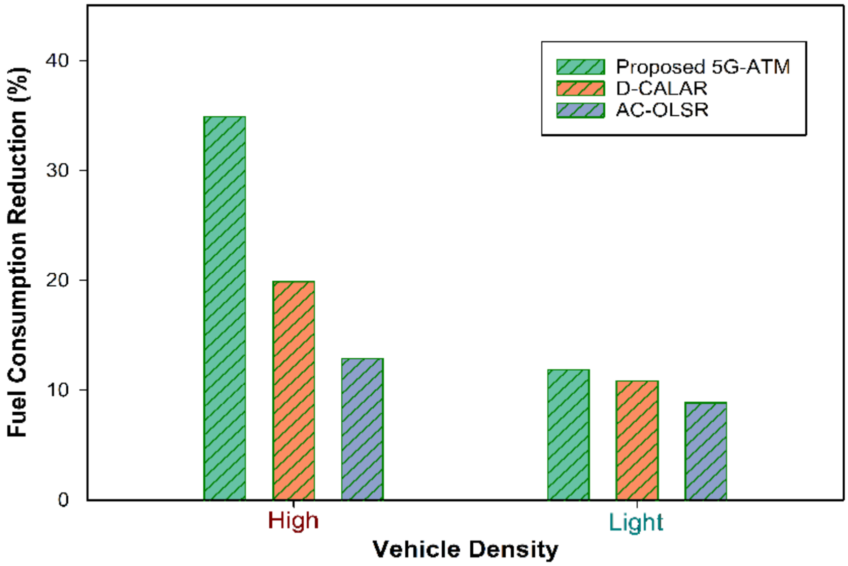

Fig. 5. Fuel consumption reduction

D. Packet Delivery Ratio

Packet delivery ratio (PDR) is a critical metric for evaluating the reliability of data transmission in vehicular networks. It measures the percentage of data packets successfully delivered to their destination compared to the total packets sent. High PDR guarantees effective communication between vehicles and infrastructure, primarily for optimal routing and traffic management. This evaluation permits the PDR rendering of the 5G-ATM, AC-OLSR, and D-CALAR, as shown in Fig. 6. The 5G-ATM has a higher PDR with 95% and 98% in high and low density, respectively. This means vehicles draw timely information about traffic situations, permitting top decision-making. The 5G-ATM leverages the elevation bandwidth and low-latency data transmission of 5G-enabled RSUs and V2X communication to obtain a consistently high PDR. It utilizes estimation traffic models to guarantee that data packets are routed efficiently, averting congested zones that can lead to packet loss. Therefore, adaptive routing decisions depend on the stream traffic situation and link quality, minimizing disruptions in packet delivery. The D-CALAR register 87% and 95% in high and low density, respectively. It utilizes location-aware routing and caching, which significantly reduces packet loss. However, its performance is less robust than 5G-ATM in environments where real-time data communication ensures high PDR. Additionally, its dependence on caching and location-based decisions may lead to incidental communication delays when distant vehicles or infrastructure updates are necessary. The AC-OLSR musters the most affronts in PDR (78% and 93% in high and low density, respectively). Its cooperative approach to routing based on link-state information requires regular updates from neighboring vehicles or nodes. In dense traffic, the overhead of constant link-state updates can lead to delays or packet loss, lowering the overall PDR. Furthermore, it lacks the high-speed, low-latency communication mechanisms in the 5G-ATM or D-CALAR. In low-density, all protocols exhibit relatively high PDR. However, the 5G-ATM maintains a slight advantage due to its integrated communication infrastructure and proactive route adjustments that reduce packet delivery delays.

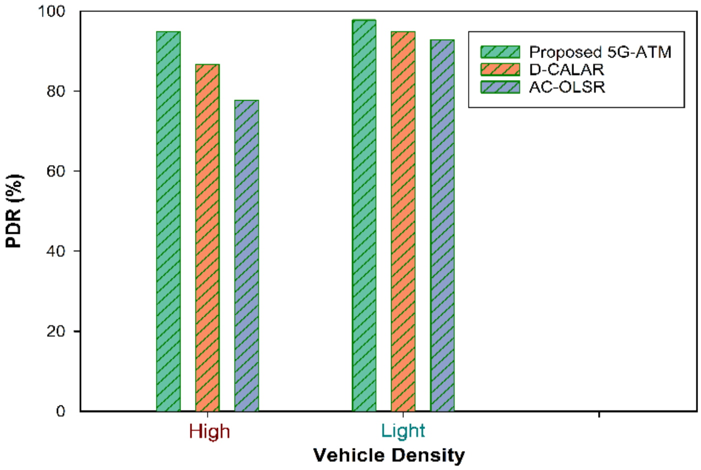

Fig. 6. Packet delivery ratio

E. Average Vehicle Density

Average vehicle density reflects the concentration of vehicles on a road segment over a given area or time. High density often leads to congestion, while low density may indicate underutilization of available road capacity. Routing algorithms aim to distribute traffic evenly to maintain an optimal density that maximizes flow efficiency while minimizing delays. This section analyzes how the 5G-ATM, AC-OLSR, and D-CALAR handle the vehicle density, as shown in Fig. 7. Due to its advanced traffic management system, the 5G-ATM performs exceptionally well (45 and 25 vehicles/ km in high and low vehicle densities, respectively). Using real-time data collection and estimation of traffic models, 5G-ATM contemplates traffic and proactively adjusts routes to avert congested zones and effectively manages vehicle density. It minimizes bottlenecks by rerouting vehicles in high-density areas, leading to smoother traffic flow and a more even distribution of vehicle density across the network. The D-CALAR shows accepted performance (65 and 28 vehicles/ km in high and low density, respectively), but it first reacts to flow traffic situations rather than estimates and averts future congestion. While it assists in minimizing congestion by guiding vehicles to less dense areas, its capability to manage density proactively is more finite than 5G-ATM, which leverages historical data and real-time monitoring to make more accurate decisions. The AC-OLSR gets 75 and 30 vehicles/ km in high and low density, respectively. It struggles with managing vehicle density. Since it first depends on link-state updates and mutual agent-based routing, it lacks the estimation abilities to optimize traffic flow and minimize vehicle density in real-time. This results in congestion possibilities, as vehicles may not be dynamically rerouted from areas with high vehicle density. All protocols do well in low-density traffic, with comparatively low vehicle density due to fewer vehicles on the road. However, the 5G-ATM guarantees that vehicles are more equally distributed across the network by proactively averting possible congestion points.

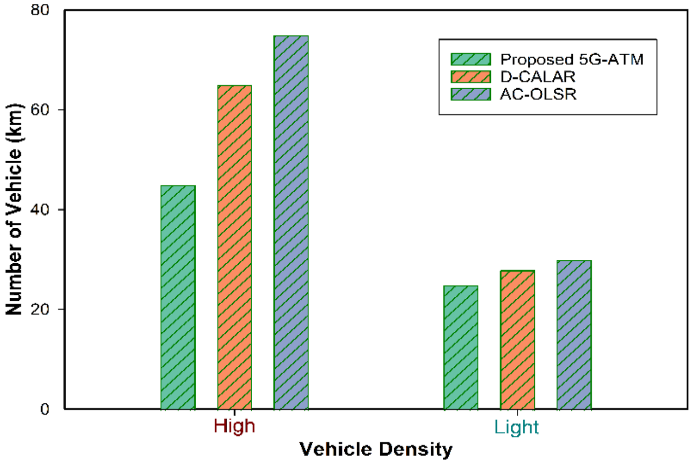

Fig. 7. Average vehicle density

5. CONCLUSION AND FUTURE DIRECTIONS

Several studies have been conducted to progress intelligent transportation systems to treat traffic congestion in urban environments. However, there is a significant lack of effective integration of real-time data, estimation analytics, and 5G abilities. In this paper, a 5G-AT routing algorithm is proposed to integrate VANETs with 5G. By merging 5G's ultra-low latency and high bandwidth with traffic estimation and sustainability-aware routing, it treats previous challenges. It performs stably even as traffic status changes. Additionally, it helps prevent congestion before it affects the network. Moreover, we used Erbil city as a case study scenario, which is experiencing significant traffic congestion, particularly during rush hours. Our proposal shows outstanding performance by minimizing average travel time and traffic congestion, while also improving fuel consumption and PDR. These refinements lead to smoother traffic flow and promote road safety. The dynamic cost functions and proactive routing for the adaptive kind of 5G-ATM make it very proper for complex urban environments. The study has specific limitations despite favorable results. Firstly, the evaluation was managed in a simulated environment. This may not fully consider real-world status, such as environmental involvement, network outage, and unexpected driver behavior. Secondly, diversity in 5G infrastructure coverage and quality, such as signal interruption and handoffs, remained unsolved. Future work can direct the merging of AI techniques to promote the speed and accuracy of traffic estimations. This can lead to more reactive routing decisions. Additionally, the 5G-ATM can be estimated under varied mobility models in freeway and rural scenarios. Furthermore, another essential direction is testing 5G-ATM under various 5G network statuses, considering potential signal variability and network handoffs. These expansions will support the 5G-ATM in real-world, heterogeneous vehicular networks.

Conflicts of Interest

The authors declare that they have no competing interests.

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