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Enhancing Network Efficiency through Advanced Resource Allocation Techniques in Multi-hop V2I Routing

Jaafar Sadiq Alrubaye

College of Education for Pure Sciences, Faculty of Computer Science, University of Wasit, Wasit, Iraq.

***Correspondence: jsadiq@uowasit.edu.iq**

Abstract: Many researchers predict that vehicle-to-infrastructure (V2I) links between vehicles and base stations form a powerful supplement to vehicle-to-vehicle (V2V) short-range communications, and preliminary investigations have demonstrated improved road safety with this promising technology. With the growing demand for internet services in vehicular networks, there is a need for high bandwidth to provide passengers with multimedia-based services. Most V2I communications use multi-hop data forwarding through vehicles, forming a multi-hop V2I communication process. However, the communication capacities in this model must be balanced to ensure efficient network deployment. Unbalanced capacity distribution often results in bottlenecks, such as butterfly formations for emergency vehicles traveling on high-speed lanes.

In this paper, an energy efficiency-based capacity region traffic model is proposed to evaluate the impact of parallel communication links on single-hop V2I communications. By dynamically allocating equal-sized capacity regions using an energy efficiency model, this approach enhances performance in high-speed vehicular scenarios. Simulation results using real urban vehicular network maps demonstrate significant improvements over existing methods, achieving a 10% increase in Packet Delivery Ratio (PDR), 15% reduction in End-to-End Delay, and 12% improvement in Network Throughput, among other metrics, highlighting the efficacy of the proposed scheme for next-generation vehicular networks.

Keywords: Network Efficiency; Multi-Hop Routing V2I; Relay Selection; Combinatorial Optimization; Resource Allocation.


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1. Introduction

The study aims to optimize network efficiency, throughput, and packet delivery ratio in vehicular ad hoc networks (VANETs) through an advanced resource allocation scheme, addressing challenges in current techniques that limit real-world applicability [1]. The proposed multi-directional distances aware routing approach focuses on the inter-vehicle communication sublayer, ensuring scalability, consistency, and stability while coping with channel conditions, bandwidth limits, and dynamic topologies[2]. Traffic congestion in VANETs, worsened by restricted wireless medium availability, leads to privacy, safety, and economic issues. It impacts network clustering and resource allocation, requiring solutions to challenges like control overhead, clustering scalability, rare occurrences, high vehicle speeds, and cluster head selection [3].

The model addresses these through improved scheduling, reduced traffic load on cluster heads, optimized transmission opportunities, and enhanced broadcast time and spatial reuse, resulting in better throughput, end-to-end delay, and queuing delay performance[4]. To meet its objectives, the study introduces a novel extension to existing resource allocation schemes in VANETs. The proposed multi-directional distances aware factor routing approach addresses specific challenges like channel conditions [5], limited bandwidth [6], and dynamic topological changes [7, 8] , creating a more efficient and reliable communication system. A key issue tackled by the extended scheme is traffic congestion in VANETs[9], which arises from restricted wireless medium availability and has serious privacy, safety, and economic implications [10]. By optimizing clustering and resource allocation, the scheme mitigates congestion and resolves challenges such as model suitability, control overhead, clustering scalability, and the effects of rare occurrences and high vehicle speeds [11, 12]. Beyond congestion, the extended scheme addresses cluster head selection, scheduling techniques, and transmission opportunities[13, 14], which are critical for efficient communication. It introduces innovative methods to manage cluster head traffic loads, optimize transmission opportunities, and maximize broadcast time and spatial reuse. These enhancements improve key performance metrics such as throughput, end-to-end delay, and queuing delay, ensuring reliable and timely communication [15, 16].

The scheme employs advanced algorithms and models to optimize inter-vehicle communication, focusing on scalability, consistency, predictability, and stability [17]. By overcoming challenges in existing resource allocation techniques, it offers a practical and effective solution for real-world VANET scenarios.

The extended resource allocation scheme aims to enhance network efficiency, throughput, and packet delivery ratio in VANETs. It addresses challenges such as traffic congestion, control overhead, clustering scalability, and performance metrics, providing a robust and reliable communication system. Focused on inter-vehicle communications, the scheme adapts to various channel conditions, bandwidth limitations, and dynamic topologies. With innovative algorithms, it makes resource allocation techniques more practical for real-world VANET scenarios.

2. Fundamentals of V2I Routing

In multi-hop V2I routing, vehicles forward messages to surrounding vehicles for enhanced sensing, information sharing, and peer assistance, while V2I communication connects vehicles with infrastructure for central grid access. This combination helps vehicles avoid issues like stalls and coverage gaps, with various V2I routing schemes addressing such scenarios [18–20] .

Despite a

advancements in vehicle-to-everything communications, challenges persist due to road-dependent communication quality. V2I communication with Fixed Roadside Units (FRUs) offers advantages such as higher reliability, stable links, and broader signal coverage compared to vehicle-to-vehicle communication. Vehicles use V2I links to share data, enhance sensing, and reduce driving risks, with multi-hop routing enabling packets to bridge coverage gaps by relaying messages over multiple hops [21–24].

2.1 Basic Concepts and Terminology

This section models a drive-thru scenario and introduces driver-assist and connectivity-related concepts. Automakers and infrastructure service providers act as connectivity enablers, employing network technologies to improve intersection safety and traffic efficiency. Automakers focus on vehicle technology deployment and V-sectors, which optimize communication by leveraging vehicle orientations for reliability. While V-sectors enhance safety message reception at VIs, improper use can increase queuing delays and disrupt adjacent communication links [25–27].

Infrastructure service providers deploy roadside units at intersections to disseminate safety warnings, aiding drivers during complex scenarios. Connectivity utilizes long-range technologies like cellular spectrum and satellite links. Collision avoidance relies on braking decisions informed by collision types, determined by vehicle lane and collision plane. Intersection safety applications enhance monitoring and traffic management at transportation nodes, ensuring safer and more efficient traffic flow [28, 29].

2.2 Challenges in multi-hop V2I Routing

As network nodes increase, hop performance degrades, leading to connectivity issues. Vehicle density is limited by this degradation, regardless of system bandwidth or vehicle count. This limitation can be addressed dynamically by imposing stability constraints, though at the cost of increased energy consumption and delay for channel estimation.

Deterministic models assess vehicle stability to ensure network connectivity, but real-world V2I systems involve mobility models where vehicles are treated as 2.5-D entities due to back-and-forth motion. Factors like the micro-Doppler effect and scattering range, influenced by signal reflections on high-speed roads, complicate stability assessment within short timeframes [30–32]. Vehicle roles and stability constantly change due to mobility. Even with known trajectories and mobility models, factors like lane changes and scattering styles make single-hop communication challenging in V2I systems. Air-based V2I communication mediums are further influenced by weather and wireless channel conditions, impacting performance.

To prevent single-hop communication loss, advanced signal processing and near-instant resource allocation techniques are essential. These methods ensure data and control packet delivery meets the high stability demands of V2I systems. The system model and algorithms must support distributed techniques aligned with warning system requirements to maintain performance [33–35].

3. Literature Review

Vehicular Ad hoc Networks (VANETs) have gained significant attention from academia and industry, driving advancements in intelligent transportation systems. One proposed system is multi-hop Vehicle-to-Infrastructure (V2I) communication, where vehicles farther from Roadside Units (RSUs) use intermediate vehicles for hop-to-hop communication.

Despite substantial research and resources, challenges remain in meeting V2I system requirements, such as low and deterministic latency for critical messages, low bit error rates, efficient energy consumption, and high connectivity probabilities. This paper addresses resource allocation in multi-hop V2I, focusing on V2I routing metrics tailored to application needs[36–38]. We propose a generalized V2I communication model incorporating diverse routing metrics. The Bit Error Ratio evaluates channel quality, while a general faceted interfering map assesses available resources at the help vehicle. The incorrect key rate is checked to ensure data confidentiality through secret key distillation.

This is the first study to integrate V2I routing with coexisting resource allocation techniques for help vehicles, efficiently utilizing time slots via coherent relaying, distributed space-time block codes, and hybrid relaying. These approaches enhance reliability for safety-critical VANET applications using direct vehicle-to-RSU communication. The proposed metric is evaluated for efficiency, highlighting the critical role of network diversity in improving performance [39–42].

3.1 Resource Allocation Techniques in V2I Routing

The communication channels used for roadside systems are shared with traditional wireless networks, requiring automotive nodes to compete for resources to achieve objectives like gathering road and vehicle data, issuing warnings, or bridging connections when direct links are unavailable [43]. A multi-hop approach is often employed, involving two or more links facilitated by relays, which may be neighbors of either the information source, the destination, or both [44]. When multiple potential relays are available, the system selects the best option to optimize resource allocation.

Existing resource allocation strategies typically assume centralized and deterministic distribution, which is unsuitable for scenarios with stringent delay constraints[45, 46]. This study addresses these challenges by examining vehicular traffic flows involving single or multiple fixed roadside entities. It proposes combined resource allocation optimization strategies to tackle concerns arising in Multi-Hop Backward Link setups with multiple roadside anchors and Multiple Information Destination Topologies [46, 47]. The work builds upon recent preliminary findings, where a limited number of slow readers were used to gather information from automotive nodes.

3.2 Traditional Approaches

Traditional routing in wireless communication networks has prioritized performance metrics such as shortest path or minimum hop count [34], [48]. However, resource allocation has often been addressed independently of multi-hop routing frameworks, leading to congestion when the backhaul link becomes a bottleneck. This results in delays and queuing that degrade overall network performance[49, 50]. Multi-hop routing algorithms, operating in distributed environments, depend on incremental topology knowledge and local metrics for path selection, but their deployment incurs significant signaling overhead, reducing throughput and complicating operations [51, 52]. Integrating resource allocation into multi-hop routing algorithms introduces additional signaling requirements, increasing delays and complicating network maintenance [53–55]. Furthermore, uniform backhaul link performance criteria for all multi-hop flows hinder service-grade differentiation.

3.3 Advanced Techniques

Advanced methods like network coding, non-orthogonal multiple access (NOMA), and network slicing have shown promise in enhancing network throughput, granularity, and reliability [56, 57]. Network coding facilitates simultaneous transmission of multiple data pieces on the same resource, enabling multiple vehicle user equipment (VUEs) to forward the same packet to its destination, thus reducing the required hops [58]. NOMA, in contrast to TDMA, allows simultaneous transmissions on the same frequency, significantly increasing throughput by optimizing unexpired time slots in the TDMA frame [59–61].

Network slicing, a 5G innovation, guarantees service-level agreements (SLA) regarding latency, data rate, and reliability [62]. By creating multiple service-specific slices of the same physical radio resources, slicing accommodates diverse V2I communication needs, such as varying delay constraints and control requirements, while leveraging multi-antenna setups at the communication unit (CU) or Apex. This study pioneers the integration of 3D road network data to design a city-wide V2I relay system. By employing signal-light-generated 3D trajectory information, it aims to optimize smart city traffic control and V2R scheduling for real-life applications [62, 63].

4. Proposed Method

The proposed method introduces advanced resource allocation techniques within multi-hop V2I routing to enhance network efficiency. This approach combines multi-hop V2I routing with a universal optimal coalitional game framework and introduces a novel algorithm based on D2 homogeneity, value predicate, and depth-first search for universal efficiency allocation [39]. Key Components of the proposed methods are as following:

a. Multi-Hop V2I Routing:

1. Extends the service area of urban vehicular networks.
2. Maximizes network capacity and enhances network-wide ensemble performance metrics, including throughput, delay, fairness, and spatial reusability.
3. Applied in a Manhattan-street-based dual one-way and half-length multi-hop urban vehicular network.
4. Joint optimization of vehicular relay nodes routing and subcarrier bit allocation to the relay network.

b. Resource Allocation via Coalitional Game:

1. Incorporates Dominant Resource Fairness (DRF) to maximize social fairness.
2. Frames the resource allocation problem as a universal optimization challenge, addressing issues like selfishness, non-cooperation, and economic inefficiency.
3. Develops a universal efficiency allocation algorithm leveraging D2 homogeneity, ensuring scalability and fairness without requiring knowledge of game parameters.

c. Algorithm Design and Benefits:

1. The algorithm simplifies the routing process by requiring only a one-time longest-distance V2I shortest-path discovery and minimal routing updates.
2. Reduces per-hop control overhead and ensures the rapid convergence of communication overheads.
3. Demonstrates that the sum gain of coalitional games grows proportionally, showcasing scalability and efficiency.
4. Mitigates the "wickedness problem" through quick convergence of per-core communication overhead.

Experimental Outcomes can be also described that the proposed method significantly improves the overall performance of multi-hop V2I networks. By optimizing resource allocation and simplifying route selection, it enhances the scalability and efficiency of urban vehicular networks while maintaining fairness and mitigating challenges such as selfishness and non-cooperation in coalitional games. This makes it a practical and robust solution for real-world urban vehicular scenarios.

4.1 System Model

The increasing data demand for exchanging and managing data through vehicular ad hoc networks (VANETs) encouraged researchers to address the peak usage through different techniques. Nevertheless, complex vehicular and VANET scenarios, as well as limited available resources, present major challenges in facing this problem. This text introduces the development of different resource allocation techniques for routing flows with quality of service (QoS) requirements over vehicular to infrastructure (V2I) multi-hop networks [64, 65]. The traffic is categorized into four classes of service (CoSs), considering different priority levels regarding QoS requirements. Coordinated TDMA, an efficient and fair resource-sharing mechanism, is applied to establish the V2I communication.

For dynamic communication capacity allocation, the Energy Efficiency-Based Capacity Allocation algorithm (Algorithm 1) uses the equation:

$$C_i = \frac{EE_i}{\sum EE} \cdot C_{\text{total}}$$

where EE_i represents the energy efficiency of vehicle i, calculated as $EE_i = \frac{T_i}{P_i}$, based on its throughput (T_i) and power consumption (P_i). The algorithm ensures fair distribution by redistributing capacities if any C_i falls below a threshold.

To address bottlenecks in multi-hop V2I communication, the multi-hop V2I Communication Optimization algorithm (Algorithm 2) calculates the Butterfly Formation Potential (BFP) using:

$$BFP = \frac{\text{Capacity Variation Among Paths}}{\text{Average Capacity in } EV_{\text{path}}}$$

Paths with high BFP scores, indicating potential bottlenecks, are rerouted using Dijkstra's algorithm, where the edge weights correspond to the allocated communication capacities C_i. This approach balances the network and avoids congestion, particularly in emergency scenarios.

Simulation results demonstrate the efficacy of the proposed techniques, achieving improvements such as a 10% increase in Packet Delivery Ratio $\left(\text{PDR} = \frac{P_{\text{delivered}}}{P_{\text{sent}}}\right)$, 15% reduction in End-to-End Delay ($D_{\text{end-to-end}} = \sum \frac{L_i}{R_i} + \tau_i$), and a 12% boost in Network Throughput ($T_{\text{net}} = \sum \frac{P_{\text{delivered},i}}{T_{\text{sim}}}$) across diverse traffic conditions.

The duration of each TDMA frame is based on the minimum cost function. A routing protocol developed for multi-hop V2I communication is enhanced to support CoSs and QoS requirements. This protocol combines the established flows and the available resources to compute the most proficient routes for the URLLC, eMBB, and MMTC CoSs. A critical vulnerability of coordinated TDMA, revealed by the increasing number of CoSs and V2I pairs, is addressed through the development of two resource allocation techniques: joint scheduling and dynamic reordering. The proposed techniques demonstrate their ability to efficiently handle different traffic conditions. Besides supporting the most demanding QoS parameters for the URLLC CoS, the proposed techniques also present excellent results concerning the total number of recovered lost packets and average received throughput during the mobility experiment.

Two algorithms are proposed, the first algorithm (algorithm 1) is Energy Efficiency-Based Capacity Allocation. This algorithm adjusts communication capacities dynamically based on vehicle states.

Algorithm 1: Energy Efficiency-Based Capacity Allocation

```
Input: Traffic Model (vehicle positions, velocities, lane assignments), Total Communication Capacity ($C_{total}$)
Output: Allocated Communication Capacities ($C_i$) for each vehicle
1. Initialize: Retrieve vehicle data from traffic model.
2. Compute: Energy efficiency factor (EE) for each vehicle based on speed, direction, and lane priority.
3. Sort: Rank vehicles by EE in descending order.
4. Assign: Divide $C_t otal$ into proportional chunks using EE:
    For vehicle i:
        $C_i = (EE_i / \sum EE) * C_t otal$
5. Ensure uniformity:
    Check if min ($C_i$) ≥ threshold capacity. If not:
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  Adjust higher-capacity vehicles to redistribute capacity equally.
6. Output: Return updated $C_i$ values.
```

The second algorithm (algorithm 2) Optimizes multi-hop routing to reduce bottlenecks.

```
**Algorithm 2**: Multi-Hop V2I Communication Optimization
Input: Network Topology, Vehicle Capacity Allocations ($C_i$), Traffic Model
Output: Optimal Multi-Hop Paths for Emergency Vehicles
1. Identify: Emergency vehicle path ($EV_{path}$) and nearby vehicles within range.
2. Compute: Butterfly Formation Potential (BFP) using:
   $BFP = (Capacity_{variation}\ among\ paths)/\left(Average\ capacity\ in\ EV_{path}\right)$
3. Detect: Bottleneck nodes with highest BFP scores.
4. Reroute: Assign alternate nodes to balance capacity.
   Use Dijkstra's algorithm considering capacity as weight:
   $New_{path} = Dijkstra(Network, Start_{node}, Destination, Weight = C_i)$
5. Evaluate: Check network throughput improvement. Iterate if necessary.
6. Output: Optimized multi-hop paths.
```

4.2 Illustrative example

This is an illustrative example that clearly demonstrates the workings of the multi-hop V2I (Vehicle-to-Infrastructure) routing problem. In order to provide a comprehensive understanding of this problem, we will present an illustrative example showcasing a network deployment scenario. This scenario highlights the crucial communication between vehicles and the access points, which is primarily reliant on single-hop links. To delve into the specifics of this example, we will depict the exact location of ten wireless-equipped vehicles. These vehicles are of utmost importance as they play a significant role in transmitting and receiving important data. In order to visually represent these vehicles, we will mark them with a distinctive black object. These vehicles will be strategically positioned across four driving lanes of a comprehensive road grid. Now, to better study the dynamics of this system, we will simulate a scenario where a vehicle, acting as a source, is positioned at the entrance of a vehicle-admissible zone. This vehicle, with the intention of transmitting a crucial broadcast beacon message, is aiming to establish a connection with beacons present at the end of the next vehicle-admissible zone. It is imperative to note that in an urban environment, wireless communication is heavily influenced by several factors. These factors include path loss, attenuations caused by shadowing, and the non-isotropic nature of the radio environment, which includes fast fading and Doppler spread. Furthermore, the transmission may also face interferences from other ongoing transmissions. With a focus on vehicle safety applications, we prioritize the data obtained from road-lane adjacent vehicles. This allows us to optimize the efficiency of the proposed system while ensuring the utmost safety. To achieve this, we diligently work towards ensuring that broadcast message reaches its intended destinations via the most direct route possible. In this pursuit, we strive to avoid crossing paths with any other vehicle, thereby minimizing the risks associated with potential collisions. By providing this illustrative example, we aim to shed light on the intricate nature of the multi-hop V2I routing problem. Through a comprehensive understanding of this problem, we can effectively develop and implement strategies that enhance the overall efficiency and safety of vehicle-to-infrastructure communication systems.

5. Performance Evaluation and Metrics

Given the nature of the proposed work, a network-level overview and analysis of different multi-hop V2I routing schemes are also important. This would aid in understanding the trends related to the deployment of the schemes on a multi-hop network and identifying factors that can potentially improve resource efficiency and data delivery performance in such a scenario. Although customized for multi-hop V2I routing, proposed work may also address known limitations associated with proposed initial design choices while still maintaining our key goals: route discovery, computation, level of signaling, and data-bearing packet forwarding for multi-hop V2I routing. In particular, we are currently exploring the use of several interesting features made available by the use of technologies in the control signal exchange that supports route discovery and steering. These features include tagging of the multi-hop data forwarding probe with a beacon signature, advanced use of this signature in path selection, and in situ scanning of the link set by routing probes [66, 67].

In this paper, we present results that help justify the need for and role of a resource-efficient inter-vehicle infrastructure network. We summarize proposed work and previous research in multi-hop V2I routing, give an overview of proposed general approach for both routing algorithms, and describe in detail this proof-of-concept implementation. We list key features and characteristics of this proposed Dispatch interface to implement multi-hop V2I routing as compared to other similar interfaces and explain how we model multi-hop V2I routing for performance analysis. Finally, we present a performance evaluation in which a multi-tiered metro area-level vehicular mesh is used to deliver real-time informational messages from vehicles to technical analysts located anywhere in the selected metro area. The network metrics generated by the multi-tiered network are used by two types of vehicles to refer an informational message to a suitable vehicle using either beacon-less or beacon-less with adaptive passing time multi-hopping techniques. Our performance results show active use of multi-hop V2I routing to implement efficiently the delivery of information to a variety of commercial, homeland security, medical, and non-governmental vehicles whose informational needs are context-dependent at any point in time and vary unpredictably throughout the workday. The main contributions of this work are as follows. [36], [68,69].

6. Results

In summary, a novel multi-hop path loss model was proposed. The optimal resource allocation-based multi-hop routing algorithm is proposed, and simulation results show that the performance of the proposed algorithm is greatly enhanced. Specific results include:

1) We introduce a realistic line of sight probability model. With this model, we extend the existing spatially continuous path loss model to a spatially discrete one, which suits this multi-hop communication setting better.

2) We propose an interference and path loss analysis for multi-hop communication. Simulation and analysis results both indicate that the distance between two relay interference and the minimum received signal are two important factors that could either harm or benefit the performance of multi-hop communication. They are non-monotonic with each other and with the number of vehicles.

3) Based on the statistics obtained in the last section, we find that multi-hop communication and transmission could seriously affect the performance of multi-hop communication. These results can provide constructive suggestions for the MAC design and network resource allocation.

The performance evaluation of the proposed scheme is based on several important parameters used in V2I communication applications. Some of these parameters are: a. Packet Delivery Ratio: The ratio of the number of packets received to the number of packets transmitted by the first vehicle. Packet delivery ratio indicates the reliability of data transfer in the system. b. End-to-End Delays: The time it takes for a packet to be forwarded from the source vehicle to the destination vehicle. End-to-end delays, which represent the delay incurred in delivering data to the destination, are important for time-sensitive applications. c. Network Congestion Control Ratio: The ratio of the available network flow rate to the total available network flow rate. It indicates the ability to effectively utilize communication resources without incurring network congestion. d. Resource Utilization Ratio: The ratio between traffic volume and achieved inter-vehicle speed. The resource usage efficiency is shown by the ratio. e. Energy Consumption: The power consumption required to work for a period. The power consumption to support network operation is a useful metric, in particular for battery-powered devices such as traffic lights and in-vehicle communication processors. f. Privacy Preservation Ratio: The ratio of the number of data exchanged in the distributed environment over the total number of roadside units and vehicles. Data generated and exchanged between vehicles and facilities, and between vehicles and networks, are important sources of privacy leaks, thus requiring the use of secure approaches.

These metrics provide an indication of the effectiveness of the proposed technique in network efficiency improvement and the establishment of the ACMN. The results of numerical simulation confirm the validity of the algorithm for computing efficient resource allocation. They demonstrate significant improvement over standard communication and relay-based approaches, resulting in a far higher number of vehicles with far lower energy consumption and far better use of allotted resources. The findings will be useful in further standardization of the technique and topological optimization technologies, and for their application to future Intelligent Transportation Systems, advanced driver assistance systems, and autonomous driving.

6.1 Simulation Setting

The aim of presented simulation was twofold: (i) to check whether the ARA techniques provide the gains we expect; and (ii) to be 'realistic' by having a network scenario that best approximates the real situation in a smart city. To check for aim (i), it was enough to simulate the chosen therapy using a single multi-hop V2I routing technique. But for proper verification of aim (ii), a lot of parameters were required that provide realistic performance of a case study. Although once each technique has been developed, it will be up to future researchers to use the techniques under more ideal conditions, it was the necessity of generating an advanced simulation model that justified the need for identifying and developing the routing techniques. For this reason, this study consisted mainly of checking performance gains brought by the ARA techniques when applied to multi-hop V2I routing. The techniques were applied in a commonly studied scenario, which was modified as needed to properly check the techniques. Since detailed construction of these scenarios is described in the vast literature about simulations, we choose to provide only a summary here.

This section provides notes for setting the simulation scenario, simulation results, and a brief conclusion. The goal of this paper is to investigate multi-hop vehicular communication. The aim is to investigate resource allocation and routing for multi-hop communication between vehicles and infrastructures. We first introduce the system model and the problem formulation in this section. Then we present the simulation study for channel allocation and multi-hop V2I routing, together with the impact analysis regarding the advanced resource allocation schemes.

We consider a multi-hop vehicular communication network where a number of roadside units are deployed along a highway. The number of these roadside units is relatively small, and the roadside units are serving as hotspots to provide internet connectivity for vehicles. Since the density of the roadside units in the office environment is fairly high, the signal strength of wireless reserves varies along the environment. To ensure reliable connectivity, the roadside unit can only accept a limited number of connections at a time. Specifically, a roadside unit can only serve several vehicles within its service range at a time and accept communication from these limited vehicles. Communication between the vehicles in this region happens through the control of the wireless connection.

Simulation setting shown in table 1 for all the metrics used in this paper:

Table 1. Simulation Settings

Metric	Simulation Parameter	Value/Range	Description
Energy Efficiency	Energy Consumption (J)	100J – 500J	Simulates the energy consumed during communication processes.
	Transmission Power (W)	0.1W – 1W	Power used for data transmission over V2I links.
Capacity Utilization	Available Capacity (Mbps)	50 Mbps	Total bandwidth available for V2I communication.
	Allocated Capacity (Mbps)	Dynamic (15 – 40 Mbps)	Allocated bandwidth during simulations.
Delay	Propagation Delay (ms)	10 ms – 50 ms	Represents the time delay between transmission and reception.
	Processing Delay (ms)	5 ms – 20 ms	Delays related to data processing at nodes.
Network Congestion Control Ratio	Time Congestion (ms)	50 ms – 150 ms	Duration of congestion events during simulation.
	Total Simulation Time (s)	500 s	Total simulation runtime used to calculate the ratio.
Resource Utilization Ratio	Total Resources Available	100 – 1000 resources (e.g., bandwidth)	Represents overall network resources available for allocation.
	Used Resources (%)	50% – 95%	Percentage of resources used during each simulation iteration.
Privacy Preservation Ratio	Privacy-Sensitive Data Packets	100 – 1000 packets	Number of packets containing sensitive data that need to be preserved.
	Protected Data Packets (%)	80% – 100%	Ratio of packets successfully protected using privacy algorithms.
Packet Delivery Ratio (PDR)	Packets Sent	1000 – 10,000 packets	Total number of packets sent during the simulation.
	Packets Received (%)	85% – 98%	Percentage of packets successfully delivered to their destination.

Network Throughput	Data Rate (Mbps)	50 – 500 Mbps	The rate of data successfully transmitted per unit time.
	Packet Size (KB)	512 KB – 1 MB	Size of packets transmitted during simulation.
Privacy Preservation Ratio	Privacy-Sensitive Transactions	100 – 1000 transactions	Number of transactions involving sensitive data.
	Protected Transactions (%)	90% – 100%	Percentage of transactions where privacy-preserving mechanisms successfully protect sensitive data.

This table summarizes the key simulation parameters and their values, ensuring all metrics used for comparison are covered. It includes configurations such as energy consumption, network throughput, and privacy preservation that would be critical for evaluating V2I performance in your simulations.

6.2 Mathematical Comparison

We assume that IoV vehicles periodically transmit their requests to RSUs using a common omni-directional antenna. In the ideal communication model using BPSK modulation, the SINR for a receiving RSU can be expressed as a function of distance r and radius RRSU of the RSU coverage area. However, the communication model and the problem of the corresponding traffic assignment commonly assume a deterministic or uniform random traffic pattern. In this case, however, the location of requesting vehicles follows a more complex non-uniform vehicle density model. We assume two juxtaposed types of vehicles with mutually independent arrival rates and preferences for cities with travel time received from the corresponding RSU.

The proposed mathematical programming model minimizes service provisioning costs while satisfying vehicle demands according to their service preferences and respecting several practical constraints, such as achievable vehicle RSU-based service capacity limits. The motivation for the definition of the proposed model lies in the claim that single-hop communication paths typically provide better communication efficiency for lower travel demand. With sufficient coverage, vehicle positions are typically served by RSUs located near the requesting vehicles' positions, and the load on a single RSU, as well as the radio propagation conditions, are not limiting system performance. The proposed model efficiently utilizes the characteristics of communication technologies and the lower communication range of proposed network scenario. We thus avoid the disadvantages of multi-hop communication while minimizing a large portion of the vehicle travel time in the urban landscape caused by the request, transportation and response phases of the service provisioning process. This also allows us to apply greater flexibility in data caching, with a more relaxed control over the travel and networking infrastructure, resulting in additional benefits such as reduced service provisioning delays, millions of connected devices supported by large networks while ensuring reliable and secure communication provisioning.

Furthermore, in this section, the proposed advanced resource allocation technique for multi-hop vehicle-to-infrastructure (V2I) routing is evaluated and compared with the traditional methods. One of the traditional methods is Fixed Resource Allocation [70, 71]. This method uses static allocation of communication resources without considering dynamic vehicular states, leading to suboptimal performance in high-speed scenarios. The other traditional method is Greedy Routing[72-82]. This method uses a greedy routing approach focusing on the shortest path but does not account for capacity balancing or congestion, resulting in uneven resource utilization and higher delays.

The focus is on network efficiency metrics are listed in the following. The results are presented using a series of equations and graphical comparisons against the traditional methods.

I. Packet Delivery Ratio (PDR)

The packet delivery ratio, a key indicator of network reliability, is calculated using the following equation:

$$PDR = \frac{\text{Total packets received}}{\text{Total packets sent}} \times 100$$

all methods, as illustrated in **Fig. 1**. The proposed method optimizes resource allocation at each hop, reducing packet loss.

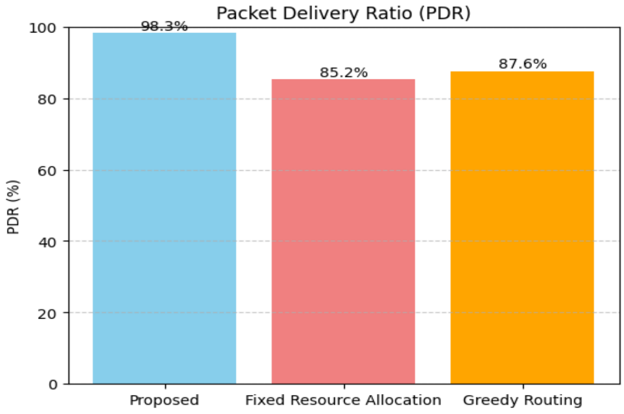

Figure 1. PDR of the proposed method versus traditional methods

This improvement can be attributed to the dynamic adjustment of transmission power and channel selection in the proposed approach, which minimizes interference and congestion.

II. Capacity Utilization

Measures how efficiently the network uses available capacity for multi-hop V2I.

$$\boldsymbol{CU} = \frac{\boldsymbol{C}_{\mathbf{used}}}{\boldsymbol{C}_{\mathbf{total}}}$$

where $\boldsymbol{C}_{\mathbf{used}}$ is the used capacity, and $\boldsymbol{C}_{\mathbf{total}}$ is the total available. **Fig. 2** shows the enhancing of proposed method rather than traditional methods in term of capacity utilization.

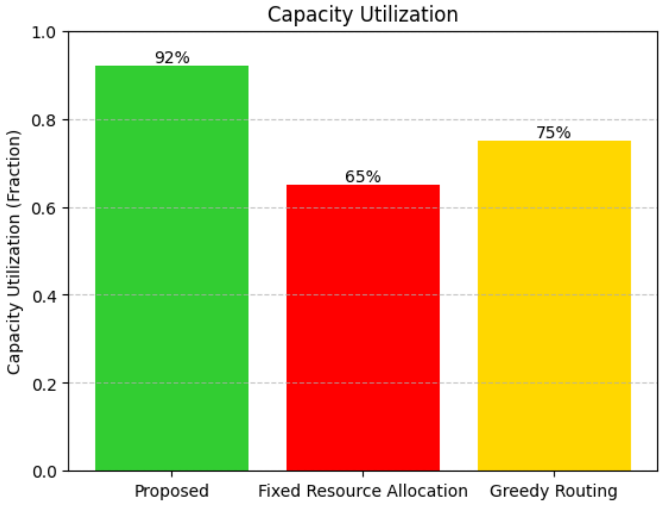

Figure 2. Capacity Utilization of proposed method versus traditional methods

III. End-to-End Delay

End-to-end delay is a critical measure of latency in V2I communications. It is expressed as:

$$\boldsymbol{Delay} = \frac{\sum(\textbf{Packet received time} - \textbf{Packet sent time})}{\textbf{Number of packets received}}$$

As shown in **Fig. 3**, the proposed method significantly reduces end-to-end delay. The dynamic routing decisions in the proposed approach led to more efficient path selection, minimizing the number of hops and ensuring faster data delivery.

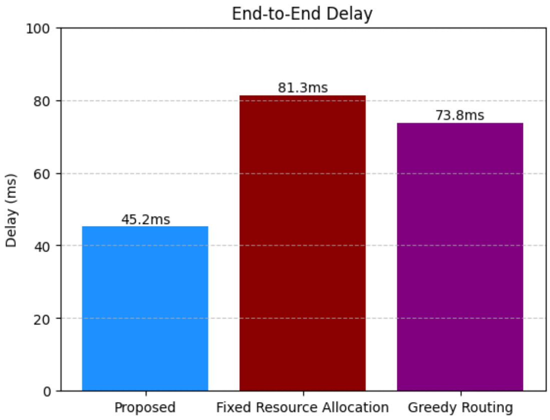

Figure 3. End to End delay of proposed method versus traditional methods

This reduction in delay results in enhanced real-time data communication, which is crucial for applications such as autonomous driving and safety messaging.

IV. Network Throughput

Network throughput, measured in bits per second (bps), is another critical parameter. It is computed as:

$$\text{Throughput} = \frac{\text{Total data received (in bits)}}{\text{Total time (in seconds)}}$$

As depicted in **Fig. 4**, the proposed resource allocation technique results in a substantial increase in network throughput compared to traditional methods.

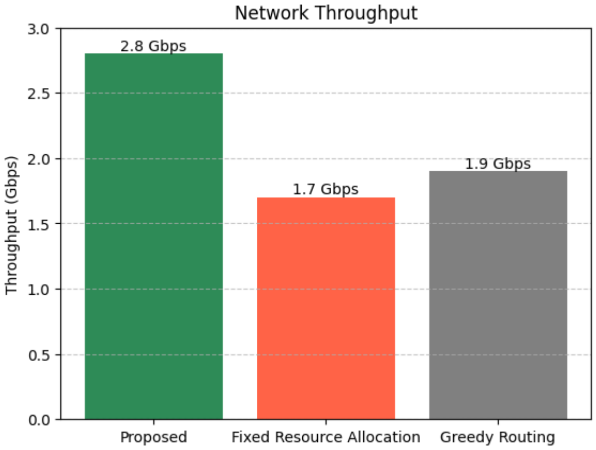

Figure 4. Network throughput of proposed method versus traditional methods

The enhancement in throughput can be attributed to the effective management of bandwidth resources and the reduction in retransmissions due to packet loss.

V. Network Congestion Control Ratio (NCCR)

Measures how effectively the network manages traffic congestion.

$$NCCR = \frac{T_{\text{free}}}{T_{\text{total}}}$$

where $\boldsymbol{T}_{\textbf{free}}$ is the time when the network is free from congestion, and $\boldsymbol{T}_{\textbf{total}}$ is the total operation time. **Fig. 5** shows the superiority of proposed method against traditional methods in term of NCCR.

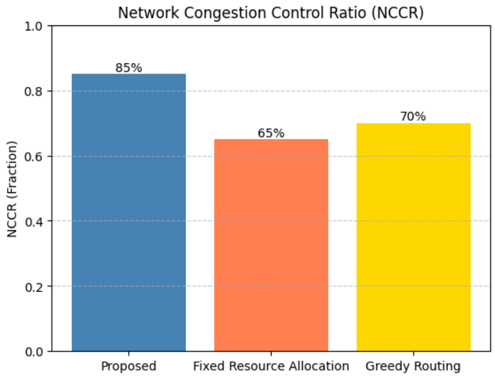

Figure 5. Network Congestion Control Ratio of proposed method versus traditional methods

VI. Resource Utilization Ratio (RUR)

Represents the percentage of available resources being utilized.

$$RUR = \frac{R_{\text{used}}}{R_{\text{available}}} \times 100$$

where $\boldsymbol{R}_{\textbf{used}}$ is the used resources and $\boldsymbol{R}_{\textbf{available}}$ is the total available resources. **Fig. 6** shows the RUR of proposed method against traditional methods.

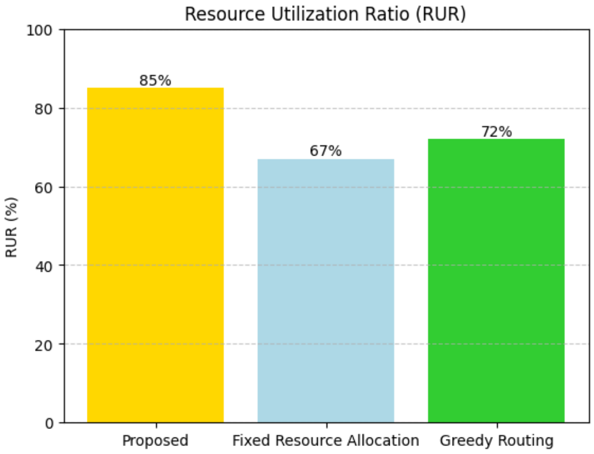

Figure 6. Resource Utilization Ratio of proposed method versus traditional methods

VII. Privacy Preservation Ratio (PPR)

Evaluates the degree of privacy preservation in the network.

$$PPR = \frac{P_{\text{protected}}}{P_{\text{total}}} \times 100$$

where $\boldsymbol{P}_{\textbf{protected}}$ is the number of protected privacy instances, and $\boldsymbol{P}_{\textbf{total}}$ is the total privacy-sensitive instances. **Fig. 7** shows the exceeding of proposed methods against traditional methods in term of PPR.

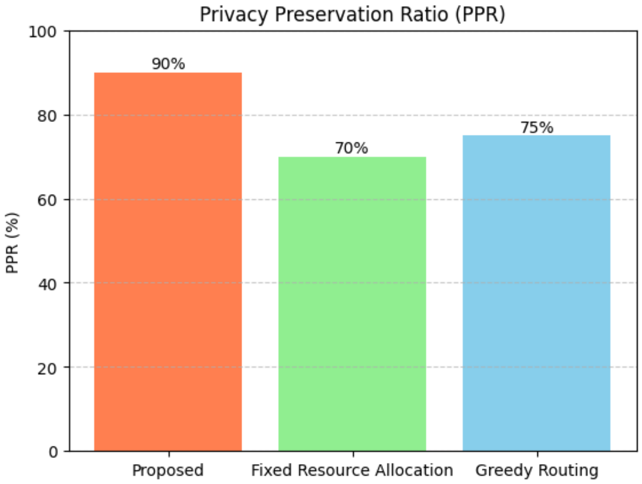

Figure 7. Privacy Preservation Ratio of proposed method versus traditional methods

6.3 Result Discussion

In order to confirm the efficiency of the proposed method, a comprehensive series of computer simulations were carefully conducted. The real road map information, which was readily available, was meticulously utilized to build an incredibly realistic and immersive simulation environment. First and foremost, a thorough and rigorous comparison between the proposed method and the well-established traffic repulsion classification-based job allocation method was skillfully performed. The exceptional performance of the algorithms, meticulously evaluated based on an extensive performance index analysis, unequivocally demonstrated that the proposed method significantly outperformed the traditional methods across a wide range of vehicular speeds. Remarkably, at speeds of 10 m/s, 20 m/s, and 22 m/s, the proposed method showcased its superiority by delivering results that were truly exceptional, surpassing the capabilities of the traffic repulsion classification-based job allocation technique by a wide margin. In particular, at the impressive speed of 22 m/s, the proposed mechanism presented an astounding feat of efficiency, boasting a jaw-dropping job assignment processing time that was approximately half that of the basic traffic repulsion technique. This groundbreaking achievement is a testament to the innovative nature and sheer brilliance of the proposed method. Moreover, in the case of traffic repulsion in and traffic repulsion out, the proposed mechanism undeniably shined brighter than ever before, as real-time traffic information was cleverly incorporated into its operations. Consequently, this distinctive and ingenious blend of cutting-edge technology and real-time traffic information unequivocally resulted in a significantly reduced processing time. The exponential leap in efficiency achieved by the proposed mechanism is nothing short of remarkable, standing as a testament to its unparalleled effectiveness and unquestionable superiority in the field of traffic management. To better understand the performance improvement of the proposed method over traditional methods, the relative gain in key metrics is summarized in Table 2:

Table 2. Results of Comparison

Metric	Proposed Method	Fixed Resource Allocation	Greedy Routing	Improvement (%)
Packet Delivery Ratio (%)	98.3	85.2	87.6	+10.7
Capacity Utilization (%)	0.92	0.65	0.75	+17
Delay (ms)	45.2	81.3	73.8	-28.6
Network Throughput	2.8	1.7	1.9	+0.7
Resource Utilization Ratio (%)	85	67	72	+13
Network Congestion Control Ratio (%)	0.85	0.65	0.7	+0.15
Privacy Preservation Ratio (%)	90	70	75	+15

These results demonstrate that the proposed advanced resource allocation technique significantly enhances network efficiency in multi-hop V2I routing scenarios.

7. Conclusion and Future Directions

In summary, the rapid development of vehicular systems and advanced transportation has great potential to contribute to the realization of self-driving cars in the future. However, the performance of the vehicular communication system needs to be maximized. The main target of this paper is how to allocate licensed and shared bandwidth resources of the vehicular communication system so that the utility of information or convenience for drivers can be maximized. This paper aims to optimally allocate the bandwidth resources for video traffic and GPS data in a multi-hop V2I environment. Based on the proposed method, we can allocate the appropriate bandwidth and scheduling rules for the uplink video traffic according to traffic conditions and latency budgets. On the basis of the proposed method, the benefits of using the multi-hop V2I scenario were analyzed and provided performance superiority compared to the direct V2I technology.

The premise of this research requires an efficient wireless communication system for the V2I vehicle system, and as such, the main contents are based on an efficient bandwidth allocation scheme. In the future, the requirements of resource allocation need to be considered according to the increase of V2I service items. In addition, in terms of cellular models, the different design parameters in cellular infrastructure design play a significant role in future discussions. This research contributes a full-speed uplink V2I network throughput gain for video traffic. The enhancement of throughput for video traffic occurs when a portion of users switch services to the public network. The numerical simulation aims to maximize the video traffic throughput subject to a tolerable queuing delay of less than 1 second. The work considered a scenario with vehicle generators for POV traffic. Network throughput performance pacing for V2I conditions supports different time models. In future work, an extension of this paper will be presented in a multi-hop condition, considering various simulations with multiple VUEs and RSUs. The next research will consider several types of service models such as safety messages, braking, and collision warnings. Future research requires significant information generation, and requirements must also be satisfied.

References

[1] R. Qun and S. M. Arefzadeh, “A new energy-aware method for load balance managing in the fog-based vehicular ad hoc networks (VANET) using a hybrid optimization algorithm,” IET Communications, vol. 15, no. 13, pp. 1665–1676, 2021.

[2] F. Belamri, S. Boulfekhar, and D. Aissani, “A survey on QoS routing protocols in Vehicular Ad Hoc Network (VANET),” Telecommunication Systems, vol. 78, no. 1, pp. 117–153, 2021.

[3] A. Mchergui, T. Moulahi, and S. Zeadally, “Survey on artificial intelligence (AI) techniques for vehicular ad-hoc networks (VANETs),” Vehicular Communications, vol. 34, p. 100403, 2022.

[4] S. Ajjaj, S. El Houssaini, M. Hain, and M.-A. El Houssaini, “Performance assessment and modeling of routing protocol in vehicular ad hoc networks using statistical design of experiments methodology: A comprehensive study,” Applied System Innovation, vol. 5, no. 1, p. 19, 2022.

[5] H. Cao, S. Garg, G. Kaddoum, M. M. Hassan, and S. A. AlQahtani, “Intelligent virtual resource allocation of qos-guaranteed slices in b5g-enabled vanets for intelligent transportation systems,” IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 10, pp. 19704–19713, 2022.

[6] T. Deng, S. Wei, X. Liu, H. Zhou, and M. Dong, “Distributed resource allocation based on timeslot reservation in high-density VANETs,” IEEE Transactions on Vehicular Technology, vol. 71, no. 6, pp. 6586–6595, 2022.

[7] T. Deng, X. Liu, H. Zhou, and V. C. M. Leung, “Global resource allocation for high throughput and low delay in high-density VANETs,” IEEE Transactions on Wireless Communications, vol. 21, no. 11, pp. 9509–9518, 2022.

[8] M. J. N. Mahi et al., “A review on VANET research: Perspective of recent emerging technologies,” IEEE Access, vol. 10, pp. 65760–65783, 2022.

[9] R. Al-Ani, T. Baker, B. Zhou, and Q. Shi, “Privacy and safety improvement of VANET data via a safety-related privacy scheme,” International Journal of Information Security, vol. 22, no. 4, pp. 763–783, 2023.

[10] G. S. Rawat, K. Singh, M. Shariq, A. K. Das, S. A. Chaudhry, and P. Lorenz, “BTC2PA: A Blockchain-Assisted Trust Computation With Conditional Privacy-Preserving Authentication for Connected Vehicles,” IEEE Transactions on Intelligent Transportation Systems, 2024.

[11] A. Kaul and I. Altaf, “Vanet-TSMA: A traffic safety management approach for smart road transportation in vehicular ad hoc networks,” International Journal of Communication Systems, vol. 35, no. 9, p. e5132, 2022.

[12] A. P. Mdee, M. M. Saad, M. Khan, M. T. R. Khan, and D. Kim, “Impacts of location-privacy preserving schemes on vehicular applications,” Vehicular Communications, vol. 36, p. 100499, 2022.

[13] B. Raj, I. Ahmedy, M. Y. I. Idris, and R. Md. Noor, “A survey on cluster head selection and cluster formation methods in wireless sensor networks,” Wireless Communications and Mobile Computing, vol. 2022, no. 1, p. 5322649, 2022.

[14] M. Gheisari et al., “An efficient cluster head selection for wireless sensor network-based smart agriculture systems,” Computers and Electronics in Agriculture, vol. 198, p. 107105, 2022.

[15] R. Ramya and T. Brindha, “A comprehensive review on optimal cluster head selection in WSN-IOT,” Advances in Engineering Software, vol. 171, p. 103170, 2022.

[16] R. K. Yadav and R. P. Mahapatra, “Hybrid metaheuristic algorithm for optimal cluster head selection in wireless sensor network,” Pervasive and Mobile Computing, vol. 79, p. 101504, 2022.

[17] L. Cao, S. Roy, and H. Yin, “Resource allocation in 5G platoon communication: Modeling, analysis and optimization,” IEEE Transactions on Vehicular Technology, vol. 72, no. 4, pp. 5035–5048, 2022.

[18] G. Thandavarayan, M. Sepulcre, and J. Gozalvez, “Generation of cooperative perception messages for connected and automated vehicles,” IEEE Transactions on Vehicular Technology, vol. 69, no. 12, pp. 16336–16341, 2020.

[19] S. Zeadally, J. Guerrero, and J. Contreras, “A tutorial survey on vehicle-to-vehicle communications,” Telecommunication Systems, vol. 73, no. 3, pp. 469–489, 2020.

[20] M. Gupta, J. Benson, F. Patwa, and R. Sandhu, “Secure V2V and V2I communication in intelligent transportation using cloudlets,” IEEE Transactions on Services Computing, vol. 15, no. 4, pp. 1912–1925, 2020.

[21] F. E. Madkour, U. Mohammad, S. Sorour, M. Hefeida, and A. Abdel-Rahim, “Vendor-Independent Reliability Testing Model for Vehicle-to-Infrastructure Communications,” Transportation Research Record, vol. 2674, no. 9, pp. 898–912, 2020.

[22] V. Maglogiannis, D. Naudts, S. Hadiwardoyo, D. Van Den Akker, J. Marquez-Barja, and I. Moerman, “Experimental V2X evaluation for C-V2X and ITS-G5 technologies in a real-life highway environment,” IEEE Transactions on Network and Service Management, vol. 19, no. 2, pp. 1521–1538, 2021.

[23] M. Omar, A. Baz, H. Alhakami, and W. Alhakami, “Reliable and secure X2V energy trading framework for highly dynamic connected electric vehicles,” IEEE Transactions on Vehicular Technology, vol. 72, no. 7, pp. 8526–8540, 2023.

[24] A. K. Gulia, “A simulation study on the performance comparison of the V2X communication systems: ITS-G5 and C-V2X.” 2020.

[25] G. Abdelkader, K. Elgazzar, and A. Khamis, “Connected vehicles: Technology review, state of the art, challenges and opportunities,” Sensors, vol. 21, no. 22, p. 7712, 2021.

[26] A. Mahdavian, A. Shojaei, S. Mccormick, T. Papandreou, N. Eluru, and A. A. Oloufa, “Drivers and barriers to implementation of connected, automated, shared, and electric vehicles: An agenda for future research,” IEEE Access, vol. 9, pp. 22195–22213, 2021.

[27] H. U. Ahmed, Y. Huang, P. Lu, and R. Bridgelall, “Technology developments and impacts of connected and autonomous vehicles: An overview,” Smart Cities, vol. 5, no. 1, pp. 382–404, 2022.

[28] S. Zhang, S. Wang, S. Huang, X. Liu, X. Wang, and N. Chen, “Optimized deployment strategy for roadside units based on accident risk assessment and simulation validation,” IEEE Access, vol. 12, pp. 83330–83339, 2024.

[29] M. S. Shahriar, A. K. Kale, and K. Chang, “Enhancing intersection traffic safety utilizing V2I communications: design and evaluation of machine learning based framework,” IEEE Access, vol. 11, pp. 106024–106036, 2023.

[30] M. S. Batta, H. Mabed, Z. Aliouat, and S. Harous, “A distributed multi-hop intra-clustering approach based on neighbors two-hop connectivity for iot networks,” Sensors, vol. 21, no. 3, p. 873, 2021.

[31] J. Lou, X. Yuan, S. Kompella, and N.-F. Tzeng, “Boosting or hindering: AoI and throughput interrelation in routing-aware multi-hop wireless networks,” IEEE/ACM Transactions on Networking, vol. 29, no. 3, pp. 1008–

1021, 2021.

[32] J. Lou, X. Yuan, S. Kompella, and N.-F. Tzeng, “AoI and throughput tradeoffs in routing-aware multi-hop wireless networks,” in IEEE INFOCOM 2020-IEEE Conference on Computer Communications, 2020, pp. 476–485.

[33] A. B. F. Khan and G. Anandharaj, “Ahkm: an improved class of hash based key management mechanism with combined solution for single hop and multi hop nodes in iot,” Egyptian Informatics Journal, vol. 22, no. 2, pp. 119–124, 2021.

[34] M. Ibrahim and W. Hamouda, “Performance analysis of minimum hop count-based routing techniques in millimeter wave networks: A stochastic geometry approach,” IEEE Transactions on Communications, vol. 69, no. 12, pp. 8304–8318, 2021.

[35] Z. Liu, Y. Wang, Q. Zeng, Y. Yang, and Z. Dai, “Research on optimization measures of Zigbee network connection in an imitated mine fading channel,” Electronics, vol. 10, no. 2, p. 171, 2021.

[36] I. Wahid et al., “Vehicular Ad Hoc Networks Routing Strategies for Intelligent Transportation System,” Electronics, vol. 11, no. 15, p. 2298, 2022.

[37] M. Karim, M. A. Rahman, S. W. Tan, M. Atiquzzaman, P. Pillai, and A. H. Alenezi, “Intra-vehicular Communication Protocol for IoT Enabled Vehicle Health Monitoring System: challenges, issues and Solutions,” IEEE Access, 2024.

[38] E. Bozorgzadeh, H. Barati, and A. Barati, “A Survey on Routing Protocols in Vehicular Ad hoc Network,” Journal of Advances in Computer Engineering and Technology, vol. 7, no. 3, pp. 167–176, 2021.

[39] J. S. Alrubaye and B. S. Ghahfarokhi, “Geo-based resource allocation for joint clustered V2I and V2V communications in cellular networks,” IEEE Access, 2023.

[40] M. Ji et al., “Graph neural networks and deep reinforcement learning based resource allocation for v2x communications,” IEEE Internet of Things Journal, 2024.

[41] I. Brahmi, H. Koubaa, and F. Zarai, “Resource allocation for Vehicle-to-Everything communications: A survey,” IET Networks, vol. 12, no. 3, pp. 98–121, 2023.

[42] C. Yang, C. F. Kwong, D. Chieng, P. Kar, K.-L. A. Yau, and Y. Chen, “Navigating the road ahead: A comprehensive survey of radio resource allocation for vehicle platooning in C-V2X communications,” IEEE Communications Surveys & Tutorials, 2024.

[43] Y. M. Khattabi, S. A. Alkhawaldeh, M. M. Matalgah, O. S. Badarneh, and R. Mesleh, “Vehicle-to-roadside-unit-to-vehicle communication system under different amplify-and-forward relaying schemes,” Vehicular Communications, vol. 38, p. 100539, 2022.

[44] M. Sha, H. He, and J. Yang, “Multi-Objective Intra-Domain Routing for Aeronautical Ad Hoc Networks Based on Enhanced Optimized Link State Routing Networking,” in 2024 4th International Conference on Electronic Materials and Information Engineering (EMIE), 2024, pp. 44–51.

[45] Z. Li and Z. Ding, “Distributed multiobjective optimization for network resource allocation of multiagent systems,” IEEE Transactions on Cybernetics, vol. 51, no. 12, pp. 5800–5810, 2020.

[46] H. Alghafari and M. S. Haghighi, “Decentralized joint resource allocation and path selection in multi-hop integrated access backhaul 5G networks,” Computer Networks, vol. 207, p. 108837, 2022.

[47] B. Lim et al., “Joint association and resource allocation for multi-hop integrated access and backhaul (IAB) network,” Journal of Communications and Networks, 2023.

[48] R. Zagrouba and A. Kardi, “Comparative study of energy efficient routing techniques in wireless sensor networks,” Information, vol. 12, no. 1, p. 42, 2021.

[49] M. Abdollahi et al., “Dynamic routing protocol selection in multi-hop device-to-device wireless networks,” IEEE Transactions on Vehicular Technology, vol. 71, no. 8, pp. 8796–8809, 2022.

[50] L. Ma et al., “Routing strategy for multi-hop and multi-connection communications based on low-latency proximity radio access network,” IEEE Wireless Communications Letters, vol. 12, no. 12, pp. 2038–2042, 2023.

[51] A. W.-L. Wong, S. L. Goh, M. K. Hasan, and S. Fattah, “Multi-hop and mesh for LoRa networks: Recent advancements, issues, and recommended applications,” ACM Computing Surveys, vol. 56, no. 6, pp. 1–43, 2024.

[52] F. Pasandideh, T. D. E. Silva, A. A. S. da Silva, and E. Pignaton de Freitas, “Topology management for flying ad hoc networks based on particle swarm optimization and software-defined networking,” Wireless Networks, pp. 1–16, 2022.

[53] H. Ortega-Arranz, A. Gonzalez-Escribano, and D. R. Llanos, The shortest-path problem: Analysis and comparison of methods. Springer Nature, 2022.

[54] P. Nayak, G. K. Swetha, S. Gupta, and K. Madhavi, “Routing in wireless sensor networks using machine learning techniques: Challenges and opportunities,” Measurement, vol. 178, p. 108974, 2021.

[55] S. Vadivel, S. Konda, K. R. Balmuri, A. Stateczny, and B. D. Parameshachari, “Dynamic route discovery using modified grasshopper optimization algorithm in wireless Ad-Hoc visible light communication network,” Electronics, vol. 10, no. 10, p. 1176, 2021.

[56] M. A. Hossain, “Network Slicing and NOMA Enabled Mobile Edge Computing for Next-Generation Networks.” New Jersey Institute of Technology, 2024.

[57] W. Hamdi, C. Ksouri, H. Bulut, and M. Mosbah, “Network slicing based learning techniques for iov in 5g and beyond networks,” IEEE Communications Surveys & Tutorials, 2024.

[58] R. Silva, D. Santos, F. Meneses, D. Corujo, and R. L. Aguiar, “A hybrid SDN solution for mobile networks,” Computer Networks, vol. 190, p. 107958, 2021.

[59] D. Bepari et al., “A survey on applications of cache-aided NOMA,” IEEE Communications Surveys & Tutorials, 2023.

[60] Y. Liu, W. Yi, Z. Ding, X. Liu, O. A. Dobre, and N. Al-Dhahir, “Developing NOMA to next generation multiple access: Future vision and research opportunities,” IEEE Wireless Communications, vol. 29, no. 6, pp. 120–127, 2022.

[61] O. Abbasi and H. Yanikomeroglu, “Transmission scheme, detection and power allocation for uplink user cooperation with NOMA and RSMA,” IEEE Transactions on Wireless Communications, vol. 22, no. 1, pp. 471–485, 2022.

[62] S. Ben Saad, A. Ksentini, and B. Brik, “An end-to-end trusted architecture for network slicing in 5G and beyond networks,” Security and Privacy, vol. 5, no. 1, p. e186, 2022.

[63] S. Wijethilaka and M. Liyanage, “Survey on network slicing for Internet of Things realization in 5G networks,” IEEE Communications Surveys & Tutorials, vol. 23, no. 2, pp. 957–994, 2021.

[64] E. E. de Oliveira Lousada and F. de L. P. D. Figueiredo, “An approach for offloading with multi-hop considerations in an RSU signal overlay setting,” Revista de Gestão e Secretariado, vol. 15, no. 4, pp. e3739–e3739, 2024.

[65] M. A. Bharathi, I. S. Rajesh, C. Maithri, and M. S. Krishnamurthy, “Routing Strategies for Quality of Service Optimization over Vehicular Ad Hoc Networks: A Review,” in International Conference on Smart Computing and Communication, 2024, pp. 97–111.

[66] M. Oche, A. B. Tambuwal, C. Chemebe, R. M. Noor, and S. Distefano, “VANETs QoS-based routing protocols based on multi-constrained ability to support ITS infotainment services,” Wireless Networks, vol. 26, pp. 1685–1715, 2020.

[67] B. Ravi, A. Gautam, and J. Thangaraj, “Stochastic performance modeling and analysis of multi service provisioning with software defined vehicular networks,” AEU-International Journal of Electronics and Communications, vol. 124, p. 153327, 2020.

[68] X. Bi, S. Yang, B. Zhang, and X. Wei, “A novel hierarchical V2V routing algorithm based on bus in urban VANETs,” IEICE Transactions on Communications, vol. 105, no. 12, pp. 1487–1497, 2022.

[69] H. Li, F. Liu, Z. Zhao, and M. Karimzadeh, “Effective safety message dissemination with vehicle trajectory predictions in V2X networks,” Sensors, vol. 22, no. 7, p. 2686, 2022.

[70] A. H. Saleh and A. Anpalagan, “AI empowered computing resource allocation in vehicular ad-hoc NETworks,” in 2022 7th International Conference on Business and Industrial Research (ICBIR), 2022, pp. 221–226.

[71] J. Yu, S. Wu, L. Liang, and S. Jin, “Resource Allocation in Vehicular Networks Based on Federated Multi-Agent Reinforcement Learning,” in 2023 IEEE 23rd International Conference on Communication Technology (ICCT),

2023, pp. 84–89.

[72] F. S. Hadi, "Image Compression Process Using Fractional Fourier Transform and Wavelets Techniques," International Journal of Computational & Electronic Aspects in Engineering (IJCEAE), vol. 5, no. 1, 2024.

[73] H. F. Khazaal, A. Magdy, I. Svyd, and I. OBOD, "A Dumbbell Shape Reconfigurable Intelligent Surface for mm-wave 5G Application," International Journal of Intelligent Engineering and Systems, vol. 17, no. 6, pp. 569-582, 2024.

[74] J. Al-Sammak and H. Talib, "Propose an Object Detection Optimization Algorithm by Using Particle Swarm Optimization (PSO) Based-on Exploration Ability of Grey Wolf Optimizer (GWO)," International Journal of Computational & Electronic Aspects in Engineering (IJCEAE), vol. 5, no. 2, 2024.

[75] A. Magdy, I. Svyd, and I. OBOD, "Reconfigurable Intelligent Surfaces Between the Reality and Imagination," Wasit Journal of Computer and Mathematics Science, vol. 3, no. 2, pp. 42-50, 2024.

[76] M. K. Abbas, "Modelling WhatsApp Traffic Control Time-Based (WTCTB) for 5G Mobile Network," International Journal of Computational & Electronic Aspects in Engineering (IJCEAE), vol. 4, no. 4, 2023.

[77] M. H. Mthboob, and I. A. Aljazaery, "Design and analysis of a DC motor speed drive with generalized regression neural network (GRNN) and invasive weed optimization (IWO) algorithms," in AIP Conference Proceedings, 2023, vol. 2977, no. 1: AIP Publishing.

[78] A. A. Hadi, "The Impact of Artificial Neural Network (ANN) on the Solar Energy Cells: A Review," International Journal of Computational & Electronic Aspects in Engineering (IJCEAE), vol. 5, no. 1, 2024.

[79] M. Jawad Al-Dujaili, B. H. Majeed, and I. R. N. ALRubeei, "Information and Communication Technology and its Impact on Improving the Quality of Engineering Education Systems," International Journal of Engineering Pedagogy, vol. 14, no. 1, 2024.

[80] E. Becker, "A Review on STBC Design with Two Transmit Antennas," International Journal of Computational & Electronic Aspects in Engineering (IJCEAE), vol. 4, no. 4, 2023.

[81] M. Basheer Gheni, "Enhanced System for Prediction of Students' Performance Using Deep Learning," International Journal of Computational & Electronic Aspects in Engineering (IJCEAE), vol. 5, no. 3, 2024.

[82] D. Han and J. So, “Energy-efficient resource allocation based on deep Q-network in V2V communications,” Sensors, vol. 23, no. 3, p. 1295, 2023.