IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 20 May 2024, accepted 12 June 2024, date of publication 20 June 2024, date of current version 28 June 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3417288

RESEARCH ARTICLE

Multi-Path Transmission Protocol for Video Streaming Over Vehicular Fog Computing Environments

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ABSTRACT Delivering real-time multimedia content for safety applications over vehicular networks presents significant challenges due to rapidly changing network topology, high node mobility, and fluctuating traffic demands, compounded by substantial data volumes and network resource limitations. This paper proposes the Multi-Path Transmission Protocol for Video Streaming (MPTP-VS) to address these issues by optimizing video transmission in road incident scenarios. Utilizing a Fog Computing architecture, the protocol enhances video delivery efficiency while maintaining high Quality of Service (QoS) and Quality of Experience (QoE) through effective management of network resources such as bandwidth, jitter, and latency. Leveraging Ant Colony Optimization (ACO), MPTP-VS establishes an adaptive multi-path routing strategy that dynamically discovers network topology and promptly transmits data, ensuring seamless video streaming without prior knowledge of the network topology. Experimental results within an OMNET++ simulation environment demonstrate that MPTP-VS reduces latency by up to 83%, increases throughput by up to 43%, and achieves a 75% improvement in path discovery time compared to Ad Hoc On-Demand Distance Vector (AODV) and Dynamic MANET On-demand (DYMO) protocols. Additionally, MPTP-VS achieves a 35% higher Peak Signal-to-Noise Ratio (PSNR) compared to current Content Delivery Network (CDN) systems employing Adaptive Bitrate Streaming (ABS). These findings highlight the significant enhancement in video streaming performance and reliability in vehicular environments using the proposed protocol.

INDEX TERMS Vehicular networks, video streaming, dynamic routing, multi-path routing, ant colony optimization, vehicular fog computing, QoS, QoE.

I. INTRODUCTION

The modern expansion of road infrastructure has led to an alarming surge in road accidents, necessitating urgent enhancements in road safety measures. Therefore, connected vehicles have emerged as a promising area of research, offering potential solutions to enhance traffic services and road safety through disseminating alarm and warning messages [1]. However, current text-based communication in connected vehicle networks may be limited in its ability to effectively convey critical information to passengers, emergency responders, and drivers [2], [3].

In an effort to transcend the constraints of conventional text-based communication, research in this domain converges towards transmitting richer, more meaningful content to fortify road safety. Among these, video streaming emerges as a crucial service, providing precise on-road information. It empowers users and authorities such as firefighters and paramedics with comprehensive insights, aiding in informed decision-making. Furthermore, video streaming

The associate editor coordinating the review of this manuscript and approving it for publication was Jie Gao.

equips paramedic vehicles, including ambulances, to prepare for medical interventions even before reaching the accident scene. However, reliably delivering video content over VANET presents numerous challenges, including bandwidth constraints, frequently changing network topology, and a lack of a comprehensive network view [4], hindering the stringent QoS that profoundly impacts the QoE required by multimedia applications [5], [6].

These delivering environments are characterized by high mobility and constantly evolving topology, which present significant challenges in maintaining stable and high-quality video transmission. The QoS and the QoE are essential metrics in delivering superior streaming video services. The QoS measures ensure network performance parameters such as bandwidth, latency, and reliability, while QoE measures indicate end-user satisfaction in terms of visual quality, playback smoothness, and loading time. Swift optimization of QoS and QoE is imperative to ensure efficient video streaming delivery, particularly by integrating connected vehicle environments with Content Delivery Network (CDN) and Fog computing architectures. We emphasize the importance and urgency of enhancing QoS and QoE for video streaming in the following connected contexts:

- Traffic management applications require stable, high-quality video streams to ensure an optimal level of road safety. Real-time video monitoring of road conditions allows autonomous driving systems to have a real-time view of current road conditions. This provides drivers with crucial information about traffic conditions, allowing them to anticipate potential dangers and accident risks on the road. Low QoS can lead to delays and loss of video data, compromising the efficiency of these critical applications.
- Due to the mobility of vehicles and traffic density, network conditions can vary significantly, affecting the quality of immersive video experiences. Improved QoS and QoE ensure efficient delivery of video content, thereby preserving immersive experiences even amidst these network fluctuations.
- A high QoE of video streaming is directly linked to user satisfaction, including uninterrupted videos, high resolution, and low loading times. Improving the QoE can increase adoption and trust in video streaming within connected vehicular networks.

A. MOTIVATIONS

Optimizing QoS and QoE in connected vehicle networks, leveraging adaptability and integration with fog computing architectures, is essential to meet real-time performance requirements, improve user experience, and ensure the reliability of video transmissions under dynamic and variable network conditions.

The need for a new routing protocol for video streaming in a vehicular fog computing architecture is driven by the desire to minimize latency and simultaneously enhance QoS and QoE through the use of cutting-edge computing technologies. By integrating fog computing, it is possible to ensure dynamic management of network resources, allowing real-time adjustments to video transmission, thus optimizing bandwidth and reducing packet loss. Network resilience is also strengthened through distributed processing and storage, thereby reducing the risk of a single point of failure and improving the availability of streaming services. This is crucial to meet the increasing demand for high-quality video streams among a growing fleet of connected vehicles.

B. OBJECTIVES

This study confronts the challenge of ensuring effective transmission of video content in connected vehicle networks, where traditional routing protocols often fail to maintain optimal quality of service in dynamic environments. This dynamism frequently leads to issues that could compromise the reliability of the distribution, such as interruptions caused by packet loss and unstable connections between the vehicle and the network, as well as high delays and bandwidth fluctuations that affect the fluidity of the streaming experience. Modern routing protocols strive to integrate technological advances to improve service quality and the streaming user experience. To meet these optimization challenges, we offer an innovative multi-path transmission approach, called MPTP-VS, which leverages the potential of a vehicular fog computing architecture to ensure adaptive routing based on the power of Ant Colony Optimization (ACO). This approach is particularly crucial in situations where incidents can occur. The protocol adapts in real-time due to a global view managed by fog servers, located as close as possible to incidents, as well as a local view dynamically managed by the nodes of vehicles. The main contributions of this work are summarized as follows:

- Propose a Vehicular Fog Computing (VFC) architecture to provide adaptive mobile video routing in emergency situations while preserving critical network parameters, such as latency, throughput, transmission time, etc.
- Propose a new efficient and adaptive video streaming delivery protocol, whose QoS and QoE are optimized by an efficient multiple-path selection approach using Ant Colony Optimization (ACO) meta-heuristics.
- Adopt a path selection control mechanism via two discovery strategies adopted for the proposed VFC architecture. A local discovery strategy allows computing and communication resources to be utilized near the nearest fog layer. A global discovery strategy is enabled for a network of fog servers covering a wider area.
- Adjust path discovery and selection processes taking into account vehicle mobility and topology fluctuations. This objective aims to maintain stable video transmission quality by controlling the path quality, path update, and lifetime of the discovered paths.

C. PAPER STRUCTURE

The paper is organized as follows: Section II presents our related works. Section III introduces the Vehicular Fog

Computing (VFC) architecture and its integral components tailored for efficient video traffic routing, specifically in emergency scenarios. Section IV denotes the problem statement of path selection for streaming video in VANET. Section V details the methodology and the innovative MPTP-VS routing protocol designed for this purpose. Section VI explores the adaptation of the Ant Colony Optimization (ACO) algorithm for discovering stable multi-paths from the vehicle source to the destination. Section VII presents a comprehensive simulation study, including the scenario setup, simulation tools, parameters, and a discussion of the findings in terms of network performance measures. The paper concludes in Section IX, summarizing the significant contributions of MPTP-VS and proposing potential directions for future research.

II. RELATED WORK

The transmission protocols in vehicular environments play a crucial role in delivering high-quality videos, ensuring smooth and stable playback to users. These protocols efficiently manage an evolving network characterized by rapid changes. They select the optimal routes based on various methods and criteria designed to minimize such disruptions as delays and data loss [7], [8]. However, due to the complexity of network conditions, these protocols may sometimes fail to meet expectations. The research works therefore continually strive to improve their performance against network fluctuations, traffic mobility, and congestion.

A. PATH DISCOVERY-BASED ROUTING PROTOCOLS

The path discovery process allows protocols to determine optimal routes by taking into account factors such as vehicle mobility, traffic density, network conditions, and QoS constraints. By dynamically adapting paths based on changes in the network environment, protocols can ensure efficient transmissions with minimal delays, thereby reducing latency and maximizing the use of available network resources. Heuristic-based path discovery techniques use rules and optimization algorithms to quickly find efficient paths through the topology. The Dynamic Source Routing (DSR) protocol starts path discovery only when necessary. Once the path to the destination is discovered, the path details are recorded in the packet header. This header also includes the addresses of all nodes that the packet must pass through to reach its destination [9]. In addition, the DSR protocol has a notable limitation in the path discovery process. It does not have a mechanism to detect unstable routes, resulting in transmissions over unstable communication paths. The route maintenance process is performed based on three specific types of control packets: route requests, route errors, and route responses. The TORA protocol provides temporally ordered routing that adapts the propagation of control messages in highly dynamic ad hoc networks. A node initiates a request only when it needs to send data to a destination. The discovery performance of this protocol significantly outperforms that of the DSR protocol under different network conditions [10]. This improvement is attributed to the protocol's ability to minimize communication overhead, thereby improving its reliability for fluctuating ad hoc networks. Additionally, the route maintenance process is based on localizing control messages to specific node sets and efficiently handling link failures [11]. The Ad hoc On-Demand Distance Vector protocol (AODV) uses a hop discovery mechanism and manages flat routing tables. Each table contains a single entry for each destination [12]. Unlike the TORA protocol, AODV adopts multi-hop routing in dynamic environments with high mobility. This protocol effectively allows mobile nodes to quickly establish routes to new destinations without keeping routes idle. Its route discovery process reduces the need for frequent broadcasts by generating on-demand routes. This benefit reduces routing overhead under unstable conditions. However, there may be delays in restoring routes after a failure and it can produce significant control traffic in dense networks, which could degrade overall performance. The Dynamic MANET On-demand (DYMO) protocol is designed to avoid route discovery defects of the AODV protocol. This protocol proactively updates routing information in real-time, allowing it to quickly adapt to changes in network topology. Despite its progress, this protocol faces challenges in handling high traffic congestion and maintaining route stability under adverse network conditions. These issues negatively impact network performance, especially in dense or highly dynamic scenarios [13], [14].

Integrating heuristic approaches into the path discovery process offers a promising solution to overcome the limitations of previous routing protocols and add increased dynamics to route discovery [15], [16]. However, these approaches face scalability and efficiency issues, often leading to increased overhead and potential delays in route establishment. To address these challenges, researchers are turning to meta-heuristic approaches, which offer more optimized, adaptive, and efficient solutions [17], [18]. These solutions make it possible to continuously optimize the discovery process based on vehicle mobility using algorithms inspired by nature such as ant colony optimization. The Ant Colony-based Dynamic Source Routing (ADSR) protocol [19] integrates ant colony optimization with traditional DSR, demonstrating its effectiveness in various ad hoc network scenarios. It aims to optimize the route discovery process by learning from continuous network feedback, although it may encounter issues related to area overlap and scaling to larger areas. In a mobility-aware context [20], an ACO algorithm is designed to meet the characteristics of high vehicle mobility, ensuring fast and efficient route discovery. However, relying on vehicle-specific measurements may limit its applicability under various network conditions. The integration of ACO and SNMP with the Qora protocol is mentioned in this work [21], the objective is to balance QoS by effectively controlling network congestion.

B. IMPROVING VIDEO STREAMING IN VEHICULAR NETWORKS

The demand for streaming services in vehicular networks, especially during emergencies, necessitates significant advancements in video streaming technology. In such scenarios, the requirements for timely and reliable streaming are paramount, yet these networks frequently face challenges with scalability, efficiency, and stability, which can lead to increased overhead and potential delays. To address these issues, innovative strategies like preallocating streaming content from computing services such as Cloud, CDN, and Fog have been adopted. By reducing latency and ensuring data redundancy, these approaches guarantee consistent and reliable quality of service for real-time streaming, even under unpredictable and high-mobility conditions. However, the application of each technology depends on the specific needs and context of the vehicular environment, ensuring a tailored solution that optimally balances efficiency and timeliness, outlined as follows:

1) CLOUD DELIVERY NETWORKS (CLOUDDN)

The CloudDN harnesses the centralized processing and storage capabilities of cloud computing (CC) to optimize resource allocation and scalability [22], significantly enhancing video streaming performance in vehicular settings. By utilizing the vast resources of the cloud, CloudDN can dynamically allocate bandwidth and computing power based on real-time demands, ensuring seamless, high-quality video streaming even during peak times or in densely populated areas. This centralized approach not only improves the efficiency and reliability of video delivery but also reduces the latency typically associated with streaming over fluctuating vehicular networks. As such, CloudDN provides a robust solution that adeptly meets the critical demands for timely and reliable video streaming in emergency scenarios.

The framework outlined in [23] seeks to improve the quality of experience (QoE) for video streaming in vehicular networks by integrating cloud computing (CC). It proposes a sophisticated system architecture involving central clouds, roadside cloudlets, and vehicular clouds to ensure seamless high-quality video streaming in the unpredictable conditions of vehicular networks. However, the paper lacks empirical validation and overlooks economic and practical deployment aspects, essential for real-world applicability and scalability. In [24], vehicles serve as mobile caches and relays for streaming content, such as videos, within a vehicular cloud system. This approach reduces congestion on cellular networks and enhances user experience by managing playout buffers and optimizing content allocation across vehicle caches. In [25], a bandwidth-aware framework utilizes volunteer fog nodes to create an edge-node-assisted real-time streaming P2P platform. The system optimizes edge resource utilization, considering varying job lengths and bandwidth consumption, and relies on the public cloud only as a backup for end-user demands. In [26], MIGRATE, an orchestrator architecture, dynamically adjusts video streaming services to improve user QoE. Operating within an edge/cloud multi-tier network, MIGRATE optimizes connections between users and services using Integer Linear Programming (ILP) and a Greedy solution, emphasizing the balance between resource usage and user satisfaction.

2) CONTENT DELIVERY NETWORKS (CDN)

Implementing CDN in vehicular networks involves strategically placed servers to enhance content delivery. CDNs help in reducing latency and buffering by caching content closer to the users, ensuring high-quality streaming across varying network conditions. The deployment of CDN effectively addresses the inherent limitations of CloudDN by offering faster response times and more reliable service in dynamic vehicular environments. In the work of [27], a method segments video content across multiple edge servers in CDNs, aiming to optimize server costs and improve efficiency. While this approach reduces storage requirements per server and enhances CDN efficiency, it may introduce operational complexity and potential latency issues due to increased HTTP GET requests. However, the paper lacks comprehensive scalability analysis and real-world applicability assessment, critical for evaluating its feasibility in existing CDN infrastructures. The concept of Reverse Content Distribution Network (rCDN) integrated with Fog Computing to manage large video data volumes from connected vehicles is introduced in [28]. This innovative approach reverses traditional CDN flows, efficiently addressing smart city and autonomous driving data challenges. Despite its technical detail and relevance to urban technologies, the paper lacks empirical validation and economic implications analysis for rCDN deployment, suggesting the need for pilot implementations and cost-benefit assessments. This work [29] explores the role of CDN technology in improving QoS for live streaming, particularly using HTTP Live Streaming (HLS). The study demonstrates the effectiveness of CDN in reducing packet loss and increasing throughput, although it could benefit from a broader literature review and discussion of scalability and technical details.

3) FOG DELIVERY NETWORKS (FDN)

Traditional CDNs struggle with high latency and limited scalability in these dynamic environments, making Fog Delivery Networks (FDNs) a better choice due to their lower latency, improved processing, and use of edge computing [30]. FDNs enhance data-intensive applications in vehicular networks by processing data locally at nearby fog nodes, such as vehicles or roadside units, significantly reducing latency compared to traditional cloud processing. This local processing minimizes delays and improves service quality, making it ideal for latency-sensitive applications like video streaming, security checks, and real-time content delivery.

In [31], soft actor-critic deep reinforcement learning (DRL) is integrated to optimize vehicle scheduling, bitrate selection, and resource allocation in a dynamic vehicular network. This optimization is treated as a Markov Decision Process (MDP), considering the time-varying characteristics of resources and channels. The system improves video quality, decreases latency, and manages bitrate variations effectively, leveraging the computational capabilities of both RSUs and vehicles within the IoV. This method notably outperforms traditional models by adapting more efficiently to network changes and resource variability. In [32], Fog4Video, a novel multi-tier fog computing content orchestrator, is designed to enhance the QoE for Video-on-Demand (VoD) services. Through detailed simulations, Fog4Video is shown to significantly improve QoE by reducing video stalls and enhancing bitrate, compared to traditional content delivery mechanisms. Despite its benefits, the implementation complexity and reliance on extensive fog node infrastructure may limit practical application. The proposal highlights the potential of fog computing in media delivery but also suggests the need for further research to address deployment challenges and economic viability in diverse environments.

To provide a more detailed analysis, we present a comprehensive comparison in Table 1. The FDN provides distinct advantages for video streaming in emergency scenarios, particularly due to its low latency, high adaptability, and effective local processing capabilities. These features ensure that FDN is capable of delivering critical real-time information reliably and securely, making it superior in contexts where rapid response and adaptation to dynamic conditions are essential. While CloudDN and CDN have their strengths in scalability and broad content distribution, respectively, FDN's edge-centric approach offers the responsiveness and flexibility needed in critical and dynamic settings such as emergency vehicular networks.

III. VFC ARCHITECTURE FOR VIDEO TRAFFIC ROUTING

In this section, we present the VFC architecture and its integrated components that we propose to solve problems related to the efficient routing of video streaming, and the optimal routing of real-time video streams in particular. The architectural design emphasizes adaptability and efficient management of video stream transmissions, especially in scenarios involving road-related events. The main goal is to preserve critical network parameters, such as latency and transmission times. Additionally, this architectural approach aims to alleviate the computational burdens borne by relay nodes by decentralizing routing decisions, thereby enabling endpoints equipped with proactive vehicle-to-infrastructure (V2I) connectivity. Figure 1 shows a vehicle network architecture integrated with a Fog Computing layer. This combination aims to provide adaptive mobile video routing while minimizing connectivity interruptions or RSU changes. For better interaction, each element uses a set of exchange protocols precisely adapted to fulfill specific tasks.

The key components within this architecture include:

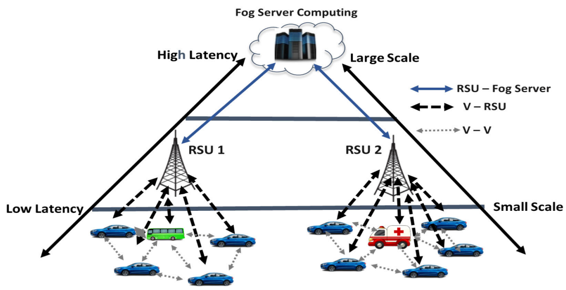


FIGURE 1. VFC architecture for critical video streaming in real-time.

Vehicular nodes encompass a variety of vehicles that are connected to edge computing infrastructure (fog computing) in a network. Specifically, we use connected emergency vehicles to respond to emergency situations, such as accidents. In this context, vehicles near the incident play the role of event detectors, for example, using cameras. These vehicles also serve as relay nodes for video transmission using vehicle-to-vehicle communication (V2V). The video transmission system uses connected emergency vehicles to create a network for detecting and transmitting information in the event of emergency incidents. This allows for a faster and more efficient response to emergency situations, which can potentially save lives and reduce damage in the event of accidents on the road.

The RSUs constitute intermediate access points, seamlessly integrated into the architecture we have meticulously crafted. Each RSU bears the responsibility of providing connectivity to a designated cluster of vehicles within its coverage area. These RSUs assume a pivotal role in facilitating vehicle-to-infrastructure (V2I) communication, thereby enabling vehicles to establish connections with the network infrastructure. This connectivity serves multifarious purposes, encompassing seamless information exchange and comprehensive data collection capabilities.

The integration of a fog computing infrastructure aims to optimize streaming routing in vehicular networks. This approach is structured around several fundamental objectives. It is crucial because it aims to establish a centralized approach to routing, thus bringing processing closer to data generated by vehicles. This centralization has notable benefits, particularly in terms of improving streaming efficiency, which is especially crucial in emergency situations on the road. A process of data collection before processing, in large part, ensures the streaming efficiency. This data comes from various vehicle nodes and is acquired via V2V and V2I communications, as well as RSUs. Once collected, this data is subjected to further processing. This is where a fog server comes in, whose crucial role is to maintain dynamic routing decision-making at scale, employing heuristic methods to optimize the routing of data flows within the VANET. This approach promotes efficient and adaptive dissemination of information within the connected vehicle environment, thereby improving the security and effectiveness of

TABLE 1. Analysis of video streaming in emergency scenarios using CloudDN, CDN, and FDN.

Criteria	CloudDN	CDN	FDN
Latency	High (due to centralized processing)	Medium to Low (due to content caching near users)	Very Low (due to edge computing close to users)
Rapidity	Slower (potential central server bottlenecks)	Faster (pre-cached content near users)	Very Fast (content processed and delivered at the edge)
Computational Performance	High (robust central servers)	Moderate (limited to caching and delivering content)	High (depends on local node capabilities)
Storage Capacity	Very High (scalable cloud storage)	High (fixed, requires physical expansion)	Lower (limited to local resources)
Scalability	High (elastic cloud resources)	Medium (requires physical infrastructure expansion)	Medium (adaptive to network changes, limited physical scaling)
Adaptability	Lower (fixed infrastructure)	Medium (somewhat flexible with edge server locations)	High (dynamic adaptation to network conditions)
Cost-efficiency	Variable (can be high due to infrastructure costs)	Generally cost-effective for broad distribution	Variable (depends on implementation and local resources)
Security	High (centralized security measures)	High (benefits from centralized management)	Medium to High (robust but decentralized)
Resilience to Network Disruptions	Moderate (vulnerable to central failures)	High (redundant paths and nodes)	Very High (distributed architecture minimizes single points of failure)
Resource Utilization	Efficient at scale (leveraging large data centers)	Efficient (optimized through global distribution)	Highly efficient locally (but dependent on edge resources)
Cost	High (significant infrastructure and maintenance expenses)	Medium to High (depends on scale and deployment)	Lower (reduced infrastructure needs)
Dynamic Adaptability	Low (changes require infrastructure adjustments)	Medium (some ability to reroute and adjust caches)	High (quickly adapts to changes at the edge)
Deployment and Management Complexity	High (complex and costly infrastructure management)	Medium (managing distributed servers)	High (requires coordination of numerous edge nodes)
Reliability	High (robust systems with backup)	High (multiple redundancies)	Medium to High (depends on edge node reliability)

communications in these constantly evolving contexts. Moreover, we explore various vehicular traffic applications integrated into the proposed architecture, including:

A. NETWORK TRAFFIC

In our scenario, all vehicles periodically send beacon messages to notify the nearest RSU of their presence. These beacon messages include a field for identifying emergency vehicles (ID, Type, Location, Movement Direction, Neighbors' IDs). Information about emergency vehicles is forwarded to the fog server. The kinetic information is utilized by the RSU to estimate when these vehicles leave its communication range. Furthermore, the RSU maintains a local cache containing a set of records, each record containing status information about neighboring vehicles. When an RSU receives a beacon message from a vehicle, it updates the local cache based on the piggybacked information. Given the high mobility of nodes in VANET, the RSU must periodically check whether a vehicle is within its communication range. The simplest approach to achieve this task is by scheduling a timer that expires after a time interval T. The value of T is calculated according to the following equation:

$$T = T_r + T_p \tag{1}$$

where T_r represents the time when a Roadside Unit (RSU) last received a beacon signal from a vehicle, and T_p is the expected interval between these beacon signals. RSUs use these beacons to track vehicles within their communication range. When an RSU receives a beacon, it updates T_r and starts a timer based on T_p. If the timer expires without receiving a new beacon, the RSU assumes the vehicle has left its range and removes the vehicle's record from its local cache. This process ensures that the RSU's cache is current and efficiently managed.

B. VEHICULAR TRAFFIC CONTROL

When a vehicle intends to transmit a video feed to an appropriate emergency vehicle, it sends an accident notification message (vehicle ID, source, movement direction, location) to the nearest RSU, requesting assistance in identifying a suitable emergency vehicle. Upon receiving the accident notification, the RSU initiates the Local Discovery Process (LDP) to identify the most suitable emergency vehicles. This approach ensures a swift and efficient response to roadside emergencies by utilizing locally available IT and communication resources. When a discovery process is initiated by the nearest RSU and an intervention vehicle is identified near the accident site, the RSU locally adapts a strategy to maintain the quality of video transmission in this specific situation. In such cases, the nearest RSU takes measures to ensure high-quality video transmission. However, if no suitable response vehicle is identified in proximity, the nearest RSU sends a notification along with its GetTable to the fog server, triggering the Global Discovery

Process (GDP). The fog server, in this context, plays a crucial role in coordinating and orchestrating the search for suitable response vehicles on a broader scale.

C. MOBILITY MANAGEMENT

As the vehicle is a highly mobile node, we have to handle its transition from one RSU to another. When a vehicle in the network is receiving video packets from an RSU, and it changes its location to the communication range of another RSU, there is a need to send a transfer notification to the new RSU. The transfer notification packet includes the IP address of the source RSU and the sequence number of the last received video packet. In turn, the new RSU sends this transfer notification packet to the source RSU. When the source RSU receives the notification, it proceeds to deliver the remaining video packets to the new destination RSU. This architecture is leveraged to search for optimal QoS paths for video streaming within the proposed architecture. The hierarchical approach ensures the efficient selection of appropriate emergency vehicles.

IV. PROBLEM STATEMENT AND OBJECTIVE FUNCTION

The complexities of path selection for video streaming in VANET arise from a combination of factors: the dynamic nature of wireless communication channels, the specific properties of video data, and the inherent characteristics of VANET. A significant challenge in VANET is the transient nature of communication links, which results from rapid changes in topology due to vehicle mobility and fluctuating vehicular densities. These factors make the estimation of QoS parameters particularly difficult in this ever-changing environment. Addressing these challenges involves reconciling conflicting objectives, making it a complex endeavor. The utilization of multi-path routing facilitates the transmission of sub-streams; however, it introduces the risk of packet loss. Therefore, an approach incorporating stable paths within the multi-path framework becomes pivotal to minimizing delays in video streaming.

A. NOTATIONS

The list of notations used in our study is shown in Table 2.

TABLE 2. List of notations.

Notation	Description
N	Set of edge nodes, including the video server, and vehicular nodes.
L	Set of interconnection links between the nodes.
P	Set of possible paths for video streaming between a source vehicle and an emergency vehicle.
x_{ijp}	Binary decision variable indicating whether the video streaming path p uses the interconnection link between a vehicle i and its neighbor j ($x_{ijp} = 1$ if path p crosses link between (i, j), $x_{ijp} = 0$ otherwise).
C_{ij}	Determines the total cost to aggregate, according to network parameters linked to mobility and QoS, from the starting node of a path $p \in P$ to the link (i, j).
Z	The objective function represents a linear combination of all the parameters in C to be optimized according to the diversity of the paths.
w_{ij}	Weight associated with each link between vehicle i and its neighbor j
α	Coefficient denotes the sum of total costs, determined according to the mobility parameters and the QoS, which are associated with each link (i, j) taken by each path p.
β	Coefficient denoting path diversity by maximizing the total number of links used by all paths.
$L_{i,j}$	Latency between $i \rightarrow j$
$H_{i,j}$	Hop count between $i \rightarrow j$
$Lf_{i,j}$	Route lifetime between $i \rightarrow j$
$D_{i,j}$	The distance between $i \rightarrow j$
$Q_{i,j}$	Path quality between $i \rightarrow j$
$Ph_{i,j}$	The quantity of pheromone deposited on a path $i \rightarrow j$
Br	The streaming bitrate
C'_{ij}	Link capacity between $i \rightarrow j$.

B. OBJECTIVE FUNCTION

In order to tackle the previous challenges, it is imperative to identify a solution that can effectively accommodate multiple objectives simultaneously. This necessitates a precise definition of the objectives inherent to the objective function. Within the context of optimizing network traffic for a video streaming application deployed in a vehicular network, the objective function integrated with the ACO algorithm offers a robust framework for identifying the most efficient routes for network-based video streaming. This optimization process centers on the refinement of criteria pertinent to both mobility and QoS parameters. Therefore, in the process of defining the objective function for a specific path, it becomes crucial to ascertain the underlying routing topology, comprising nodes, the interconnecting links between these nodes, and the pertinent routing information disseminated among them. The computation of the objective function is intrinsically tied to an aggregate function representing the overall cost incurred by each path as it traverses the interconnecting links between the nodes within the network. The comprehensive evaluation of this total cost function for each path entails the summation of the cost contributions associated with the individual links. Notably, each criterion contributing to these costs is assigned a weight that signifies its relative significance in the optimization of video streaming performance.

$$Z = \alpha \sum_{p \in P} \sum_{(i,j) \in L} \omega_{ij} \cdot c_{ijp} \cdot x_{ijp} + \beta \sum_{p \in P} \sum_{(i,j) \in L} x_{ijp} \quad (2)$$

Subject to the following constraints:

- $$\begin{cases} \sum_{j \in N} x_{sij} = 1, \forall i \in N \\ \sum_{i \in N} x_{ijd} = 1, \forall j \in N \end{cases} \quad (3)$$
- $$\sum_{i \in N} x_{ijp} - \sum_{k \in N} x_{kjp} = 0, \forall j \in N, p \in P \quad (4)$$
- $$\sum_{i \neq j} X_{ij} \cdot Br_{ij} \leq C'_{ij}, \forall i, j \quad (5)$$

The objective function Z aims to optimize streaming routing by evaluating the weighted sum of the costs linked to each link taken by each path, while taking into account the diversity of the available paths. The first constraint (Equation 3) states that each streaming path must start from a source node and end at a destination node. The second constraint (Equation 4) specifies that each relay node in a streaming path $p \in P$ must have precisely one predecessor and one successor. The third constraint (Equation 5) ensures that the sum of the video streaming rates on all the routes between vehicles i and j does not exceed the capacity C'_{ij} of the link connecting them.

V. PATH DISCOVERY STRATEGIES

In our proposal, the considered protocol uses two discovery strategies: a local discovery strategy and a global discovery strategy. These processes help identify appropriate vehicles for video transmission in an emergency. These processes quickly identify appropriate emergency vehicles for video transmission in the event of an accident. Local discovery searches for vehicles in the immediate area, while global discovery extends the search on a wider scale via the Fog server, ensuring a coordinated and efficient response.

A. LOCAL DISCOVERY PROCESS (LDP)

This process is triggered when a vehicle detects an accident and aims to route streaming video to the appropriate emergency vehicle within the coverage area of an RSU or Fog node. In this situation, the vehicle sends an accident notification message to the nearest RSU, requesting its assistance in identifying and locating the nearest emergency vehicle. If no emergency vehicle is identified within the coverage area of the RSU, a Fog node can undertake this process on a larger scale to locate such a vehicle within another RSU. In particular, the identification of suitable emergency vehicles is carried out using various measures and criteria defined in Table 3.

B. GLOBAL DISCOVERY PROCESS (GDP)

This process is initiated when an RSU is unable to locate a suitable emergency vehicle within its coverage area. In this situation, the RSU sends a notification to the fog server and shares its data table containing information about the accident. The fog server then coordinates the search for suitable response vehicles on a large scale, leveraging data from multiple RSUs within the network. Then, the fog server creates a global view by combining this data from multiple sources. This aggregation makes it possible to efficiently locate appropriate response vehicles on a larger scale. To illustrate this process, we assume that a base station, named "RSU1", reports an accident on the main street, indicating that two vehicles are involved and that there are no emergency vehicles nearby. At the same time, another base station, "RSU2", reports another accident on the highway, involving a broken-down truck, but also reports that an emergency vehicle is available a few kilometers away. Finally, a third base station, "RSU3", detects an accident on a secondary road and reports that an ambulance is nearby.

In this context, the Fog layer integrates a video streaming server which manages several content servers distributed over a network. Each of these servers is considered a potential

FIGURE 2. Global and Local Discovery.

"node" for streaming video. The main goal is to ensure efficient video streaming by considering the proximity of emergency vehicles in each situation while accounting for the network traffic constraints mentioned previously, such as latency and bandwidth. When streaming video through this server, it uses the heuristics of the ant colony algorithm to establish a global view of the network. This process can be explained as follows:

- The ant colony algorithm is used to optimize delivery by identifying the fastest and most reliable routes for each emergency vehicle. In particular, the path discovery process is responsible for finding an optimal path for a vehicle involved in an accident, taking into account various factors, such as broadcast quality, bandwidth preservation, latency, and other considerations.
- The discovery process explores different possible paths between network nodes, ensuring that the selected paths are the most appropriate to meet the needs of each emergency vehicle.
- Information about the paths explored by the discovery process is then shared with a central server. The latter uses this data to make informed decisions about streaming video, ensuring that emergency vehicles are optimally served depending on the situation.

Following this approach, the central server aggregates this data to establish a complete perspective of the network, allowing it to determine the most appropriate servers to satisfy the requirements of each vehicle. If a transmitting vehicle is in a low-bandwidth area, the preview can signal that the nearest emergency vehicle (UV1) is already in high demand, while another emergency vehicle (UV2) is benefiting from a better connection. The central server can redirect video streaming from this transmitting vehicle to the UV2, ensuring a higher-quality streaming experience for a more comprehensive Figure 2.

VI. PATH DISCOVERY AND TRANSMISSION PROCESS

The transmission of video streaming with the MPTP-VS protocol is triggered by the path discovery process. This

TABLE 3. Emergency vehicle situations.

Case	Location	Movement Direction	Description
1. Nearest RSU: The emergency vehicle is close to the nearest RSU.			
1.1	Before Source	Forward	The emergency vehicle is positioned ahead of the source vehicle in the same direction.
1.2	After Source	Forward	The emergency vehicle is located after the source vehicle in the same direction.
1.3	-	Opposite	The emergency vehicle is moving in the opposite direction.
2. Distant from Nearest RSU: The emergency vehicle is outside the coverage area of the nearest RSU.			
2.1	Before Source	Forward	The emergency vehicle is located ahead of the source vehicle in the same direction.
2.2	After Source	Forward	The emergency vehicle is located after the source vehicle in the same direction.
2.3	-	Opposite	The emergency vehicle is moving in the opposite direction.

process is designed to ensure that emergency videos are transmitted via the fastest possible paths, taking into account the overall network condition. Specifically, the path discovery process enables dynamic path discovery, thereby optimizing video flow between vehicles involved in near-miss scenarios and emergency response units. The process starts with the vehicle closest to the accident, which sends a route discovery packet *ACO_RREQ* to neighboring vehicles. Each vehicle receiving this packet records it in its neighborhood table, thus contributing to a coordinated network response.

A. VEHICLE ROUTING TABLE (VRT)

The Vehicle Routing Table (VRT) is a dynamic structure containing information crucial for routing in the vehicular network, as shown in Table 4. This table evolves in real-time as intermediate nodes exchange data until reaching the final destination. Once the destination is identified, the server updates the overall network view to adapt to current traffic needs. In particular, this table provides a detailed description of the information needed for the discovery process. Each networked vehicle uses this data structure to record routes to their destination, as discovered by the discovery process. Each route includes the following:

- R_{id}: The identifier of the routing route.
- O_{addr}: Origin address of the *ACO_RREQ* packet.
- D_{addr}: Destination address of the *ACO_RREQ* packet.
- $Ph(p)$: Pheromone value of a route (p), set upon reception of an *ACO_RREP* packet, where $Ph(p) = \sum_{i \in N-1} Ph_{i,i+1}$ is the cumulative quantity of pheromones for a route p.
- $gtw : V_{id}$: Indicates the next hop address of the vehicle V_{id}.
- ρ presents the pheromone evaporation rate from a routing route.
- Lf_p represents the length of time a route p remains active.

B. PATH REQUEST

When an accident occurs on a roadway, a nearby intelligent vehicle triggers a video streaming to the nearest fog server. However, initiating streaming without precise information about the vehicular topology can be challenging. The source vehicle initiates a topology discovery process by broadcasting an *ACO_RREQ* packet to its neighbors. This packet contains an identifier *ID_ACO_RREQ*, a stack of nodes (*Stack_nodes*) to record the intermediate nodes receiving the packet, and an original packet address field. Additionally, it includes a destination address field to reach, a neighbor's address field of the emitter of the packet, and the latency of each link (i, j) as shown in Figure 3. If a node has never received this packet (i.e., *ID_ACO_RREQ*), then this node increments the H. It also adds a new routing route to its VRT by assigning the address of the neighbor who sent the *ACO_RREQ* packet as $gtw : V\_id$.

If a vehicular node is not the recipient of the packet, it stacks its address in the (*Stack_nodes*) stack. Afterwards, it updates its routing table and broadcasts the packet with the same *ID_ACO_RREQ* to its neighbors. If a neighboring node has already received the same *ID_ACO_RREQ*, it drops this packet, as this can lead to a network loop-back problem caused by broadcast storms. To avoid broadcast storms, this packet will not be rerouted to nodes that already have the receipt. All neighboring vehicles follow the same process if they are not the destination vehicles. Once the *ACO_RREQ* packet is received by a server or destination vehicle, a reception timer is initiated to await the arrival of other packets sharing the same *ID_ACO_RREQ*, as shown in Figure 3. Upon expiration of the reception timer, the path replay process is triggered, generating a replay packet of type *ACO_RREP*. The details of this process will be outlined in the following section.

C. PATH REPLAY

The Route Replay mechanism responds to discovery requests by transmitting an *ACO_RREP* packet when the reception timeout expires, signaling the discovery of a destination server or vehicle—as shown in Figures 4_(b) and 4_(c)—or a fog server, as detailed in Figure 4_(a). This packet carries essential routing information, including a list of intermediate nodes and pheromone updates, which are crucial for initiating streaming and adapting to changes in network topology.

Each node involved in the route updates its routing table with this new information upon receiving the *ACO_RREP* packet, ensuring all nodes are aware of the most efficient route to the destination. This process enhances network responsiveness to dynamic conditions and maintains the reliability of video streaming in vehicular networks.

1) PATH QUALITY

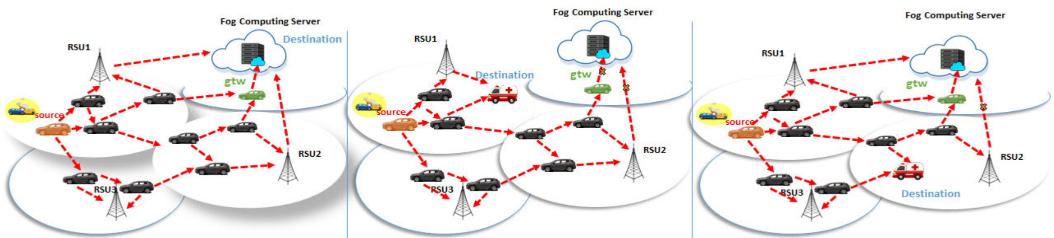
Once the timeout expires, the fog server or an emergency vehicle collects the received packets for an evaluation step.

TABLE 4. Vehicle Routing Table (VRT).

R_{id}	O_{addr}	D_{addr}	Ph_p	H	$gtw : V_{id}$	ρ	D_p	Lf_p	nPh_p	$\sum nPh_p$

ID_ACO_RREQ	O_{addr}	D_{addr}	Stack$_{nodes}$ 1… N	gtw: $V_{(ij)}$	H	$L_{(ij)}$

ACO Route Request Packet Format (ACO_RREQ).



(a): Absence of Emergency Vehicles in the Network
(b): Shared RSU Presence: Vehicle Source and Emergency Vehicle.
(c): Emergency Vehicle Not within Proximity of the Nearest RSU Network.

FIGURE 3. Scenarios in Vehicular Networks during *ACO_RREQ* Transmission.

First, the paths found are identified by their identifiers (*ID_ACO_RREQ*). Then, the destination evaluates the quality of each path (Q_p) based on several criteria, such as latency, number and distance of hops, and lifetime. Particularly, higher-quality paths will have higher pheromone values. The quality of each path for streaming is calculated by taking into account the relative importance of each evaluation criterion, as follows:

$$Q_p = w_L \cdot L_p + w_H \cdot H_p + w_D \cdot D_p + w_{Lf} \cdot Lf_p \quad (6)$$

w_L, w_H, w_D, w_{Lf} represent the weights assigned to the evaluation criteria, a higher weight w_L implies a faster path, a higher weight w_H implies a path with fewer hop counts, a higher weight w_D implies a path with a minimum distance, a higher w_{Lf} weight indicates a stable path. The parameters L_p, H_p, D_p, Lf_p are normalized using Equation 7.

$$Criterion_p = \frac{Current\_value\_between(i \rightarrow j)}{Maximum\_value\_between(i \rightarrow j)} \quad (7)$$

Subsequently, a fog server or destination node calculates the quantity of pheromones conveyed by the *ACO_RREP* packet along path p. This amount is computed using Equation 8.

$$Ph_p = \frac{1}{Q_p} \quad (8)$$

2) PATH UPDATE

Ensuring a stable and reliable streaming transmission is a crucial perspective to address the dynamic nature of the topology and adapt to the high frequency of connectivity disruptions. Faced with this challenge, continuous updating of pheromone values for paths is necessary. Specifically, when an *ACO_RREP* packet traverses a path p, it dynamically adjusts the pheromone values along the links it traverses. This measure enhances the path selection process by preserving accurate network information. Along this path, intermediate nodes update the amount of pheromones for that path in their routing table according to the new value using Equation 9.

$$Ph_p^{t+1} = Ph_p^t + Ph_p \quad (9)$$

This passage is an iterative process that persists until the source vehicle is finally reached.

The previous update is a cumulative process that provides information about preferred paths but does not take into account the dynamics of the network. For better adaptation to network changes, it is necessary to incorporate an evaporation process to dynamically adjust the routes using Equation 10.

$$Ph_p^{t+1} = (1 - \rho) \cdot Ph_p^t \quad (10)$$

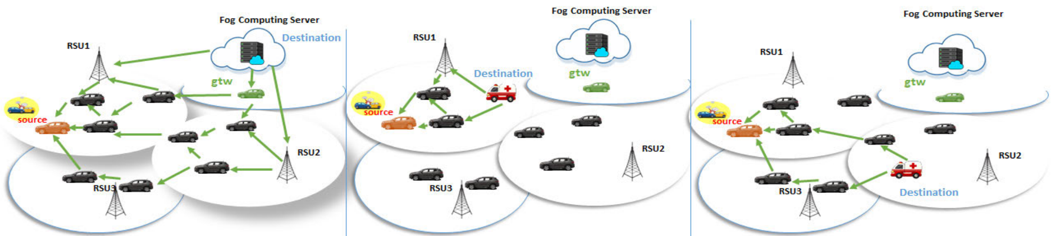
where Ph_p^t denotes the current pheromone value associated with a path p, ρ is the rate of progressive evaporation of pheromones over time, Ph_p^{t+1} represents the new value deposited for the path p.

3) PATH LIFETIME

We previously discussed the influence of network dynamics, highlighting the constant topology changes induced by vehicle mobility. These variations can significantly impact the quality and availability of connectivity links between these vehicles, subject to a specific lifetime. Specifically, the lifetime of the path Lf_p is the period during which a particular route is considered functional and usable for streaming. In other words, due to frequent topology changes, established routes between vehicles do not remain constant indefinitely. The vehicles periodically initiate a process to check the status of their paths based on the lifetime of these paths in their routing table. This update is carried out as follows:

ID_ACO_RREP	O_{addr}	D_{addr}	Stack$_{nodes}$ 1… N	gtw: $V_{(ij)}$	H	Ph_p

ACO Route Replay Packet Format (ACO_RREP).



(a): Absence of Emergency Vehicles in the Network (b): Shared RSU Presence: Vehicle Source and Emergency Vehicle. (c): Emergency Vehicle Not within Proximity of the Nearest RSU Network.

FIGURE 4. Dynamic Scenarios in Vehicular Networks during *ACO_RREP* Transmission.

- **Active State:** A path p is marked as active if every link $(i, j) \in p$ between two vehicles remains functional for an additional specified duration, where destination nodes periodically send an *ACO_RLT* packet along path p to maintain the lifetime of this route.
- **Inactive State:** A path p is marked as inactive when the active state timer expires, and no *ACO_RLT* packet passage is detected. In this case, the vehicle triggers another timer to wait for the route to recover. If the new timer also expires, the vehicles remove this path from their routing table.

VII. PERFORMANCE EVALUATION

This section evaluates the effectiveness of the proposed protocol through various experiments in an OMNET++ [33] simulation environment. The study focuses on a video streaming scenario within a simulated Vehicular Fog Computing (VFC) environment. The aim is to assess the protocol's ability to handle real-time video transmission during road events, aiming to minimize interruptions and improve QoS and QoE. Additionally, we compare the QoS performance of the MPTP-VS protocol in terms of latency, response time, path discovery time, and throughput with those of competing protocols, including the Ad Hoc On-Demand Distance Vector (AODV) [12] and the Dynamic MANET On-demand (DYMO) [13]. To evaluate the QoE, we analyze the impact of the optimized path selection approach by the MPTP-VS protocol on various criteria such as the visual quality as perceived by users in rapid vehicle movement, specifically in terms of received image quality, Peak Signal to Noise Ratio (PSNR), and resolution. In particular, we compare the QoE achieved with MPTP-VS to that obtained with current Content Delivery Network (CDN) systems using Adaptive Bitrate Streaming (ABS), which adjusts video quality based on network conditions.

A. STUDY SCENARIOS

We consider a simulation context involving a vehicular environment, which includes a fog computing server and two base stations (RSUs). Vehicles are equipped with connected sensors such as cameras and vehicle event detection systems, as well as hybrid radio interfaces including DSRC and LTE to ensure seamless internet connectivity. Additionally, these vehicles are equipped with built-in GPS devices to retrieve their location coordinates. The fog server, acting as a streaming server, establishes connections with RSUs and vehicles via Vehicle-to-Fog (V2F) communication. RSUs extend coverage to two distinct areas, facilitating vehicle-to-infrastructure (V2I) communication. We implement our streaming protocol in an urban scenario in the city of Manhattan using OpenStreetMap and integrating the Veins framework, as shown in Figure 5.

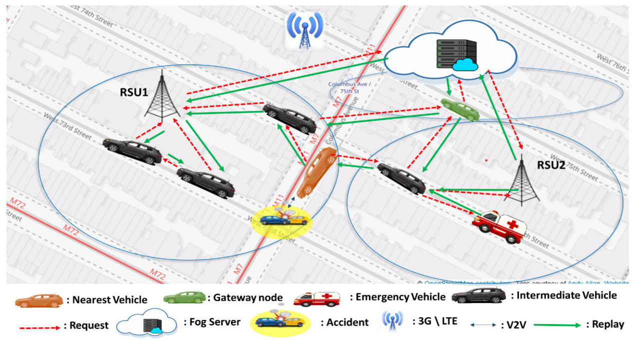


FIGURE 5. Study scenario with manhattan city.

TABLE 5. Simulation tools.

Category	Tool	Version
Network interface	OMNeT++	V 5.6.2
Model library	INET	V 3.6.8
Network mobility framework	Veins	V 5.0
Traffic generator	SUMO	V 1.8.0
Operating system	Windows	Windows 10 (64 bits)

We combine a set of open-source tools to achieve an advanced simulation framework for video streaming in a Vehicular Fog Computing environment. Table 5 illustrates these tools.

Initially, the OpenStreetMap (OSM) tool was used to extract a map of the city of Manhattan, thus constituting a road topology for streaming routing. The OSM data is

TABLE 6. Simulation parameters.

Parameters	Values
Area of simulation	$1200 \cdot 1200m^2$
Number of vehicles	25, 50, 75, 100, 125, 150, 200, 250
MAC protocol	802.11p
Vehicle communication range	500 m
RSU communication range	700 m

imported into the Urban Mobility Simulation Environment (SUMO) [34]. This makes it possible to simulate and analyze the study scenario by taking advantage of the mobility constraints on the road network provided by OSM [35], [36].

The study scenario is configured with simulation parameters, including network topology and vehicle mobility models, etc. The simulation values used to configure the scenario are presented in Table 6.

In this simulation scenario, a vehicle involved in an accident initiates an emergency event to start streaming video via the UDP protocol. The source vehicle, faced with this emergency, launches a local discovery process to identify a nearby emergency vehicle or a streaming server. For this, it sends *ACO_RREQ* packets through the available communication modes, targeting neighboring vehicles and connected RSUs. Following the activation of this discovery process, RSU1 implements a Local Discovery Protocol (LDP), specifying the exact location of the appropriate emergency vehicle. If RSU1 fails to find an emergency vehicle in its area, the Fog server is then alerted via the transmission of its VRT table and accident details. The fog computing system takes over to orchestrate an extensive search for appropriate response vehicles by leveraging data from multiple RSUs in the network. If no emergency vehicle is found, the Fog server becomes the repository to temporarily store the emergency video. The selection of the destination then triggers the transmission process on the most suitable paths, thereby minimizing network congestion and optimizing data load management.

B. QOS PERFORMANCE

Assessing the QoS of the MPTP-VS protocol is essential for ensuring efficient video transmission in connected vehicle networks. This evaluation contrasts the performance of MPTP-VS with that of the AODV and DYMO protocols, focusing on key benefits such as network performance, adaptability, stability, and resource efficiency. The aim is to ascertain whether MPTP-VS can maintain satisfactory video quality for recipients amid the dynamic changes and constraints of vehicle networks, thereby enhancing the user experience compared to traditional approaches.

1) NETWORK PERFORMANCE OPTIMIZATION

To improve the QoS of video routing for the proposed scenario, we focus on optimizing the transmission efficiency of video segments. The main goals are to reduce latency and increase throughput. These objectives enable a smoother

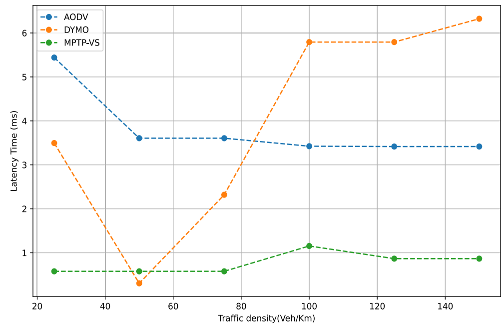


FIGURE 6. Streaming latency.

and more responsive video streaming experience, which is essential for sensitive applications such as real-time emergency management.

- **Latency (L):**

Latency depicts the transmission time of video data from the sending vehicle to the recipient. This measure is a critical QoS metric, including propagation, transmission, and processing delays. Minimizing this latency is crucial to ensure the rapid delivery of critical video content, thereby facilitating rapid response in emergency situations and increasing the efficiency of the network protocol. Latency performance, shown in Figure 6, highlights the capabilities of each analyzed protocol. It is observed that the latency of the AODV protocol decreases with increasing vehicle density, ranging between 3.42 ms and 3.61 ms. By contrast, the latency of the DYMO protocol, although initially effective, increases significantly as vehicle density increases, reaching up to 6.32 ms. By comparison, the MPTP-VS protocol consistently maintains low latency, from 0.58 to 1.15 ms, significantly outperforming the AODV and DYMO protocols. This stability makes MPTP-VS a suitable solution for real-time streaming applications in dynamic vehicular networks.

- **Throughput (Th):**

Throughput measures the rate of successful data transmission during emergency video streaming. This QoS metric evaluates the efficiency of the video streaming service by evaluating the amount of data transmitted per unit of time. Higher throughput values indicate a network's ability to handle more data, helping to deliver emergency video content quickly and efficiently in our scenario. Maximizing throughput is crucial to maintaining a robust and responsive video streaming service during emergency scenarios.

By analyzing Figure 7, it is evident that the AODV protocol shows moderate throughput in smaller networks, with a gradual increase as the number of vehicles grows. However, this increase is not proportionate, suggesting potential efficiency issues related to network size and congestion. The DYMO protocol starts with relatively high throughput in smaller networks but experiences a significant decrease as the network's size grows, indicating

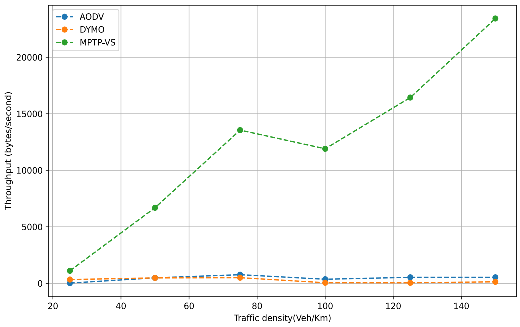


FIGURE 7. Throughput.

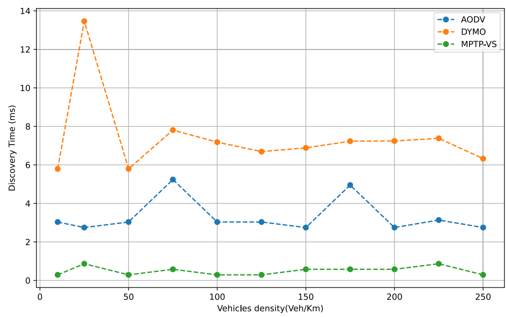


FIGURE 8. Path discovery time.

reduced data transfer efficiency, likely due to route discovery overhead. The MPTP-VS protocol consistently maintains the highest throughput among the three protocols across different network sizes. Even with more vehicles, MPTP-VS achieves significantly higher throughput, making it the suitable choice for applications requiring efficient data transfer, especially for data such as video data.

2) ADAPTABILITY AND STABILITY

Due to the dynamics of vehicular networks, transmission adaptability and stability are two essential aspects of QoS, ensuring that the video transmission protocol can not only handle rapid network changes but also maintain consistent performance despite these fluctuations. Given the dynamic nature of vehicle networks, adaptability and transmission stability are key elements of QoS. It is crucial that the video transmission protocol can not only respond quickly to network changes but also maintain stable performance despite these variations. With this in mind, we focus on two key performance indicators: Path Discovery Time (PDT) and Jitter.

- **Path Discovery Time (PDT):**

Path discovery time refers to the time required to run the ACO algorithm to identify and establish a multiple path between the source vehicle and the appropriate destination vehicle. This is an essential measure to minimize latency when initiating video transmission, ensuring rapid and efficient emergency communication. The performance of the PDT process is illustrated in Figure 8, and is compared to the performance of the AODV and DYMO protocols.

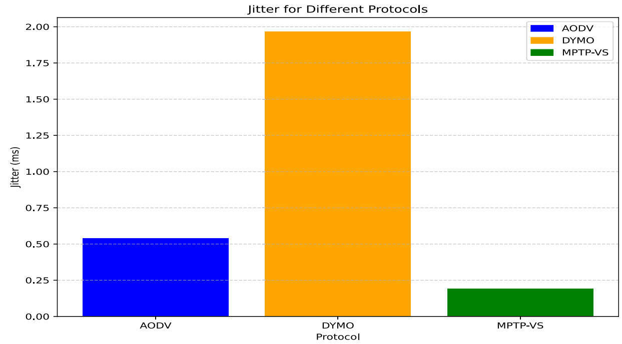


FIGURE 9. Jitter.

The AODV protocol demonstrates consistently low PDT across different network sizes, demonstrating the effectiveness of route discovery. However, a slight increase in PDT occurs as the network size increases due to the increased route discovery overhead. In contrast, the DYMO protocol exhibits significantly higher PDT than AODV, especially in larger networks. This suggests a longer route discovery process, influenced by the increased number of vehicles and route requests. Meanwhile, the MPTP-VS protocol presents as the most efficient protocol, consistently maintaining the lowest PDT even when the network expands. Leveraging a multi-path transmission approach and a pheromone-based routing mechanism, MPTP-VS proves to be well suited for video streaming in these environments, highlighting its effectiveness in fast and reliable path discovery, especially in dynamic and large-scale vehicular networks.

- **Jitter:**

In this scenario, jitter represents the variability in the delay of video packet reception during emergency video streaming. It quantifies the irregularity in the timing of consecutive video frame arrivals, affecting the stability and fluidity of the video playback. Lower jitter values signify a more consistent and reliable delivery of video, enhancing the overall quality of the viewing experience. It is vital to minimize jitter to ensure a dependable and clear emergency vehicle video streaming service. Figure 9 illustrates the jitter performance of the routing protocols under evaluation.

The AODV protocol has the lowest jitter (0.541 ms), ensuring stable and predictable packet arrivals, contributing to consistent QoE. Although the DYMO protocol has higher jitter (1.965 ms), this indicates less predictable packet delivery, potentially affecting QoE. The MPTP-VS protocol performs exceptionally well with remarkably low jitter (0.192 ms), providing very stable packet arrival times, significantly improving QoE. As a result, the MPTP-VS stands out as the highest performer, ensuring smoother and more consistent data transmission in real-time communications applications.

3) NETWORK RESOURCE EFFICIENCY

In this context, optimizing the use of network resources is essential to improve the efficiency of video transmissions,

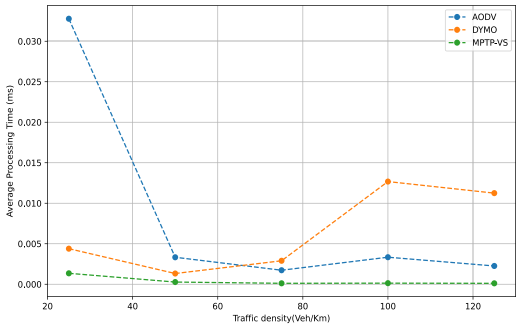


FIGURE 10. Average processing time.

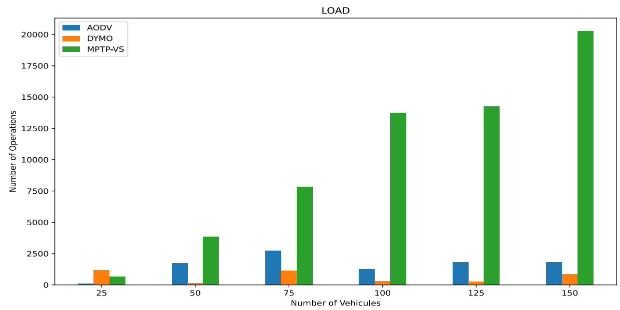


FIGURE 11. Traffic load.

especially in environments where resources are limited. By evaluating how each protocol uses bandwidth and manages traffic load, it is possible to identify aspects of optimizing network resource usage. This is crucial to facilitate fast routing and avoid wasted bandwidth, which is fundamental to maintaining high network performance without unnecessary overhead.

- **Average Processing Time (APT):**

The average processing time refers to a determining factor of QoS in video transmission networks. A low APT indicates that the network is able to process and transmit data quickly, which is essential for applications requiring real-time responses, such as emergency situations in our scenario.Reducing the APT not only improves the responsiveness of the video streaming service but also contributes to more efficient use of bandwidth, as less time is required to process each data packet.

Figure 10 presents a performance comparison among routing protocols. Particularly, the AODV protocol exhibits relatively high Average Processing Time (APT) across different network sizes, indicating that its computing operations, including route discovery and maintenance, are time-consuming. The consistent increase in APT with network expansion suggests scalability issues. In contrast, the DYMO protocol begins with a lower APT in smaller networks. However, as the network size expands, DYMO APT increases markedly, reflecting a higher computational load in larger vehicular networks, which could impair its efficiency. The MPTP-VS protocol consistently maintains the lowest APT among the protocols, even as the number of vehicles increases. This capability is particularly advantageous for real-time applications like video streaming, where minimizing processing time is crucial for optimal performance. The consistently low APT positions MPTP-VS as an ideal protocol for scenarios requiring fast, demanding, and efficient data processing.

- **Traffic Load (TL):**

Traffic load measures the volume of data transmitted over the network during emergency video streaming. This QoS metric is crucial for assessing network capacity, managing congestion, and ensuring efficient use of multiple paths to maintain a stable and reliable video streaming service in VFC environments. The traffic load performance for the proposed scenario is depicted in Figure 11.

On the one hand, the AODV protocol has a moderate traffic load in small networks, but this load increases significantly as the network expands. This indicates an accumulation of computational needs for path management in large vehicular networks. On the other hand, the DYMO protocol initially shows higher traffic load than AODV in small networks. However, this load decreases as the network grows, suggesting a decrease in computational intensity. By contrast, the MPTP-VS protocol maintains a consistently high traffic load across all network sizes, reflecting adaptable computational capacity through its multi-path transmission approach.

C. QOE PERFORMANCE

The QoE of the proposed protocol was assessed based on several fundamental aspects of video transmission: visual quality, playback fluidity, and transmission stability. Each aspect significantly influences the end-user experience and is crucial for the deployment of our protocol in real-world applications.

1) THE VISUAL QUALITY

For visual quality, we measured the delay in transmitting video segments, taking into account the size of the video and the available bandwidth. These segments were categorized into five quality levels: perfect, excellent, moderate, low, and very low, allowing us to evaluate how the protocol manages quality under various network conditions. In accordance with ITU recommendations, the duration of each video segment was limited to 15 seconds or less for testing purposes and to ensure efficient transmission. This temporal limitation is designed to minimize the risk of quality degradation during significant network fluctuations, thereby facilitating a quick and effective recovery in case of signal degradation between two vehicles. The figure 12 illustrates the segment transmission time between two vehicles and for each quality level. This time was measured taking into account variations in network conditions, influenced by factors such as vehicle mobility, resource availability, network saturation, and buffer capacity.

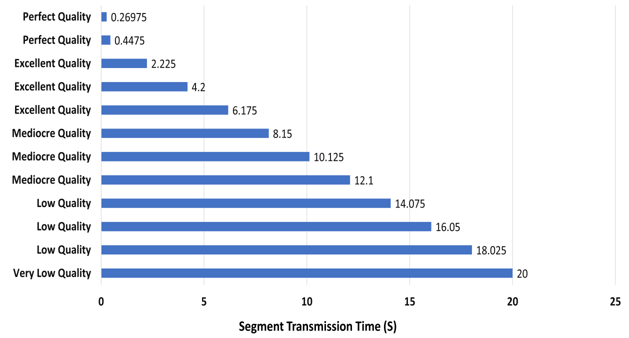


FIGURE 12. Video segment transmission time.

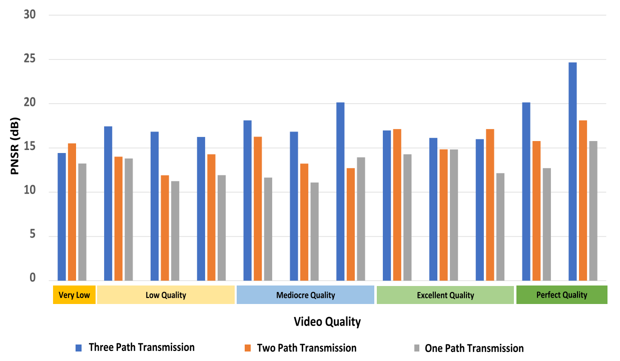


FIGURE 13. PSNR of received quality.

According to the performance shown in the figure, the transmission times for perfect quality videos are the shortest, ranging between 0.26975 seconds and 0.4475 seconds, indicating almost instantaneous transmission. This demonstrates that the MPTP-VS protocol, with its multiple path selection approach, is very effective under optimal network conditions. For excellent quality videos, the transmission time increases slightly, varying from 2.225 to 6.175 seconds, reflecting a slight reduction in transmission efficiency due to factors such as a moderate increase in packet loss or delays caused by moderate congestion.

For mediocre video quality, transmission times increase to between 8.15 and 12.1 seconds. This increase can be attributed to larger network issues, such as more frequent packet losses, increased delays, or noticeable fluctuations in bandwidth. For low-quality videos, transmission times lengthen further, ranging from 14.075 to 16.05 seconds, indicating that lower-quality videos are more affected by severe bandwidth limitations or significant network disruptions.

At the very low quality level, the transmission time is the highest, reaching 18.025 seconds. This performance indicates that network conditions were extremely poor, marked by potential interruptions and severely reduced transmission capacity, seriously affecting the quality of user experience.

2) THE PLAYBACK FLUIDITY

The smooth streaming is crucial for an immersive and satisfying viewing experience. To test the streaming smoothness of the proposed protocol, we evaluate the continuity and regularity with which streaming is delivered without interruptions or visible anomalies such as buffering and jitter. The Figure 13 illustrates the Peak Signal-to-Noise Ratio (PSNR) for different video qualities as a function of the number of paths used for data transmission (one, two, or three paths). We measure the PSNR as an indicator of the received streaming quality relative to the transmitted quality by the source vehicle, measured in decibels (dB). As a result, a higher PSNR value indicates better perceived video quality.

For very low quality, increasing the number of paths results in a noticeable improvement in PSNR, which is crucial for very low quality videos where every small gain in streaming quality is significant for user perception. For low and moderate qualities, moving from one to three paths also shows a gradual increase in PSNR. This indicates that the proposed protocol handles fluctuating network conditions well, thereby improving the robustness of video transmission. For excellent and perfect ratings, although the improvement in PSNR is less marked (because the starting values are already high), the use of multiple paths continues to provide benefits, further reducing transmission errors and refining the streaming quality.

These results highlight pleasant playback fluidity by the MPTP-VS protocol. This performance shows a notable improvement in received streaming quality when using multiple transmission paths, compared to a single path, as shown by the increase in PSNR. This also shows the robustness of the MPTP-VS protocol against harsh network conditions, as well as its ability to effectively mitigate disruptions, reduce buffering and minimize packet losses, thereby helping to improve streaming quality.

3) THE TRANSMISSION STABILITY

Figure 14 presents the received quality index for video transmission using one, two or three stable transmission paths. To evaluate the stability of video transmission according to this index, attention is paid to the variability of this quality index. The shaded areas surrounding the curves of each path configuration illustrate this variability, where a wider shaded space indicates better reception quality, thus reflecting greater stability.

With a single stable path, the quality index is lower, revealing sensitivity to network fluctuations and resulting in a fluctuating user experience. With two stable paths, there is a significant improvement in received quality, and the quality index shows increased stability and better resilience to network disturbances. The three stable path option provides the best received quality and the smallest variability, demonstrating the highest stability and efficient management of network resources.

Using multiple paths for streaming allows for more stable delivery of received video quality by reducing the chance of disruption, even in adverse network conditions. Indeed, several paths can compensate for the shortcomings of a single path.

TABLE 7. Comparison of transmission stability performance between MPTP-VS protocol and Adaptive Bitrate Streaming (ABS) under various vehicular network conditions.

Transmission Path(s)	Mobility	Density	Max received Quality	Transmission time interval	Buffer size	Received quality rate	PSNR
1 path	Low	Low	480	≤ 10.125s	1-2 Mo	13.33% - 31.85%	11.31 - 12.91
	Low	High	720p - 240p	6.21s - 13.54s	≤ 4 Mo	23.66% - 48.11%	12.14 - 14.91
	High	Low	720p - 240p	3.83s - 15.12s	≤ 8 Mo	27.4% - 61.48%	12.48 - 17.23
	High	High	480p - 240p	6.35s - 14.42s	≤ 2 Mo	11.33% - 45%	11.17 - 14.47
2 paths	Low	Low	720p - 480p	2.38s - 7.61s	< 2 Mo	40.74% - 77.72%	13.92 - 21.67
	Low	High	720p - 360p	2.85s - 9.55s	≤ 4 Mo	37.03% - 77.72%	13.48 - 21.67
	High	Low	720p - 360p	1.78s - 7.93s	≤ 4 Mo	54.07% - 74.96%	15.85 - 20.71
	High	High	720p - 480p	2.15s - 8.07s	≤ 4 Mo	41.48% - 77.72%	14.01 - 21.67
3 paths	Low	Low	720p	1.43s - 5.09s	≤ 6 Mo	56.29% - 88.57%	16.23 - 27.21
	Low	High	720p	1.58s - 5.52s	≤ 6 Mo	54.29% - 81.03%	15.88 - 23.00
	High	Low	480p - 720p	1.32s - 6.31s	≤ 6 Mo	44.44% - 88.57%	14.39 - 27.22
	High	High	720p	2.00s - 4.57s	≤ 6 Mo	56.29% - 77.72%	16.23 - 21.67
Adaptive Bitrate Streaming	Low	Low	480p - 720p	6.25s - 8.65s	≤ 6 Mo	50% - 66.66%	15.19 - 18.39
	Low	High	480p - 720p	6.25s - 7.45s	≤ 6 Mo	53.24% - 66.66%	15.70 - 18.39
	High	Low	480p - 720p	6.25s - 8.95s	≤ 6 Mo	46.25% - 62.03%	14.64 - 17.34
	High	High	480p - 720p	8.05s - 8.95s	≤ 6 Mo	46.25% - 58.33%	14.64 - 16.61

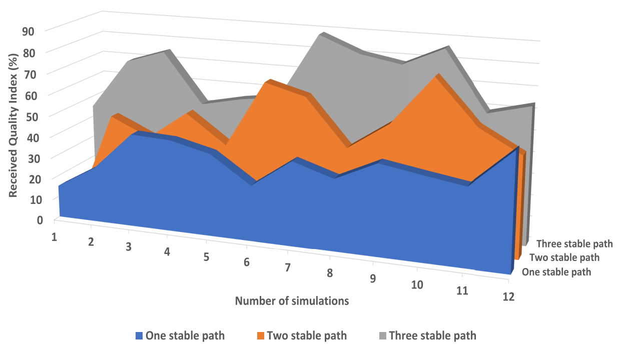


FIGURE 14. Comparative analysis of path stability across multiple simulation.

The table 7 illustrates the transmission stability performance of the proposed MPTP-VS protocol compared to that of the Adaptive Bitrate Streaming (ABS) protocol used in a vehicular architecture. The analysis focuses on the effectiveness of these protocols in optimizing content delivery across different mobility and traffic density scenarios. We evaluate QoE metrics such as received video quality, transmission time interval, buffer size, received quality rate and Peak Signal-to-Noise Ratio (PSNR) of received quality, to determine their respective performance in improving transmission stability under various network conditions.

The study results reveal that using a single transmission path is particularly vulnerable to variations in network conditions, leading to marked fluctuations in video quality and user experience. In contrast, the adoption of two transmission paths by the MPTP-VS protocol significantly improves stability, with higher PSNR values and higher received quality rates, demonstrating a better ability to handle network disturbances. The Adaptive Bitrate Streaming (ABS), using a CDN architecture, displays more balanced performance by dynamically adjusting video quality based on actual network variations, contributing to a more stable video stream despite fluctuations. However, the implementation of three transmission paths by the MPTP-VS protocol clearly stands out, offering the best performance in comparison with transmission using the ABS technique. This type of transmission effectively mitigates the impacts of adverse network conditions and ensures the highest stability of the video streaming experience. Accordingly, these performances indicate that the use of multiple transmission paths for video streaming in connected vehicular environments provides robust, adaptive, and high-quality solutions for video data transmissions, essential for critical applications such as emergency response.

VIII. DISCUSSION

We evaluate the effectiveness of MPTP-VS compared to traditional mobile CDNs for content distribution in emergency video streaming contexts. The data presented previously reveals that the QoS offered by MPTP-VS multipath transmission exceeds those of traditional protocols such as AODV and DYMO. In addition, this performance also exceeds that of mobile CDN architectures in terms of transmission adaptability, reception quality, buffer size, and PSNR. The table 8 illustrates the advantages of our innovative method over traditional CDNs. Our analysis focuses on their ability to meet various bandwidth requirements, their effectiveness in reducing delays, their resilience to variations in the network environment, maintaining QoS, and their efficiency in content delivery.

The CDN technique for video streaming in mobile networks adjusts for bandwidth through streaming updates and uses edge caching to reduce latency. However, it has storage limitations and requires static QoS configuration. In contrast, the MPTP-VS offers enhanced bitrate control mechanisms for optimized QoS, reducing latency through Fog Computing architecture and ACO optimization. Additionally, it provides greater network resilience and automated QoS optimization.

The methodology outlined in this study aims to improve video streaming in emergency situations, ensuring clarity of critical scenarios to facilitate informed decision-making during rescue operations. Challenges in the context of vehicular networks, characterized by their sporadic nature,

TABLE 8. Comparison between Mobile CDN and MPTP-VS.

Criteria	Mobile CDNs	MPTP-VS
Bandwidth Adaptability	Adaptive Bitrate Streaming (ABS) adjusts video quality based on bandwidth.	Potential for integrating bitrate adjustment features to maintain high QoS.
Latency Management	Caching at the network edge to reduce latency.	Using Fog Computing and ACO to optimize paths and reduce latency.
Resilience to Network Conditions	Use of P2P and Multi-CDN to improve resilience to network fluctuations.	Multi-path routing and dynamic adaptation for superior resiliency in VANET environments.
QoS	Management through priority classes, sometimes requiring manual adjustments.	Intelligent traffic management based on ACO to automatically optimize QoS.
Content Distribution Effectiveness	Techniques like prefetching and caching improve efficiency, limited by storage capacities.	Uses Fog Computing for responsive content distribution tailored to immediate needs.

include issues such as the lack of a global view of the network topology, a large volume of video data, and the limitations imposed by restricted bandwidth. Frequent intermittency in vehicular networks, resulting from high mobility and node distribution, makes it difficult to achieve optimal data transmission performance, affecting the rapid and reliable dissemination of critical information.

Our MPTP-VS protocol, while effective for optimizing video transmission in vehicular networks, has some limitations in terms of increased complexity in path selection. Using the multi-path routing approach, based on ant colony optimization (ACO), introduces additional complexity into the path discovery and maintenance process. This complexity can lead to an overload of computing and network resources, particularly in highly dynamic vehicle environments where topologies change frequently. The constant need to update pheromone information, manage multiple paths, and continuously adapt to changing network conditions requires considerable computing power and bandwidth. This can potentially degrade overall network performance, particularly in terms of latency and resource consumption, which could limit the effectiveness of our protocol in scenarios where resources are already constrained. Solutions to reduce this overhead, such as optimizing update algorithms and more efficient resource management, are necessary to improve protocol performance in these demanding environments.

IX. CONCLUSION

This paper presents an innovative protocol, named MPTP-VS (Multi-Path Transmission Protocol for Video Streaming), specifically designed to enhance video streaming transmission in connected vehicular environments. The methodological approach of this protocol aims to improve video streaming during critical situations, such as road incidents, while ensuring superior Quality of Service (QoS) and high Quality of Experience (QoE) to facilitate informed decision-making during rescue operations. Specifically, this protocol addresses the architectural and transmission efficiency challenges in Vehicular Fog Computing (VFC) frameworks. It adopts a multi-path transmission approach guided by Ant Colony Optimization (ACO) heuristics to automate QoS optimization, improve bitrate control, and reduce latency.

In the evaluation phase, the performance of the study demonstrated that MPTP-VS is positioned as an innovative video streaming solution in these environments, outperforming existing protocols in terms of QoS and QoE. Its innovative approach and consistent performance significantly contribute to stable vehicular communication, paving the way for a future where quality and efficiency are key elements in dynamic network environments. Future research will focus on enhancing the capabilities of MPTP-VS, adapting it to real-world scenarios, integrating it with emerging technologies such as next-generation networks, and exploring its potential in various vehicular communication applications.

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