



Multi-Agent AI Systems for Cooperative Communication in Hybrid MANET-VANET Architectures

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ABSTRACT

Hybrid Mobile Ad Hoc Network–Vehicular Ad Hoc Network (MANET-VANET) architectures have emerged as an important solution for enabling reliable, intelligent, and adaptive communication in next-generation wireless networks. The integration of MANET and VANET technologies provides enhanced connectivity, decentralized communication, and efficient data dissemination in highly dynamic transportation environments. However, challenges such as rapid topology changes, routing instability, high mobility, network congestion, packet loss, and security vulnerabilities significantly affect communication performance. To address these issues, Multi-Agent Artificial Intelligence (AI) systems have gained considerable attention due to their capability to provide distributed intelligence, cooperative decision-making, and adaptive communication management. This review paper presents a comprehensive study of Multi-Agent AI systems for cooperative communication in Hybrid MANET-VANET architectures. The paper analyzes the role of intelligent agents in improving routing efficiency, resource allocation, congestion control, trust management, and Quality of Service (QoS). Various AI techniques including Machine Learning (ML), Deep Reinforcement Learning (DRL), Fuzzy Logic, Swarm Intelligence, and Neural Networks are reviewed in the context of cooperative vehicular and mobile ad hoc communication. The study further examines communication models such as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Everything (V2X) integrated with intelligent agent-based frameworks. Additionally, the paper discusses existing routing protocols, security mechanisms, and optimization approaches used in Hybrid MANET-VANET systems. Comparative analysis of recent research contributions highlights the advantages of Multi-Agent AI systems in terms of scalability, adaptability, energy efficiency, reduced latency, and improved packet delivery ratio. The review also identifies major research challenges including computational complexity, communication overhead, synchronization issues, and cyber-security threats. Finally, future research directions involving 6G communication, edge intelligence, blockchain integration, and federated learning are explored to support the development of secure and autonomous cooperative communication systems. The findings of this review demonstrate that Multi-Agent AI-enabled Hybrid MANET-VANET architectures offer a promising framework for intelligent transportation systems, smart cities, and next-generation wireless communication networks.

INDEX TERMS- Artificial intelligence, software-defined networking, routing, vehicular ad hoc networks, wireless networks.

I. INTRODUCTION

More than 50% of the world's population currently lives in cities, and this percentage is projected to rise. According to forecasting organizations, this proportion will represent almost 66% of the global population. In terms of road safety, 92% of accidents are frequently attributed to errors in human judgment (such as driver inattention, insufficient supervision, and distraction) and human decision-making errors (such as driving too fast, reacting slowly, safety distance, and misjudging) [1]. In addition, numerous people lose their lives in traffic accidents every year, despite the development of numerous safety-oriented procedures in cars such as anti-lock braking systems (ABS), seat belts, airbags, and rear-view cameras [2]. Therefore, establishing a vehicle communication network that enables vehicles to communicate with the roadside infrastructure and share their data between them to avoid traffic congestion and lead to the realization of an intelligent transportation system is urgently required if there is to be a reduction in vehicle accidents and ongoing optimization of the transportation system. These networks, known as vehicular ad hoc networks (VANETs), are designed to offer low-latency infotainment services and safety-related alerts to both drivers and driverless vehicles [1], [2]. VANET can offer a range of services, including traffic control, entertainment, safety applications, driving assistance, collision avoidance, and safety services. However, due to traffic problems that could have a deadly outcome and cause considerable delays for travelers, VANET developers gave the transmission of vital safety-related information the highest priority [2], [3]. Modern vehicles that are VANET nodes can now offer high computation, storage, sensor, and networking capabilities due to developments in vehicular networks. In a VANET, each vehicle is a potent node that, when grouped together as a cluster, can function as a vast farm of moving supercomputers. Due to this unique characteristic, cars are encouraged to be used not only as mobile machines but also as VANET clouds to utilize their resources and share information. The outcome is a completely new kind of ad hoc vehicular network known as VANET Cloud, in which any vehicles that wish to share their resources must cooperate and join together to share their resources [4], [5].

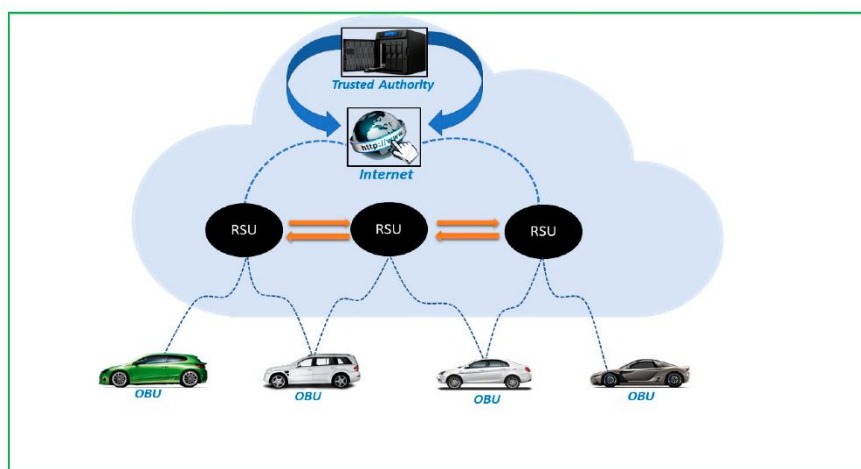


Fig.1. VANET Cloud

II. MOBILE ADHOC NETWORKS (MANETs)

Mobile Ad Hoc Networks (MANETs) form a crucial subset within the intricate tapestry of the ad hoc network paradigm. These dynamic and self-organizing networks of mobile devices create a versatile fabric of connectivity, enabling seamless communication without the need for a fixed infrastructure. In this exploration of interconnected threads, we unravel the unique attributes, challenges, and potential applications of MANETs, shedding light on their role in shaping the broader ad hoc network landscape.

1. Introduction to Mobile Adhoc Networks

- **Definition:** Mobile Ad hoc Networks (MANETs)[2] are self-configuring networks of mobile devices that communicate with each other without relying on any fixed infrastructure or centralized control.

- **Characteristics:** MANETs are highly dynamic networks with nodes that can move freely, resulting in frequent changes in network topology.

- **Applications:** MANETs have applications in various fields, including military operations, emergency response systems, collaborative mobile environments, and mobile sensor networks.

2. Routing Protocols of Manets:

- **Importance of Routing:** Due to the dynamic nature of MANETs, efficient and adaptive routing protocols are essential for establishing and maintaining communication paths.

- **Proactive Routing Protocols:** Protocols like Optimized Link State Routing (OLSR) and Destination-Sequenced Distance Vector (DSDV) maintain up-to-date routing tables to enable fast route discovery and minimize latency.

- **Reactive Routing Protocols:** Protocols like Ad hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) establish routes on-demand, reducing overhead in highly dynamic environments.

- **Hybrid Routing Protocols:** Protocols like Zone Routing Protocol (ZRP) combine proactive and reactive approaches to achieve a balance between efficiency and adaptability

Challenges in MANETs

- **Node Mobility:** Frequent node mobility leads to rapid changes in network topology, requiring robust and efficient routing protocols to adapt to these changes.

- **Scalability:** As the number of nodes increases, the complexity of route discovery and maintenance grows, making scalability a challenge in MANETs.

- **Energy Constraints:** Mobile devices in MANETs often have limited battery power, necessitating energy-aware routing protocols and optimization techniques.

- **Security:** MANETs are vulnerable to various security threats, including unauthorized access, data tampering, and node impersonation. Ensuring secure communication is crucial in MANET deployments.

MANET Routing Metrics

- **Metrics for Route Selection:** Routing protocols in MANETs utilize metrics to evaluate and select the most suitable routes for data transmission.

- **Metrics Based on Distance:** Euclidean distance, hop count, and geographic information are commonly used to calculate route quality.

- Metrics Based on Quality of Service (QoS): Delay, throughput, packet loss, and bandwidth can be considered to prioritize routes based on specific application requirements.

III. HYBRID MANET-VANET ARCHITECTURE

Hybrid MANET-VANET architecture is an advanced communication framework that combines the features of Mobile Ad Hoc Networks (MANETs) and Vehicular Ad Hoc Networks (VANETs) to achieve reliable, flexible, and intelligent wireless communication in dynamic transportation environments. In this architecture, vehicles equipped with On-Board Units (OBUs) communicate not only with other vehicles but also with mobile devices, roadside infrastructure, and temporary wireless nodes. MANET characteristics provide decentralized communication, self-configuration, and infrastructure-less networking, while VANET characteristics contribute high-speed vehicular communication, traffic management, and road safety support. The hybrid approach enhances network scalability, connectivity, and data dissemination efficiency, especially in urban and highway scenarios where node mobility changes rapidly.

In a Hybrid MANET-VANET system, vehicles act as mobile nodes that dynamically form communication links using Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication mechanisms. MANET nodes such as smartphones, drones, rescue units, or portable devices can join the vehicular network and extend communication coverage in areas with limited infrastructure. This integration supports intelligent transportation applications including accident warning systems, emergency message dissemination, traffic congestion monitoring, smart navigation, autonomous driving assistance, and disaster management communication. The hybrid model also improves routing reliability by using adaptive routing protocols that can handle frequent topology changes caused by vehicle mobility.

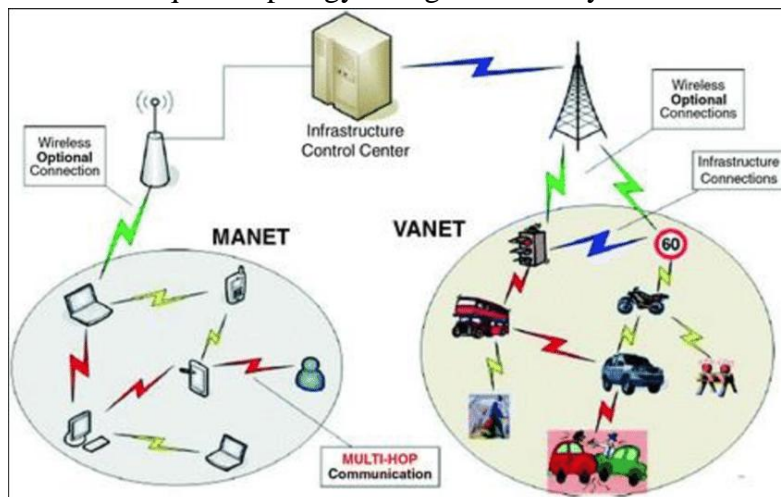


Fig.2. Hybrid MANET-VANET system.

The architecture generally consists of three major layers: the vehicular layer, infrastructure layer, and mobile ad hoc layer. The vehicular layer includes moving vehicles exchanging real-time information. The infrastructure layer contains Road Side Units (RSUs), cloud servers, and base stations that provide internet connectivity and centralized services. The MANET layer includes portable wireless devices capable of forming temporary ad hoc connections.

Communication among these layers is achieved through wireless technologies such as IEEE 802.11p, Wi-Fi, LTE/5G, and Dedicated Short Range Communication (DSRC). The hybrid architecture enables seamless data transfer, low latency communication, and efficient resource utilization under highly dynamic conditions.

Hybrid MANET-VANET architectures are widely used in Intelligent Transportation Systems (ITS) because they improve network robustness, reduce packet loss, and increase communication reliability in both dense and sparse traffic environments. However, challenges such as routing instability, security threats, high mobility, bandwidth limitations, and energy consumption still exist. To overcome these issues, researchers are integrating Artificial Intelligence (AI), Machine Learning (ML), fuzzy logic, and optimization algorithms into hybrid routing frameworks. These intelligent techniques help in predicting vehicle movement, selecting optimal routes, detecting malicious nodes, and improving Quality of Service (QoS). Thus, Hybrid MANET-VANET architecture represents a powerful and future-oriented networking solution for smart cities, connected vehicles, and next-generation transportation systems.

IV. MULTI-AGENT AI SYSTEMS FOR COOPERATIVE

Multi-Agent AI Systems for Cooperative Communication represent an advanced intelligent networking approach in which multiple autonomous agents collaborate with each other to achieve efficient, reliable, and adaptive communication in distributed environments. In this system, each agent acts as an intelligent entity capable of sensing the environment, processing information, making decisions, and communicating with other agents to accomplish common objectives. These agents can be vehicles, wireless sensors, drones, robots, mobile devices, or software-based controllers operating within a communication network. The cooperative nature of the system allows agents to share knowledge, coordinate actions, and optimize network performance dynamically without relying entirely on centralized infrastructure.

In cooperative communication networks, Multi-Agent AI systems enhance data transmission efficiency by enabling intelligent resource allocation, routing optimization, congestion control, and fault tolerance. Each agent continuously monitors network conditions such as signal strength, bandwidth availability, node mobility, latency, and energy consumption. Based on this information, agents use Artificial Intelligence techniques such as Machine Learning (ML), Deep Reinforcement Learning (DRL), Fuzzy Logic, Swarm Intelligence, and Neural Networks to make adaptive decisions in real time. For example, in vehicular networks and wireless sensor networks, intelligent agents can cooperate to select optimal communication paths, avoid network congestion, and ensure reliable packet delivery even under highly dynamic conditions. The architecture of Multi-Agent AI systems generally consists of perception, decision-making, communication, and action layers. The perception layer collects environmental data through sensors and monitoring devices. The decision-making layer applies AI algorithms to analyze the collected information and generate optimal strategies. The communication layer enables interaction and information sharing among agents through wireless communication technologies such as Wi-Fi, 5G, LTE, ZigBee, and IoT protocols. Finally, the action layer executes decisions such as route selection, spectrum allocation, load balancing, or task



scheduling. Through continuous cooperation and learning, the system becomes more intelligent and capable of handling uncertain and changing environments efficiently.

Multi-Agent AI Systems are widely applied in Intelligent Transportation Systems (ITS), autonomous vehicles, smart grids, industrial automation, military communication, drone coordination, healthcare monitoring, and Internet of Things (IoT) applications. In VANETs and MANETs, these systems support cooperative driving, accident prevention, traffic flow optimization, and emergency communication. In Wireless Sensor Networks (WSNs), intelligent agents help improve energy efficiency and network lifetime through cooperative clustering and adaptive routing strategies. The distributed intelligence of multi-agent systems also enhances scalability, robustness, and fault recovery compared to traditional centralized communication systems.

Despite their advantages, Multi-Agent AI systems face several challenges including high computational complexity, communication overhead, synchronization issues, security vulnerabilities, and trust management problems among agents. Researchers are actively integrating blockchain technology, federated learning, edge computing, and secure AI frameworks to improve privacy, reliability, and decentralized coordination. Future developments in 6G communication, autonomous systems, and smart city infrastructure are expected to further expand the role of Multi-Agent AI systems in enabling intelligent cooperative communication for next-generation wireless networks.

V. LITERATURE REVIEW

Lopamundra Hota, Biraja Prasad Nayak, Arun Kumar et al.[1] Wireless sensor networks (WSNs), mobile ad hoc networks (MANETs), vehicular ad hoc networks (VANETs), and underwater sensor networks (USNs) are dynamic and resource-constrained wireless communication environments that face numerous challenges. Machine learning algorithms have emerged as powerful tools to tackle these challenges and improve these networks' performance, efficiency, and security. This survey explores the application of machine learning algorithms in WSNs, MANETs, VANETs, and USNs. This chapter provides an overview of each network type's fundamental concepts and characteristics, emphasizing their unique requirements and constraints. Next, the chapter delves into various machine learning (ML) algorithms commonly employed in these networks, including traditional ML and reinforcement learning (RL) algorithms.

MA Naeem, R Ullah, S Chudhary, Y Meng et al.[2] The exponential growth of wireless traffic has imposed new technical challenges on the Internet and defined new approaches to dealing with its intensive use. Caching, especially cooperative caching, has become a revolutionary paradigm shift to advance environments based on wireless technologies to enable efficient data distribution and support the mobility, scalability, and manageability of wireless networks. Mobile ad hoc networks (MANETs), wireless mesh networks (WMNs), Wireless Sensor Networks (WSNs), and Vehicular ad hoc Networks (VANETs) have adopted caching practices to overcome these hurdles progressively. In this paper, we discuss the problems and issues in the current wireless ad hoc paradigms as well as spotlight versatile cooperative caching as the potential solution to the increasing complications in ad hoc networks. We classify and discuss

multiple cooperative caching schemes in distinct wireless communication contexts and highlight the advantages of applicability. Moreover, we identify research directions to further study and enhance caching mechanisms concerning new challenges in wireless networks. This extensive review offers useful findings on the design of sound caching strategies in the pursuit of enhancing next-generation wireless networks.

Haque Nawaz et al.[3] The unmanned aerial vehicle communication networks (UAVCN) comprises of a collection of unmanned aerial vehicles (UAVs) to build a network that can be used for many applications. These nodes autonomously fly in free space in ad-hoc mode to carry out the mission. However, the UAVs face some challenging issues during collaboration and communication. These nodes have high speed, hence the communication links fail to route the traffic that affects the routing mechanism. Therefore, UAVCN communication affecting the quality of service and facing the performance issue. Power is another major problem to limit and optimize the use of power, the energy-efficient mechanism is needed. In this paper, an attempt is made to explore the issues of unmanned aerial vehicle communication networks: UAVCN characteristics, UAVCN design issues, UAVCN applications, routing protocols, quality of service, power issue and identify the future open research areas which could be considered for further research to explore the UAVCN technology.

Y Ifourah, LT Pouyap, S Boudjit, S Bouzefrane, A Balla, R Boussaha et al.[4] Road safety remains a pressing global challenge, with speeding accounting for a significant proportion of traffic fatalities. While conventional speed enforcement systems, such as fixed cameras, have demonstrated limited effectiveness due to driver evasion tactics, and aerial patrols prove cost prohibitive for widespread implementation, emerging drone technologies offer new possibilities for dynamic traffic monitoring. This paper introduces an innovative Collaborative Highway Surveillance (CHS) system that addresses critical gaps in current enforcement methodologies. The proposed solution combines Unmanned Aerial Vehicles (UAVs) with a distributed network of groundbased wireless sensors to create an adaptive, closed-loop monitoring framework.

A Shankar, R Dayalan, C Chakraborty, C Dhasarathan, M Kumar et al.[5] Technical growth in the field of communication and information is an important aspect in the development and innovation of industrial automation and in the recent advances in the field of communications. The recent development of mobile communications has led to worldwide ubiquitous information sharing and has rehabilitated human lifestyles. This communication revolution is now introducing effective information sharing into the automotive industry. The current technology is extending this field of applications for vehicle safety, improving the efficiency in traffic management, offering reliable assistance for drivers and supporting the modern field of vehicle design. With these advances, the vehicular network concept has grabbed worldwide attention. In this article, a novel sampling-based estimation scheme (SES), to initiate the involvements and increase the probabilistic contacts of vehicle communication. The scheme is divided into a few segments, for ease of operations with a perfect sample. The contact duration between two vehicles moving in opposite directions on their overlapped road is lower, but their contact probability is higher. By contrast, the duration of the contact between two vehicles

moving in the same direction on their overlapped road is higher, but their contact probability is lower. SES can easily obtain efficient routing by considering the above-mentioned stochastic contacts. Furthermore, we investigate the content transmission among the probabilistic contacts, by using the flow model with probabilistic capacities. The performance of the proposed SES is experimentally validated with the probabilistic contacts in VANETs.

X Qiu, Y Xie, Y Wang, L Ye, Y Yang et al.[6] The utilization of UAVs in various fields has led to the development of flying ad hoc network (FANET) technology. In a network environment with highly dynamic topology and frequent link changes, the traditional routing technology of FANET cannot satisfy the new communication demands. Traditional routing algorithm, based on geographic location, can “fall” into a routing hole. In view of this problem, we propose a geolocation routing protocol based on multi-agent reinforcement learning, which decreases the packet loss rate and routing cost of the routing protocol. The protocol views each node as an intelligent agent and evaluates the value of its neighbor nodes through the local information. In the value function, nodes consider information such as link quality, residual energy and queue length, which reduces the possibility of a routing hole.

M Jamil, U Haider, IU Khan, TK Bhatia et al.[7] The world is entering a new era where all things could be dramatically changed in intelligent transportation systems. This network system will break all the traditional ways of living. All the limitations and problems in various domains of application will need to be well addressed. Every new product has some pros and cons, but the core challenge in this field is to deliver security in dynamic way. Through this work, we raise the issues of privacy, security, and intrusion attack in a discriminating approach. This chapter is focused on a comprehensive survey of the security attacks in the UAV network and other intelligent transport systems.

J Luo, Z Wang, M Xia, L Wu, Y Tian, Y Chen et al.[8] Path planning has been a hot and challenging field in unmanned aerial vehicles (UAV). With the increasing demand of society and the continuous progress of technologies, UAV communication networks (UAVCN) are also flourishing. The mobility of UAV nodes allows for flexible network deployment, but some challenges are brought, such as power constraints, throughput, cost, and time efficiency. Therefore, path planning is significant for UAVCN. This article presents a review of UAVCN path planning. We first introduce the network structure and performance evaluation of UAVCN. We then investigate the generic UAV path planning algorithms and the path planning algorithms in UAVCN. In this article, the advantages and disadvantages of each path planning algorithm and the functional problems. The challenges faced in path planning for UAVCN, the solutions, state-of-the-art, and representative results are also presented. In addition, we illustrate future research directions for UAVCN path planning as well, which can provide some help to researchers.

F Jahan, J Devore, Q Niyaz, W Sun et al.[9] Autonomous systems are soon expected to integrate into our lives as home assistants, delivery drones, and driverless cars. Given the importance of cybersecurity of these systems, game-theoretic solutions provide a mathematical modeling of the interaction between malicious users and the system. This work introduces a novel framework for analyzing potential denial of service (DoS) attacks on autonomous

vehicular networks by integrating a non-cooperative, non-zero-sum game model with a comprehensive simulation environment (VEINS/OMNET++/SUMO). Our key contribution lies in the systematic quantification of attacker and defender payoffs based on realistic network metrics, enabling the identification of optimal strategies across 21 distinct attack/defense scenarios derived from tunable network parameters. We specifically emphasize the model's ability to provide a predictive, all-scenario evaluation to aid system designers in preparing for real-time cyber attacks on driverless cars.

RM Almutairi et al.[10] The Internet of Things (IoT) has rapidly evolved over the past two decades, transforming the way we interact with the environment through a network of interconnected devices. The purpose of this thesis is to explore the integration of IoT with Vehicular Ad-Hoc Networks (VANETs) in order to enhance intelligent transportation systems (ITS) and smart city infrastructure through the use of IoT. VANETs, characterized by high mobility and dynamic topology, play a crucial role in enhancing traffic safety, efficiency, and vehicular services. They improve traffic safety by enabling real-time communication between vehicles and roadside infrastructure, allowing the sharing of critical information such as accident warnings and road conditions to prevent collisions and enhance emergency response times.

J Ghelani, P Gharia, H El-Ocla et al.[11] Unmanned Aerial Vehicles (UAVs) have several military and civilian applications to perform tasks that do not require a central processing unit or human involvement. There are various vulnerable characteristics, alternatively limitations, in UAV systems such as data loss, signals interference, disabling sensors, misleading weapons, cyber attacks, disrupting services, etc. Jamming attack is one of the cyber threats that likely lead to denial of service that often occurs in wireless communication systems like Flying ad hoc networks (FANETs) and Internet of Drones (IoD). Over years, there are several approaches proposed by researchers to detect jamming attacks such as rule-based jamming attack detection mechanism, Bayesian game-theoretic mechanism, IoD-based protection mechanism, communication channel techniques (channel hopping, spectrum spreading, MIMO-based jamming mitigation, coding, etc), delay tolerant networking technique, and cryptographic algorithms, however, these methods were not suitable for jamming detection in UAV environment.

K Abid et al.[12] This thesis focuses on resource allocation in wireless communication at the Medium Access Control (MAC) layer. Resource allocation has been extensively studied to maximize system-wide throughput or minimize the average delay per user. One of the main challenges in wireless networks is mitigating communication collisions caused by simultaneous transmissions from multiple nodes located close to one another over a common channel. As the number of devices increases, the usability of the spectrum decreases due to interference. Additionally, high mobility, variable topology, and high density pose significant challenges for MAC protocols to handle communication collisions, leading to network disruptions, high delays, packet loss, and energy wastage. In the first part of this thesis, we review the existing research works on contention-free MAC protocols for wireless networks.

First, we discuss the challenges and requirements that MAC protocols face in wireless networks.

VI. CONCLUSION

Multi-Agent AI systems significantly enhance cooperative communication in Hybrid MANET-VANET architectures by providing intelligent decision-making, adaptive routing, efficient resource management, and reliable data transmission in highly dynamic environments. The integration of AI techniques such as Machine Learning, Deep Reinforcement Learning, and Fuzzy Logic improves network performance, scalability, security, and Quality of Service (QoS). This review highlights that Hybrid MANET-VANET frameworks supported by Multi-Agent AI can effectively address challenges related to mobility, routing instability, congestion, and communication reliability. Furthermore, emerging technologies such as 6G, edge computing, blockchain, and federated learning are expected to further strengthen intelligent vehicular communication systems for future smart transportation and connected network applications.

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