Integrated AI and Metaverse Rendering for 6G Vehicular Networks: New Perspectives and Technical Solutions

Minghui Dai, Xin Li, Shan Chang, Anwer Al-Dulaimi, Shahid Mumtaz, and Jiaming Pei

Abstract

The evolution of 6G technology towards integrated computing and fusion, with its ultra-low latency and high reliability, is a critical enabler for seamless Metaverse rendering in future vehicular networks. However, vehicular Metaverse rendering faces critical issues of untrustworthy and unbalanced resource distribution. To promote the quality of service (QoS) in vehicular Metaverse, this article proposes a cooperative vehicular Metaverse rendering mechanism by integrating 6G and artificial intelligence (AI) to achieve low-latency, high-fidelity, and trustworthy in-vehicle rendering. We first introduce the framework of vehicular edge-enabled Metaverse rendering through the collaboration of roadside unit (RSU) and in-vehicle rendering. Then, the cooperative AI agent scheduling strategy is proposed to improve the resource utilization. An adaptive privacy preservation scheme is developed to protect the privacy information of vehicle users. Next, a case study by considering three scenarios for edge-enabled vehicular Metaverse is exploited. Performance evaluations are conducted to validate the advantages compared to baseline schemes.

Introduction

The rapid development of intelligent internet of vehicles (IoVs) is driving the transportation system toward Metaverse era of integrated physical-virtual connectivity [1]. By building real-time digital twins of the road environment, vehicle status, and user interactions, the in-vehicle Metaverse not only enables immersive experiences such as augmented reality (AR) navigation and virtual social interaction, but also improves traffic efficiency and safety through multi-vehicle virtual collaboration (e.g., virtual warnings to predict potential collisions). Moreover, the application of vehicular Metaverse rendering requires ultra-low latency, ultra-high fidelity, and dynamic consistency. However, the resource bottleneck of existing heterogeneous networks and the static allocation model make it difficult to support these requirements [2], [3].

The 6G technology provides support for overcoming the network resource bottleneck in vehicular Metaverse [4]. The integrated computing and communication features enable dynamic channel optimization and build a high-performance transmission for in-vehicle Metaverse rendering. Moreover, through intelligent scheduling and adaptive resource allocation, it can dynamically match the network status and rendering requirements of vehicle users. However, the high dynamic topology of 6G vehicular networks, the heterogeneity in computing capacity between vehicles and roadside unit (RSU), and multi-dimensional collaboration requirements still pose challenges to vehicular Metaverse rendering [5], [6]. First, the dynamic adaptation of rendering tasks and resource allocation is difficult. Traditional models of local rendering on vehicles or centralized rendering in cloud server cannot cope with the requirement of real-time rendering during vehicle mobility. How to implement real-time splitting and migration of rendering tasks and determine the allocation strategy between vehicle and RSU should be investigated. Second, collaborative rendering between vehicles and RSUs is challenging due to the lack of interaction between each participant. It is necessary to design collaborative mechanisms while guaranteeing resource load-balancing. Third, security and privacy risks are critical. The interactivity of vehicular Metaverse requires sharing sensitive data such as vehicle location and user behavior. Achieving trusted rendering is significant to in-vehicle Metaverse applications [7].

Artificial intelligence (AI) offers a new paradigm for vehicular Metaverse [8]. AI enables autonomous decision-making regarding rendering resources, balancing efficiency and quality through intelligent resource scheduling algorithms. Driven by 6G and AI, vehicular Metaverse rendering is able to build a comprehensive framework for perception, scheduling, and rendering, while addressing the bottlenecks of real-time performance, fidelity, and security for immersive applications in 6G vehicular networks. This article presents an AI-driven Metaverse rendering framework in 6G vehicular networks, with the

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Digital Object Identifier: 10.1109/MNET.2025.3637137

objective of achieving low-latency, high-fidelity, and trustworthy in-vehicle Metaverse. The main contributions of this work are as follows.

- **Collaborative Vehicular Metaverse Rendering Framework**. The collaborative framework includes edge rendering tier, network transmission tier, and in-vehicle tier. The edge rendering tier with powerful computing capacity provides low-latency task processing. The network transmission tier supports reliable communication between RSUs and vehicles. The in-vehicle tier is responsible for low-latency rendering composition.
- **Intelligent Resource Scheduling.** The AI agent (i.e., in-vehicle agent, edge agent) collaboratively optimizes the resource scheduling of communication and computing to achieve load-balancing during collaborative Metaverse rendering.
- **Adaptive Privacy Preservation.** The dynamic privacy domain is adopted to achieve flexible privacy preservation for vehicle users. The adaptive privacy preservation mechanism is implemented during collaborative rendering through adding controllable noise to location data.

This article is organized as follows. The section "Requirements of Vehicular Metaverse" discusses the requirements of vehicular Metaverse. The section "Framework of Vehicular Edge-Enabled Metaverse Rendering" introduces the framework of vehicular edge-enabled Metaverse rendering. The intelligent and secure resource scheduling is presented in the section "Intelligent and Secure Resource Scheduling for Edge-Enabled Vehicular Metaverse." The section "Case Study for Edge-Enabled Vehicular Metaverse" demonstrates the case study of the proposed framework. The section "Conclusion and Future Work" concludes this paper with future directions.

Requirements of Vehicular Metaverse

In this section, we introduce the requirements in 6G vehicular Metaverse including real-time rendering, intelligent scheduling, security and privacy.

Real-Time Rendering. The vehicular Metaverse needs to process multidimensional data in real-time, such as user behavior data, virtual environment data, and physical interaction data. When multiple vehicular users access the Metaverse server simultaneously, the network will suffer from computing overload due to the surge in concurrent requests from vehicular users, and lead to channel resource shortages. This results in long rendering delays, affecting the quality of users' immersive experience and the stability of vehicular Metaverse services.

Intelligent Scheduling. Vehicular Metaverse rendering relies on multimodal interaction in complex scenarios and high-precision predictive reasoning. However, vehicular Metaverse lacks intelligent resource scheduling algorithms, making it impossible to build a real-time perception and allocation mechanism. Therefore, it is necessary to design intelligent scheduling mechanisms according to diverse demands in complex driving scenarios, thus promoting reliable and sustainable development of vehicular Metaverse.

Security and Privacy. The vehicular Metaverse contains massive amounts of vehicle sensing data, the security affects the operation of the system [9], [10]. To promote high-quality immersive experience, the system needs to sense and collect real-time dynamic data such as vehicle's position and speed, as well as biometric features like users' facial expressions and voice commands during vehicular interactions. Once the private data is stolen, it may bring serious risks to vehicular Metaverse system, such as real-time tracking of vehicular users, malicious tampering with driving records, and eavesdropping on sensitive voice content.

Framework of Vehicular Edge-Enabled Metaverse Rendering

In this section, we introduce the proposed framework of vehicular edge-enabled Metaverse rendering. The detail of each component is first described, followed by the collaboration mechanism.

As shown in Fig. 1, the framework is divided into three tiers including the edge tier, network transmission tier, and in-vehicle tier. The system consists of two domains (i.e., the Metaverse rendering domain and the network control domain), with the objective of providing immersive Metaverse experience in 6G vehicular networks. Its core is to migrate the computationally intensive rendering tasks from resource-constrained in-vehicle terminals to powerful edge servers via intelligent scheduling algorithms. The rendering results are streamed back to vehicular users with high-bandwidth and low-latency. The main tiers and components are introduced as follows.

Edge Rendering Tier

The edge tier in the proposed framework incorporates diverse servers to support various applications.

- **Distributed Rendering Server:** The high-performance GPU servers deployed in RSUs are responsible for real-time graphics rendering for Metaverse scenarios like virtual social interactions and immersive navigation. Distributed rendering techniques including parallel rendering and tile rendering are leveraged to process complex scenes.
- **Metaverse Scene Server:** This server supports the operation of virtual scenes, the real-time operational status of the system, high-precision spatial data, user personalized information, and dynamic event data within the scene. Moreover, it ensures consistency in scene cognition for all vehicle users during cross-terminal and multi-user interactions by synchronizing these core elements in real-time.
- **Rendering Task Scheduling and Management Server:** This server is responsible for receiving rendering requests from vehicle terminals including user perspective, location, and action commands. In addition, it intelligently dispatches them to appropriate rendering nodes to optimize resource utilization and load balancing via AI algorithms.

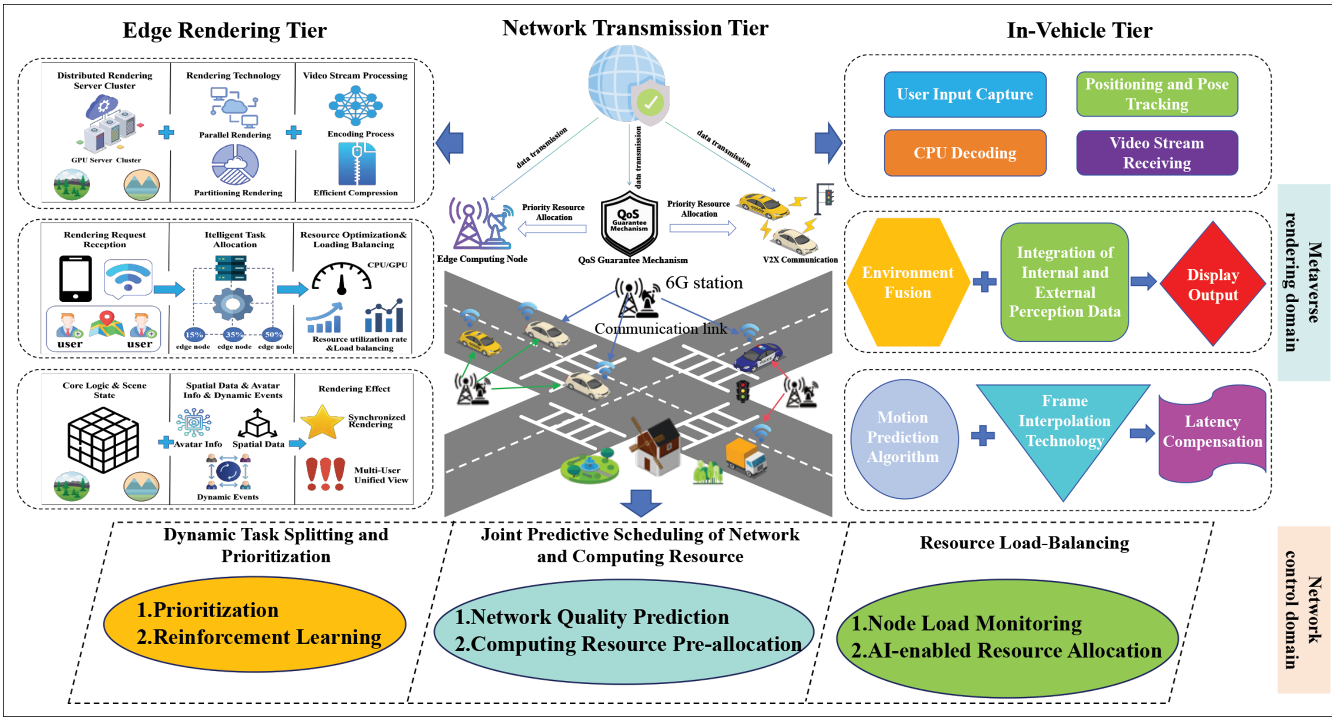

FIGURE 1. Framework of vehicular edge-enabled Metaverse rendering.

Network Transmission Tier

The network transmission tier guarantees reliable connectivity and high efficiency communication between edge and vehicle terminals.

- **Internet of Vehicles Protocol:** Utilizing vehicle-to-everything (V2X) communications, vehicle users can not only communicate with edge, but also exchange contextual information (such as location, status, and virtual object interaction intentions) with surrounding vehicles and infrastructure. This enhances the realism and coordination of the scene. Moreover, RSUs are deployed at the network edge. They can handle some lightweight rendering, local content caching, protocol conversion, and network acceleration, which reduces transmission distance.
- **Low-Latency and High-Bandwidth Connectivity:** Relying on 6G networks and vehicular ad-hoc networks, these networks prioritize bandwidth and low latency for Metaverse rendering. It provides ultra-low end-to-end transmission latency and ultra-high throughput, which ensures smooth interactions and immersive experiences.

In-Vehicle Tier

The in-vehicle tier receives the Metaverse data and conducts scene composition and display to vehicle users.

- **Rendering Composition and Display:** Integrating vehicle internal and external environment data to provide contextual information for Metaverse rendering. The rendering image is fused with the real-world environment acquired by local sensors, and ultimately output to terminal devices. The main responsibilities include: 1) Capture user input. 2) Upload it to edge in real-time to determine the rendering perspective. 3) Receive compressed video streams from the edge. 4) Perform efficient video decoding by leveraging on-board GPU.
- **Prediction and Compensation:** Considering the high mobility of vehicles, the motion prediction algorithms and frame interpolation techniques are applied to compensate for latency introduced by network transmission while improving the interactive responsiveness.

Collaboration Mechanism of Edge Rendering and In-Vehicle Rendering

The collaborative mechanism among three tiers for task rendering improves vehicle user's quality of experience (QoE). In specific, the vehicle terminal collects user input and transmits them to the edge tier via network transmission tier. The following collaboration mechanism is conducted. 1) The edge-based Metaverse scene server updates the state based on the received vehicle state and user commands. 2) The rendering server assigns rendering tasks for specific viewpoints to these nodes in the edge rendering cluster. 3) The rendering nodes perform complex scene rendering. 4) The rendered frames are encoded and compressed. 5) The encoded video stream is transmitted to the vehicle via an optimized network path. 6) The vehicle terminal receives the video stream and composites it with local information for presentation to the user. The summary of existing studies on vehicular Metaverse rendering is provided in Table 1.

Intelligent and Secure Resource Scheduling for Edge-Enabled Vehicular Metaverse

To cope with the high mobility of vehicles, network volatility and security requirements, in this section,

Category	Cooperation	Sustainability	Pros	Cons	Ref
Cloud rendering	No	High	Reliability and security	Complex authentication	[11]
Edge rendering	No	Medium	High efficiency consensus	High computational overhead	[12]
Local rendering	No	Medium	Low-latency service	High energy consumption	[13]
Cooperative rendering	Yes	High	Low consumption	Computational complexity	This article

TABLE 1. Summary of existing studies on vehicular metaverse rendering.

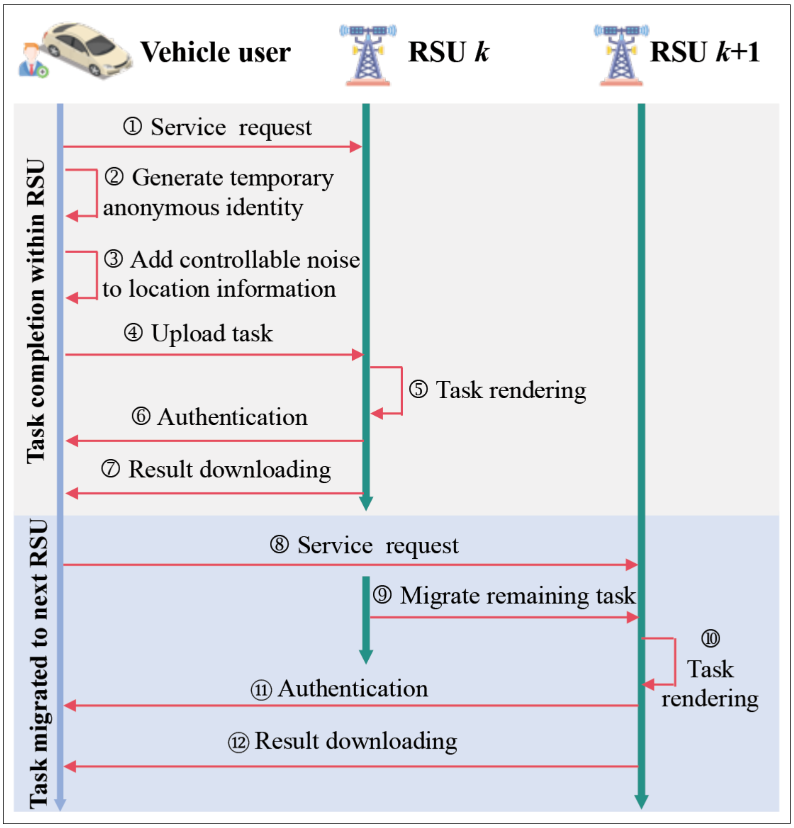

FIGURE 2. Resource scheduling based on adaptive privacy preservation.

we present resource scheduling for the proposed vehicular Metaverse rendering framework through the collaboration of in-vehicle agent and edge agent, followed by the adaptive privacy preservation mechanism.

Intelligent Resource Scheduling

- **In-Vehicle Agent:** The in-vehicle agent runs on the vehicle's onboard computing unit. It monitors the vehicle's computing power, energy consumption, and local sensor data (e.g., vehicle location, speed, and surrounding environment) in real-time [14]. Moreover, the in-vehicle agent is responsible for reporting local resource states to the edge agent, while processing lightweight rendering tasks and decision-making for rendering task allocation.
- **Edge Agent:** The edge agent runs on RSU servers or regional edge servers. The agent coordinates the cross-regional resource scheduling and manages the cluster of vehicle nodes within the coverage geographic area. In addition, the edge agent collects the information of vehicle trajectories, network link quality, communication and computing resources in real-time. Then, it coordinates rendering task allocation and yields the communication and computing strategy.

The cooperative AI agent scheduling strategies are as follows.

- **Dynamic Task Splitting and Prioritization:** The in-vehicle agent dynamically splits tasks based on the characteristics of Metaverse rendering tasks such as frame rate requirements, resolution. Tasks requiring low latency (e.g., collision warning virtual signs) are marked as high priority and assigned to the vehicle or the nearest RSU. Non-real-time tasks (e.g., background environment texture rendering) are marked as low priority and dispatched to idle RSU. Reinforcement learning models are used to continuously optimize priority weights, balancing user experience and resource utilization.
- **Joint Predictive Scheduling of Communication and Computing:** The in-vehicle side agent predicts network quality based on historical network data. The edge agent pre-allocates computing resource to nearby RSUs based on vehicle movement trends. For instance, if a vehicle is leaving the coverage of RSU, it migrates rendering tasks from RSU to the vehicle's local computing and dynamically adjusts the rendering resolution to match local computing capacity.
- **Resource Load-Balancing:** The AI agent monitors the load of RSUs in real-time and uses AI algorithm to assign rendering tasks [15]. If a RSU node fails, an adjacent edge agent quickly takes over its task queue to ensure the rendering continuity. Furthermore, the AI agent dynamically adjusts resource allocation among RSUs based on vehicle density to avoid resource overload in popular areas.

Adaptive Privacy Preservation

Due to the mobility of vehicles, the location data of vehicles for migration rendering may be exposed to malicious users. Privacy-preservation is significant in the proposed Metaverse rendering. The dynamic privacy domain is introduced, which is determined based on the coverage of RSU. The adaptive privacy preservation mechanism is implemented through adding controllable noise to rendering data before the vehicle agent sends it to RSU. When a vehicle enters a new domain, the disturbance location can be obtained based on Laplace mechanism, which is related to the sensitivity and privacy budget parameters. The position trajectory generates fuzzy range with ϵ-differential privacy, which supports edge rendering scheduling while meeting privacy budget. When a vehicle migrates rendering task to RSU, the in-vehicle side agent automatically negotiates privacy policies with the RSU agent. The resource scheduling based on adaptive privacy preservation is shown in Fig. 2. For instance, the vehicle needs to increase the encryption level of location data when entering a commercial area, and reduce the decryption intensity when entering highway to ensure smooth rendering. The policy parameters (i.e., differential privacy budget) are dynamically adjusted based on the vehicle's distance from the domain boundary. When a vehicle leaves the coverage area of current RSU and needs to migrate unfinished rendering tasks to the next RSU, the vehicle generates a temporary anonymous identity and migrates with the encrypted rendering status data while removing the original private information. The new RSU then completes the task relay based on the anonymous identity, avoiding cross-node data association and tracking.

To promote the adaptive privacy preservation for edge-enabled vehicular Metaverse, the Q-learning-based privacy resource allocation is introduced. During Q-learning process, the state of edge agent is the privacy budget. The action of edge agent is the strategy of privacy budget. The profit for rendering task of vehicle user is regarded as the system reward. The edge agent combines vehicle trajectory prediction (such as inferring the driving direction and historical paths) to pre-deploy privacy computing resources on the next RSU to be connected. This ensures that privacy preservation cannot be interrupted during task migration, while avoiding the impact of privacy processing delays on rendering.

Case Study for Edge-Enabled Vehicular Metaverse

In this section, we consider three scenarios for edge-enabled vehicular Metaverse rendering based on different rendering models. 1) Metaverse rendering in-vehicle. 2) Metaverse rendering in-edge. 3) Collaborative Metaverse rendering.

Scenario of Vehicular Metaverse Rendering

Fig. 3(a) shows the scenario of Metaverse rendering in-vehicle. When vehicle users are sensitive to data, the rendering tasks are executed locally. The task rendering is processed locally via onboard units without network transmission, thus protecting the data privacy and avoiding the communication latency of RSU. The local rendering delay of vehicle is associated with the size of rendering task and the computing capacity. For instance, when a vehicle is driving on a rural road, it requires the local pre-trained model to complete environmental rendering. The local rendering can avoid privacy leaks caused by uploading data to RSU. In addition, when vehicle detects an obstacle ahead, local rendering can generate environmental perception results to make decisions in real-time.

Fig. 3(b) shows the scenario of Metaverse rendering in-edge. The edge rendering enables in-vehicle Metaverse applications that leverage multi-user collaboration and cross-domain data sharing. This requires edge-based coordination of multi-user interactions. For instance, the RSUs need to synchronize the information of all vehicles in real-time and render a unified application scene to avoid rendering inconsistency. Moreover, AI models of the in-vehicle Metaverse (e.g., traffic flow prediction) require large-scale data training in RSUs, while the computing and storage resources of local hardware cannot complete such tasks. The rendering delay by the edge consists of the uploading latency to RSU, the rendering latency by RSU, and the downloading latency to vehicle.

Fig. 3(c) shows the scenario of collaborative Metaverse rendering. Through the collaboration

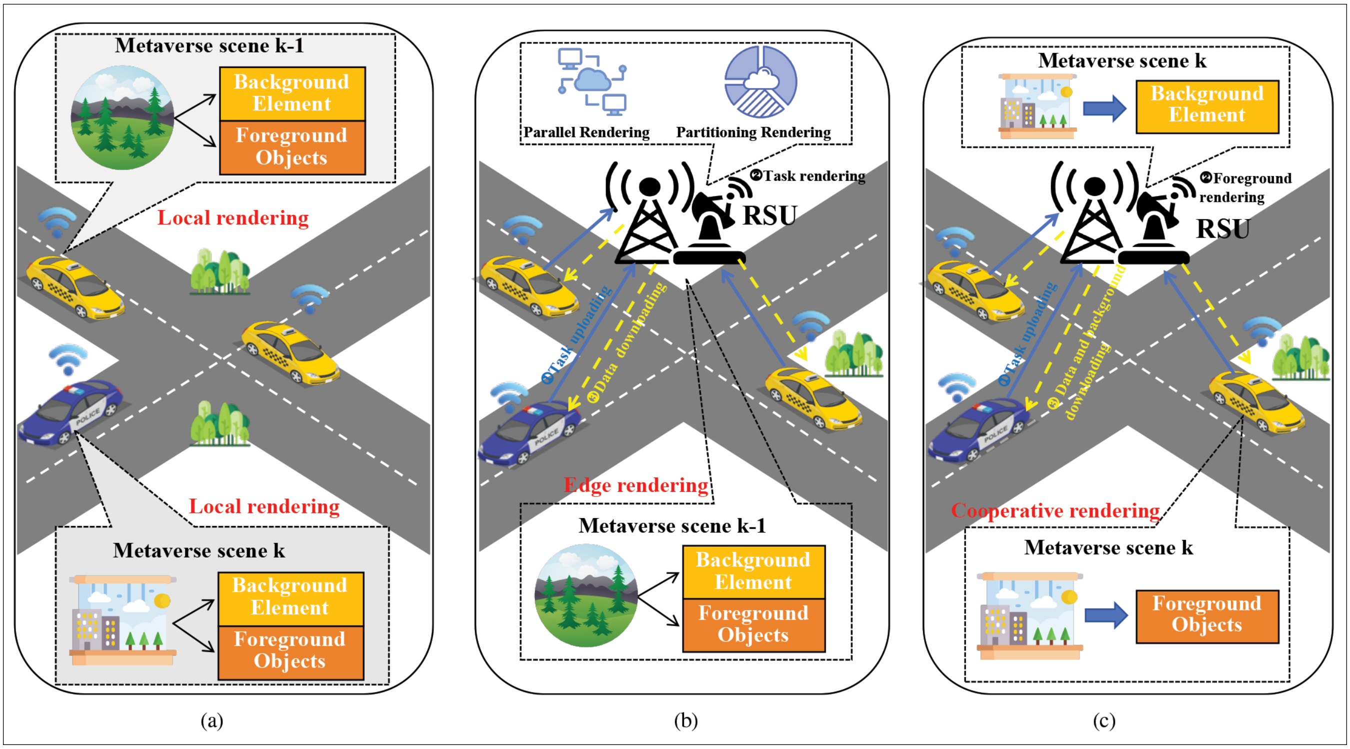

FIGURE 3. Three scenarios for edge-enabled vehicular Metaverse rendering. a) In-vehicle rendering. b) Edge rendering. c) Cooperative rendering.

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and task division between RSU and vehicle, it achieves low-latency and high-fidelity rendering for vehicle users. The vehicle side focuses on lightweight real-time interaction, which is responsible for preprocessing of local perception data, low-latency rendering tasks in the vehicle. The RSU side is responsible for processing high-complexity tasks. The collaborative scheduling scheme is achieved as follows. RSUs and vehicles exchange status information in real-time through a lightweight protocol. The rendering tasks are dynamically adjusted via the splitting ratio determined by AI algorithms. The collaborative rendering delay comprises two parts including the local processing and the partial offloading processing, i.e, the local rendering latency by vehicle, the uploading latency to RSU and the rendering latency by RSU and the downloading latency to vehicle. For instance, when vehicle enters a computing-intensive area, RSU automatically takes over more than half of rendering tasks. When vehicle is driving at high speeds, the vehicle prioritizes local rendering to avoid edge switching delays.

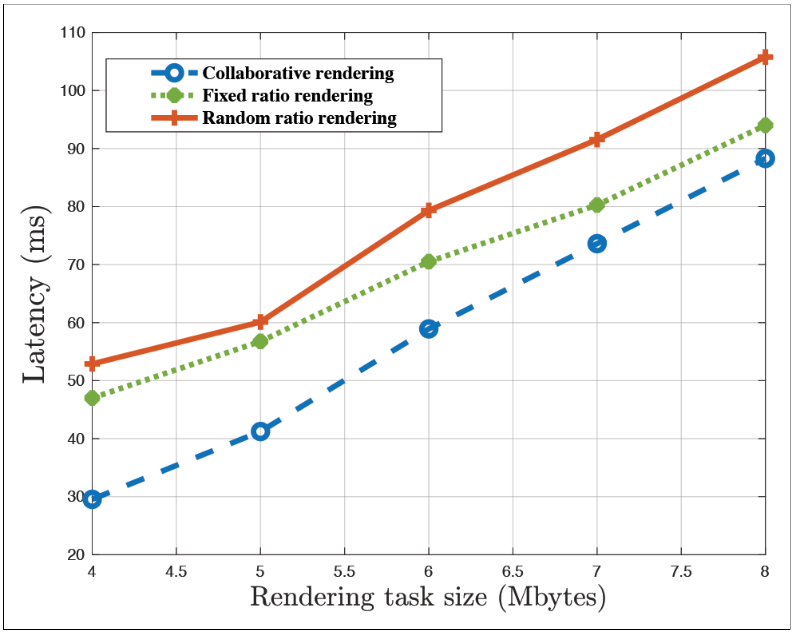

FIGURE 4. Rendering latency with different rendering task sizes.

Performance Evaluation

The performance of edge-enabled vehicular Metaverse is validated via simulation. We consider the scenario consisting of five vehicles and one RSU within a 1km×1km area. The rendering tasks are within the interval [5,10]Mbytes. The background is rendered at RSU. The foreground can be partially rendered at RSU and vehicle. The computing rates of RSU and vehicle are set as 1×10^{10}cycles/ms and 1×10^{9} cycles/ms, respectively. To improve the bandwidth utilization, five vehicles communicate with RSU via non-orthogonal multiple access. The transmission bandwidth is set as 1 kHz. The transmission power of vehicle is set as 5mW. The white Gaussian noise is 1×10^{-11}dBm. We compare the proposed cooperative rendering scheme with baselines as follows. The fixed ratio rendering scheme means that the task offloading ratio to RSU is a predetermined value. The random ratio rendering indicates that the task offloading ratio to RSU is a random value.

Fig. 4 shows the performance of rendering latency with different rendering task sizes. It can be seen that the latency in the proposed cooperative rendering is lower than that of baselines. The reason is that the proposed cooperative rendering scheme achieves the optimal rendering strategy by taking advantage of local rendering and edge rendering. In addition, the latency in three schemes increases with the increase of task size, as the larger the task size, the longer the computing time.

Fig. 5 demonstrates the performance of energy consumption under different scenarios. Fig. 5(a) shows the performance of energy consumption

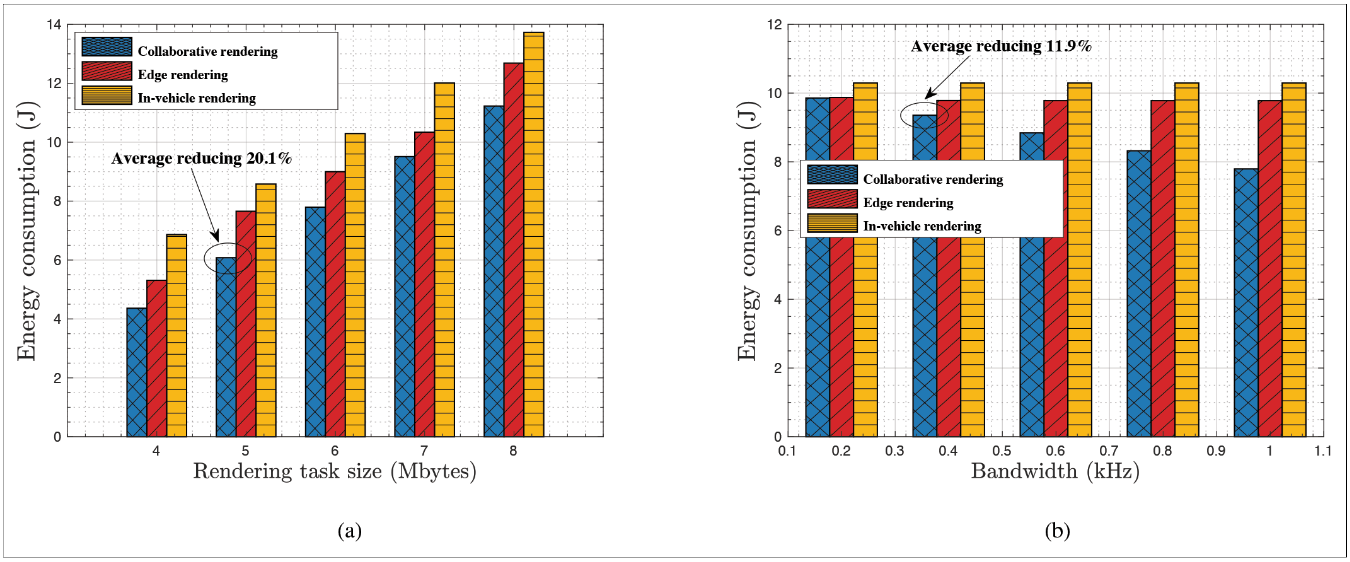

FIGURE 5. Performance of energy consumption under different scenarios. a) Energy consumption with different task sizes. b) Energy consumption with different bandwidths.

with different task sizes. It can be seen that the performance of cooperative rendering is superior to edge rendering and in-vehicle rendering. Moreover, as the task size increases, the energy consumption shows an upward trend, and the cooperative rendering achieves low energy consumption. The reason is that more energy is consumed when increasing task size. While the cooperative rendering migrates partial tasks to RSU for processing via optimizing the rendering ratio, thus reducing the energy consumption. Fig. 5(b) depicts the performance of energy consumption with different bandwidths. The cooperative rendering can attain lower energy consumption than edge rendering and in-vehicle rendering. Moreover, it can be seen that the energy consumption shows a downward trend as bandwidth increases. The reason is that a larger bandwidth leads to less energy consumption for transmitting rendering tasks.

Conclusion and Future Work

In this article, we have presented the vehicular Metaverse rendering by integrating 6G with AI, with the objective of achieving low-latency, high-fidelity, and trustworthy in-vehicle Metaverse. The framework of vehicular edge-enabled Metaverse rendering through the collaboration of RSU and in-vehicle rendering is first introduced. Then, we have provided the cooperative AI agent scheduling strategy to improve the resource utilization. To protect the privacy information of vehicle users, we have proposed an adaptive privacy preservation scheme. Moreover, a case study for edge-enabled vehicular Metaverse by considering three scenarios has been presented. Performance evaluations have validated the advantages in comparison with baseline schemes. Finally, we discuss the future directions as follows.

- **Enhanced Rendering With Generative AI.** Generative AI-driven Metaverse dynamic modeling and real-time rendering are significant in next generation vehicular networks. By leveraging generative AI such as diffusion models, the rendering quality caused by packet loss or insufficient computing resource can be improved based on historical rendering data and real-time scene characteristics, thereby reducing the amount of raw data transmitted and improving the visual quality of rendering.
- **Trusted Verification of Rendering Content.** It is important to build lightweight Blockchain nodes in vehicle networks to sign and verify Metaverse rendering results in real-time, preventing malicious nodes from injecting false rendering content. Moreover, AI anomaly detection algorithms can be adopted to identify abnormal behaviors in rendering data transmission such as data tampering and fake node access.
- **Cross-Domain Resource Collaboration Based Reinforcement Learning.** The AI agent dynamically allocates rendering computing and communication resources among vehicles, edge and cloud, and optimizes the proportion of edge and cloud rendering tasks. Moreover, the AI agent has the ability to migrate high-priority tasks to vehicles before the channel deteriorates. Thus, the cross-domain resource collaboration in next generation vehicular networks should be considered.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China under Grant 62501137 and Grant 62472083 and in part by the AI-Enhanced Research Program of Shanghai Municipal Education Commission under Grant SMEC-AI-DHUZ-01.

References

[1] L. U. Khan et al., "Edge intelligence empowered vehicular metaverse: Key design aspects and future directions," *IEEE Internet Things Mag.*, vol. 7, no. 1, pp. 120–126, Jan. 2024.
[2] P. Dong et al., "Enhancing vehicular communication using 5G-enabled smart collaborative networking," *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 72–79, Dec. 2017.
[3] M. Dai et al., "A trust-driven contract incentive scheme for mobile crowd-sensing networks," *IEEE Trans. Veh. Technol.*, vol. 71, no. 2, pp. 1794–1806, Feb. 2022.
[4] M. Adil et al., "Role of 5G and 6G technologies in metaverse, quality of service challenges, and future research directions," *IEEE Netw.*, vol. 39, no. 4, pp. 211–219, Jul. 2025.
[5] X. Luo et al., "Privacy attacks and defenses for digital twin migrations in vehicular metaverses," *IEEE Netw.*, vol. 37, no. 6, pp. 82–91, Nov. 2023.
[6] Z. Su et al., "UAV enabled content distribution for Internet of Connected Vehicles in 5G heterogeneous networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 8, pp. 5091–5102, Aug. 2021.
[7] L. Basyoni et al., "Navigating privacy challenges in the metaverse: A comprehensive examination of current technologies and platforms," *IEEE Internet Things Mag.*, vol. 7, no. 4, pp. 144–152, Jul. 2024.
[8] B. Mao et al., "AI-assisted edge caching for metaverse of connected and automated vehicles: Proposal, challenges, and future perspectives," *IEEE Veh. Technol. Mag.*, vol. 18, no. 4, pp. 66–74, Dec. 2023.
[9] R. Cheng, S. Chen, and B. Han, "Toward zero-trust security for the metaverse," *IEEE Commun. Mag.*, vol. 62, no. 2, pp. 156–162, Feb. 2024.
[10] J. Pei et al., "FL meets LLM: A hybrid security framework for the Internet of Energy," *IEEE Netw.*, early access, Oct. 1, 2025, doi: 10.1109/MNET.2025.3612271.
[11] Y. Gong et al., "RSMS: Towards reliable and secure metaverse service provision," *IEEE Trans. Veh. Technol.*, vol. 73, no. 11, pp. 17430–17442, Nov. 2024.
[12] L. Liu et al., "Reputation management for consensus mechanism in vehicular edge metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 919–932, Apr. 2024.
[13] G. Xie et al., "Towards the vehicular metaverse: Exploring distributed inference with transformer-based diffusion model," *IEEE Trans. Veh. Technol.*, vol. 73, no. 12, pp. 19931–19936, Dec. 2024.
[14] X. Yu et al., "When connected and automated vehicles meet mobile crowdsensing: A perception and transmission framework in the metaverse," *IEEE Veh. Technol. Mag.*, vol. 18, no. 4, pp. 22–34, Dec. 2023.
[15] H. Zhang et al., "Artificial intelligence-based resource allocation in ultradense networks: Applying event-triggered Q-learning algorithms," *IEEE Veh. Technol. Mag.*, vol. 14, no. 4, pp. 56–63, Dec. 2019.

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