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Blockchain-Based Distributed Collaborative Computing for Vehicular Digital Twin Network

Lei Liu, Junqi Fu, Jie Feng, Guopeng Wang, Qingqi Pei, and Schahram Dustdar

***Abstract*—Being the main starting point for intelligent transportation systems, internet of vehicles has entered a rapid development period. This motivates a large number of novel vehicular applications with diversified and personalized demands. Distributed collaborative computing provides a promising solution to meet these applications by on-demand resource management, but is faced with tremendous challenges in achieving trusted resource cooperation and accurate decision making. In this paper, we propose a blockchain-based vehicular digital twin architecture for distributed collaborative computing. In this architecture, blockchain facilitates the opening and sharing of vehicular resources, while digital twin enables the accurate management decision. Then, we investigate the computation offloading in blockchain-based vehicular digital twin networks to demonstrate the effectiveness of the proposed architecture. Finally, several important open issues are discussed in detail for further investigation on blockchain-based vehicular digital twin.**

***Index Terms*—Internet of vehicles, collaborative computing, digital twin, blockchain, resource allocation.**

I. Introduction

With the remarkable development of digital economy, Internet of vehicles is bound to usher in a rapid development period. Accordingly, a wide variety of new applications will be born, covering every aspect of our lives, including information services (e.g., vehicular entertainment and augmented reality), driving safety (e.g., autonomous driving and collision warning), and traffic efficiency (e.g., parking space sharing and collaborative navigation). These applications not only require high data transmission rate, but also large computing and storage capabilities. The explosively growing demands are becoming increasingly diverse and personalized. It is extremely difficult for traditional vehicular networks to meet these demands. Future vehicular networks should have the ability to support enormous access demand, massive data transmission and high quality of service guarantee. It is crucial to satisfy the differentiated service requirements from different users by efficient and flexible resource management.

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Cloud computing can provide immense computational capacity, but result in unpredictable latency due to the remote deployment. Benefiting from the proximity to users, edge computing is able to reduce the task latency. However, edge computing has limited computational capacity compared with cloud computing. Cloud-edge-end collaboration represents a promising paradigm by the integration of cloud computing and edge computing, which contributes to improving the user experience by making use of all available network resources [1]. Despite the significant contributions, this paradigm still faces many problems to be solved in vehicular networks. Suffering from the dynamic (vehicle mobility), uncertainty (channel state) and heterogeneity (network resources), it is extremely challenging to manage vehicular networks. The topology changing and the network unpredictability have a substantial impact on the collaborative computing decision.

Digital twin (DT) is viewed as one innovative technology to address the stated problem above [2]. Being a dynamic virtual representation of physical entity, the digital twin can accurately map the physical space to the virtual space for monitoring, controlling, optimizing and decision making [3]. The real-time allocation decision is fed back to the physical space from the digital space, making the collaborative computing more intelligent in real networks. The work in [4] leverages the digital twin to perceive the mobile edge computing environment for computation offloading. The digital twin in [5] is employed to optimize the network resource management. The network state is predicted accurately using the digital twin in [6]. Specially, the training for intelligent models requires a great amount of data, and the digital twin can be used to effectively train the intelligent model when there is no enough available data in real networks, and also even create rare network conditions for model training. Benefiting from the decoupling between the physical entity and the digital twin, any operation performed by the digital twin can not bring about risks to the physical entity [7].

However, there exist security and privacy issues for collaborative computing and digital twin [8]. For collaborative computing, a malicious node is able to steal the user information by pretending the computing node, and there is possibility that the calculation is manipulated. Therefore, the trust barrier between nodes hinders the resource opening and sharing. For digital twin, a huge amount of data computation is required to run the simulation process. Frequent data interactions occur between physical entity and digital twin. In addition to the trusted data, digital twin also requires the reliable computing infrastructure to ensure that the calculation results are accurate. Blockchain is naturally appealing technology to guarantee the security and

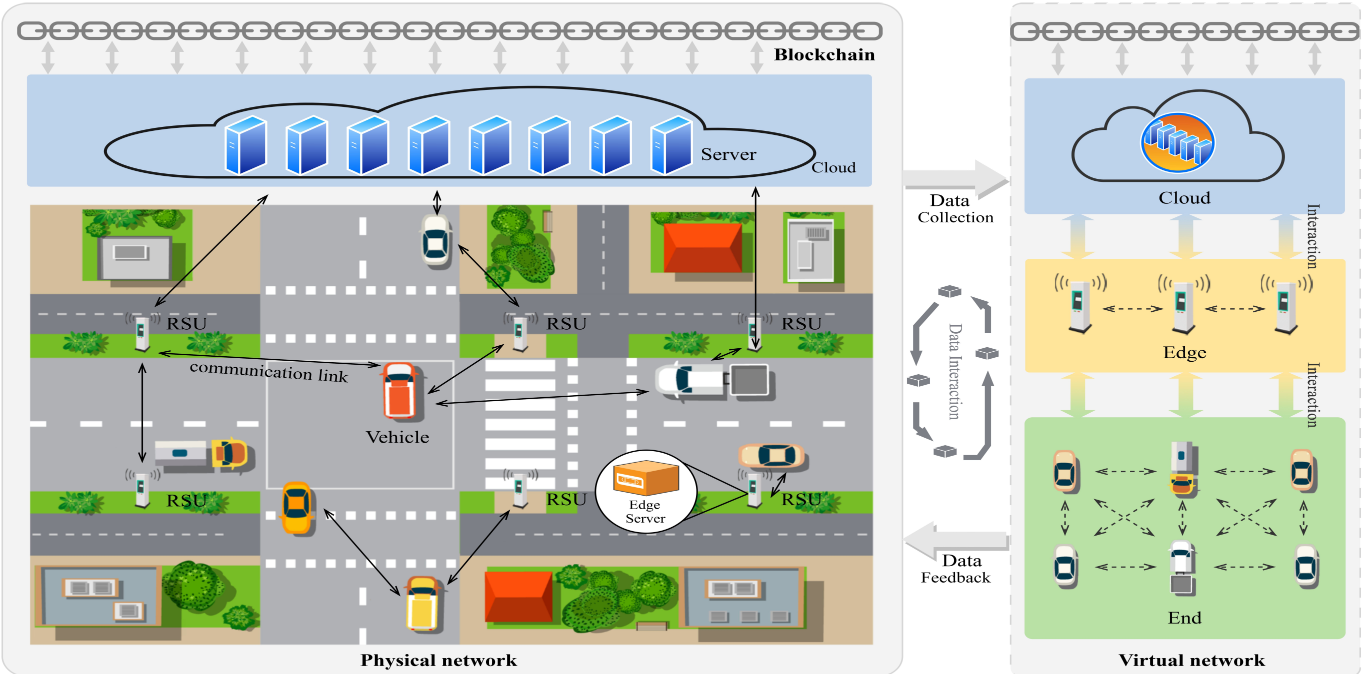

Fig. 1: The proposed blockchain-based vehicular digital twin architecture

privacy [9]. Blockchain is a new application paradigm for computer technologies, including distributed data storage, peer-to-peer transmission, consensus mechanism, and encryption algorithm, which is characterized by decentralization, transparency, tamper-resistant and anonymity. Blockchain utilizes consensus algorithm to manage ledger data, cryptography to ensure data access and transmission security, and smart contract to operate data automatically. The work in [10] leverages blockchain to devise a privacy-preserving authentication system, which achieves the automated authentication and guarantees the node privacy simultaneously. In [11], smart contracts are employed to ensure the secure data sharing among nodes and prevent the malicious behaviors. The security and reliability of computation offloading is guaranteed by blockchain in [12]. The convergence of collaborative computing, digital twin and blockchain offers an appealing solution to support various vehicular applications.

In this paper, we propose a vehicular cloud-edge-end collaboration architecture empowered by digital twin and blockchain. The cloud-edge-end collaborative computing can aggregate all available resources for task implementation through vertical collaboration and horizontal collaboration, maximizing the resource utilization. The digital twin enables the real-time decision making by accurately modeling physical entities and the blockchain facilitates the resource circulation with its inherent characteristics. Based on the architecture, we design a resource allocation model to improve the user experience by creating a credible network environment and providing accurate task scheduling and resource management decisions. Several open issues are pointed out for further investigation.

The reminder of this paper is as follows: we first propose the blockchain-based vehicular digital twin architecture in Section II, then present a resource allocation model in Section III, next describe several open issues in Section IV. The numerical results are given in Section V followed by conclusion and further work in Section VI.

II. Blockchain-based Vehicular Digital Twin Architecture

We propose a blockchain-based vehicular digital twin architecture for collaborative computing, as shown in Fig. 1. Digital twin creates virtual replicas of physical entities, such as vehicles and Road Side Units (RSUs), to facilitate learning and simulation, enabling real-time decision making. Meanwhile, blockchain enhances decentralization and security through its distributed ledger, providing a more reliable environment for data exchange and resource management and solving the security concerns arising from digital twin technology.

Resource collaboration: The physical entities are distributed in edge and end, e.g., RSUs and vehicles. From the vertical level, the task vehicle can offload its task to the cloud or the edge based on its task property and service requirements. The cloud is inclined to process the delay-tolerant task, while the edge is suitable to implement the delay-sensitive task. From the horizontal level, the task migration is allowed in the edge to achieve load balancing, while vehicles in the end can process their tasks locally or through surrounding vehicles with idle resources by one-hop vehicle-to-vehicle offloading or multi-hop vehicle-to-vehicle offloading [13].

Digital twin: Based on the mechanism of physical entity and the data from physical entity, digital twin builds the replicate of each physical entity in virtual space with modeling and simulation [14]. Real-time data, such as mobility characteristics, channel environment and resource status, is synchronized to the virtual space. The built digital twins

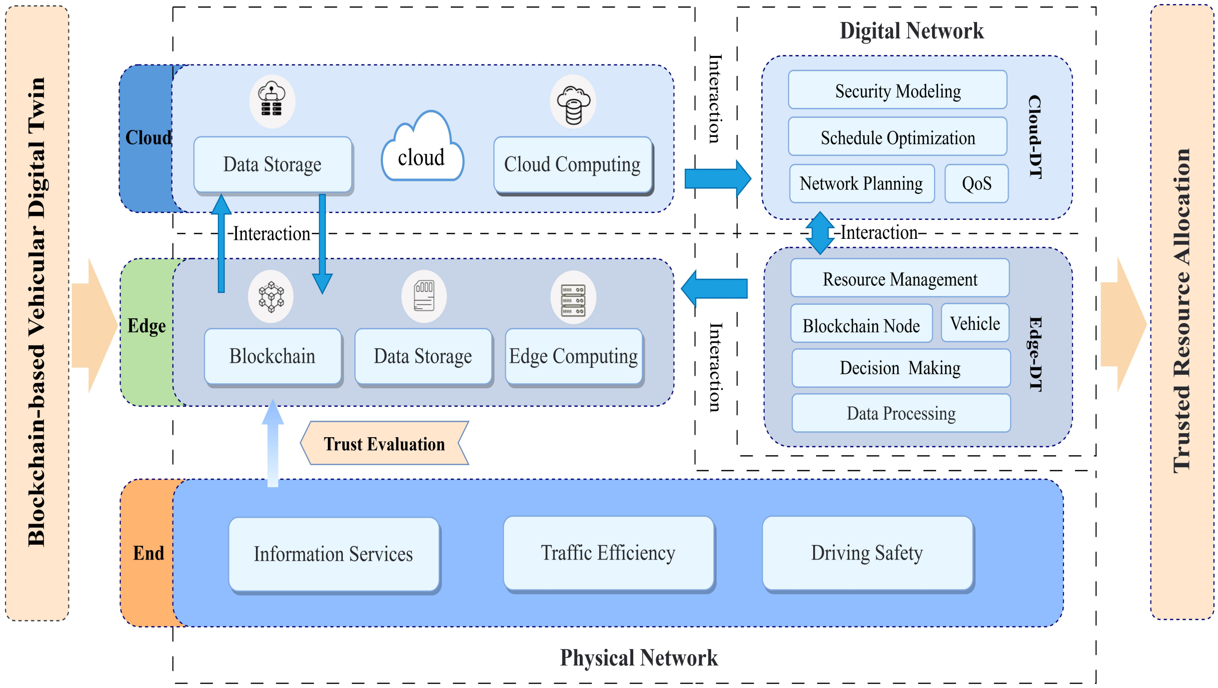

Fig. 2: Computation offloading under blockchain-based vehicular digital twin networks

is optimized iteratively through the received data sent from physical entities. Each physical entity's behavior in the real environment can be simulated using the digital twin. By analyzing the simulation results, the valuable information will be fed back for network management, resource optimization and decision control. The virtual network provides intelligent services through data processing and algorithm learning, such as monitoring, congestion prediction, route selection, and assisted driving.

Trust guarantee: The core of digital twin is modeling, the ultimate goal of which is to make decisions. This is dependent on frequent data interactions. If the data security is not effectively guaranteed, it poses a great threat to any participant who uses the simulation results for decision-making. Blockchain is able to construct a trustworthy computing platform because of its decentralized and tamper-resistant nature. Benefiting from the secure and transparent characteristics, blockchain fosters the data sharing and data collaboration simultaneously. By leveraging the distributed ledger technology, blockchain ensures the authenticity of the data and the effectiveness of the results by saving all data from the virtual space in blockchain.

Communication interaction: There are frequent interactions between physical entities and digital twins, which includes intra-twin interaction and inter-twin interaction. The intra-twin interaction is bidirectional. For a collaborative computing task, each task vehicle will send its sensing data and service demand to the digital twin, while the digital twin can implement an allocation algorithm to get the optimal decision. For the intra-twin, data sharing can be implemented between different digital twins. This helps in obtaining the global information for digital twins, thereby extending the perception range of vehicles and enabling the optimal decision.

Intelligence deployment: The modeling accuracy for physical entity determines the performance of digital twin. Traditional mathematical methods fail to represent accurately physical entity with certain assumptions. In addition, traditional mathematical methods can not provide the optimal resource allocation decision in time-varying and randomness vehicular networks. Due to the remarkable advantages in analyzing, predicting, judging and controlling, artificial intelligent is the best option. Limited by the resources for vehicles, the intelligence is mainly deployed in the cloud and the edge.

III. Computation Offloading in Blockchain-based Vehicular Digital Twin Networks

Based on the digital twin technology, the blockchain-enabled vehicular network can be mapped to the virtual network, which includes vehicle digital twin, blockchain digital twin and RSU digital twin, as shown in Fig.2. Blockchain performs operations such as generation block, transaction publishing, and digital signatures. Computation offloading is implemented based on the cloud-edge-end collaboration. The blockchain system and the collaborative computing system are coupled, inevitably leading to resource competition. Suffering from the limited computing capacity of RSU, this will result in performance degradation. Therefore, the resource allocation should strike a balance between the blockchain system performance and the collaborative computing system performance. Specially, considering that untrusted computing nodes may cause the leakage of user privacy data, it is crucial to call trusted nodes to perform tasks. The optimal resource allocation decision is made by using intelligent algorithms.

A. *Trust evaluation*

The collaborative computing aims to make full use of available idle resources for task implementation. The selection

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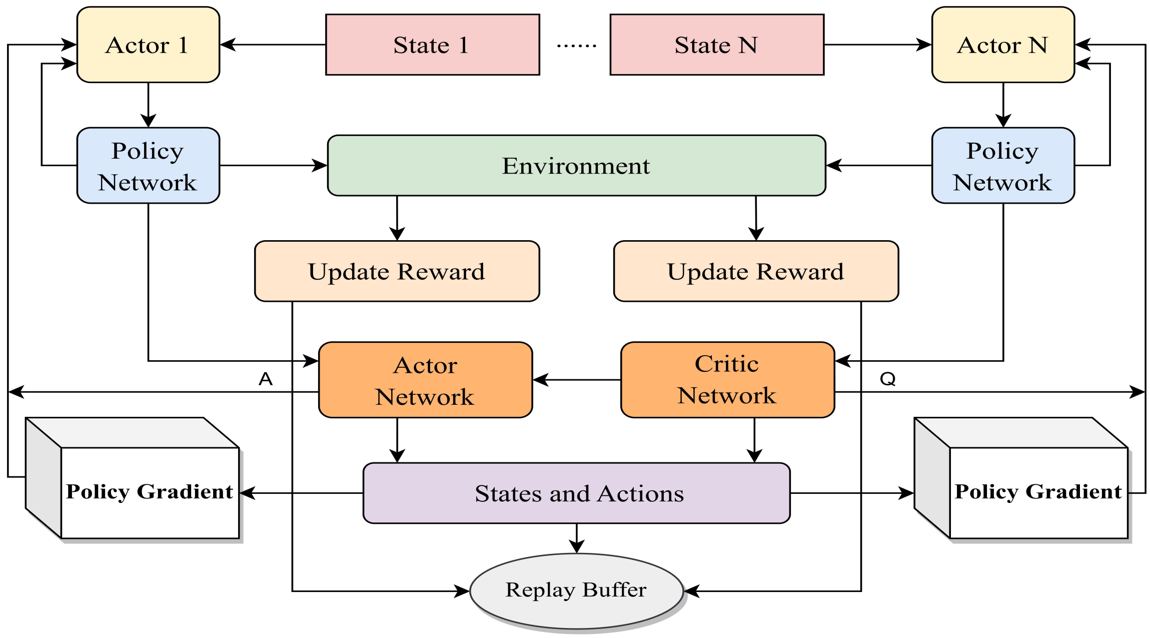

Fig. 3: The workflow of the used intelligent algorithm

of computing node is critical for collaborative computing. In order to guarantee the computing performance in terms of efficiency, reliability and security, it is required to evaluate the computing node from different aspects, including identify trust, behavior trust and ability trust. The reputation evaluation can be implemented for each computing node using multi-index fusion as the guidance of selecting the suitable service node.

1) Identity trust: After a vehicle obtains the identity information certificate from a trusted third party, it uploads this certificate to the blockchain. The blockchain shares the credential information on the chain through consensus. Benefiting from the transparency of blockchain, the vehicle credential information is stored in ciphertext to protect the user private data. When invoking this vehicle for task calculation, its identity can be proved through the blockchain.

2) Behavior trust: By analyzing the communication and computing data of vehicles and RSUs, the behavioral credibility attributes of vehicles and RUSs are constructed according to their interactive environments. The trusted attributes of computing nodes are stored through the blockchain. The trust evaluation for each node behavior is conducted by accessing the trust attributes of computing node's behaviors.

3) Ability trust: Each computing node has the opportunity to participate in task implement if it has sufficient computation resources, which can be reflected by its load. In comparison, the light load node is preferred for task processing.

B. Digital twin and blockchain-empowered resource scheduling

1) Blockchain-enabled resource scheduling: Each RSU deploys an edge server, which is responsible of calculating tasks and maintaining the blockchain system's operation. The blockchain system is used to evaluate the reputation of each user by packaging the calculation transaction on the chain. The node reputation should be considered when implementing resource scheduling in order to protect the data privacy and security.

Computing tasks are completed collaboratively by vehicles or RSUs. This process incurs the communication latency and the computation latency. In addition to task processing, running the blockchain, which involves blockchain generation, consensus and signature, also consumes certain costs. In order to evaluate the blockchain system's performance, the throughput is regarded as an important metric. Then, the task processing delay and the blockchain throughput can be jointly optimized to improve the quality of experience (QoE).

2) Digital twin-enabled service guarantee: Given the large scale and high dynamic of vehicular networks, we adopt the multi-level digital twin network strategy to support diverse applications, which includes the edge digital twins and cloud digital twins. The former are deployed in the edge layer, which facilitates the real-time operations, while the latter are deployed in the cloud layer, which offers the global network management an optimization by aggregating the required information from different edge digital twins. The virtual network obtains the data from the physical network in real time and construct a virtual QoE model. The bidirectional interaction between physical entities and digital twins include the data exchange and QoE model presentation. The QoE model is built in real time by evaluating the task processing delay and the blockchain throughput. We introduce the user engagement into the digital twins, which is utilized to compute the QoE reference value. By utilizing the nonlinear regression method, the parameters of the QoE model are achieved in the digital twins.

C. *Artificial intelligence-enabled decision making*

To adapt to the dynamic network environment, the formulated optimization problem is modeled as an Markov decision process (MDP) process. We adopt a Multi-Agent Deep Deterministic Policy Gradient (MADDPG) algorithm for decision making [15], which has upstanding performance in resource scheduling, as shown in Fig.3. Similar to reinforcement learning, the agent interacts with the environment and receives rewards according to the principles of MDPs. Compared with single-agent algorithms, MADDPG is more suited to vehicular networks for the reason that this algorithm contributes to modeling the complex interactions and coordination among multiple agents, which facilitates the accurate representation of vehicle networks where vehicles and infrastructures interact collaboratively. Besides, the algorithm is leveraged to continuously accumulate experience and make better decisions that adapt to the environment.

IV. Open Issues

In this section, several important open issues are presented in detail for further investigation.

Connectivity. The high mobility of nodes will cause intermittent connectivity, which may interrupt the ongoing data transmission between nodes. This is unfavourable for the consensus-building in blockchain system and the data interaction between physical entities and digital twins. Therefore, the mobility of nodes should be considered when running the blockchain-based vehicular digital twin system. The connectivity between nodes is required to support the successful data interaction.

Resource measurement. Vehicular computation resources are widely distributed in cloud, edge and end, which include different types, e.g., CPU, GPU and FPGA , thereby exhibiting ubiquitous and heterogeneous. These computation resources are measured using different units. How to aggregate them and map them to a unified measurement unit for shielding their differences is of great importance for efficient task scheduling and resource management.

High fidelity. Digital twin is the digital representation of physical entity in virtual space, which can be used to reflect the state and behavior of physical entity in the real environment. Therefore, its performance is determined by the fidelity level to physical entity. Due to the complex characteristics of physical entity, multi-physics multi-scale integrated modeling is a promising solution to achieve high fidelity, promting accurate management decisions.

Real-time. The real-time is an important indicator to measure the digital twin performance, which is dependent on the efficient data interaction between physical entities and digital twins and the high computing performance for running digital twin. The former contributes to reducing the data transmission latency with the support of reliable transmission network, and the latter can greatly improve the task execution speed by strengthening the computation platform and optimizing the data structure and algorithm structure.

Incentive scheme. Resource sharing and collaboration is viatl to run distributing computing, digital twin and blockchain systems. Given the selfishness of nodes, an incentive scheme should be provided to ensure their sharing benefits. Each node can get certain income once sharing its resources, by which nodes are willing to participate in task computation. Therefore, how to evaluate the contributions of nodes is of importance for the incentive scheme design.

V. Numerical Results

In this section, the proposed computation offloading model is evaluated by simulation experiments to demonstrate the performance of our blockchain-enabled vehicular digital twin network architecture.

The simulation runs on the WIndows 10 system, and its CPU and GPU versions are 10900 and RTX 3060 respectively. The framework of deep learning network uses Pytorch 1.13.1. The considered vehicular network system includes 10-15 randomly moving vehicles, 8 RSUs, and a cloud server, where each RSU deploys an edge server. Only trusted nodes are allowed to participate in task processing which can be determined using the blockchain. The MADDPG algorithm is employed to find the offloading decision assisted by the digital twin. For the MADDPG algorithm, the initialization settings for relevant parameters are as follows: the discount factor is set to 0.80; the batch size for each training sample is set to 2048; the size of the replay buffer is set to 10^5, and the network parameters are updated every time the number of samples added to the replay buffer reaches 64; the agent's training policy is parameterized by a two-layer MLP, each layer containing 64 units, which uses ReLU as the activation function and Adam as the optimizer to update the target network with a learning rate of 0.10.

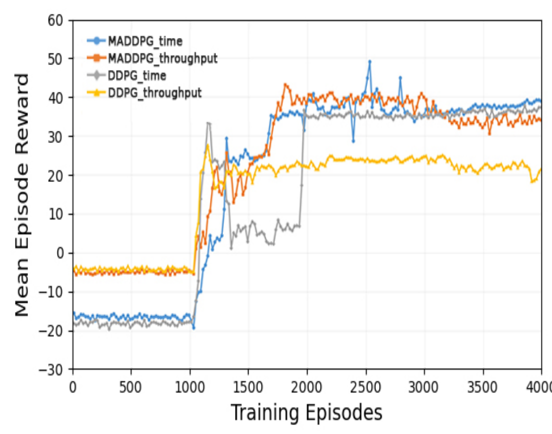

Fig. 4: Comparison of mean episode reward

Fig. 4 represents the mean episode reward by changing the number of training episodes, where the reward is characterised by the delay and throughput, respectively, and the delay and throughput are normalized to make their dimension unity. The Deep Deterministic Policy Gradient (DDPG) algorithm is selected for performance comparison with our MADDPG scheme. It can be found that because the delay performance and the throughput performance is closely coupling, they should be well balanced to meet the system requirements. Fig.

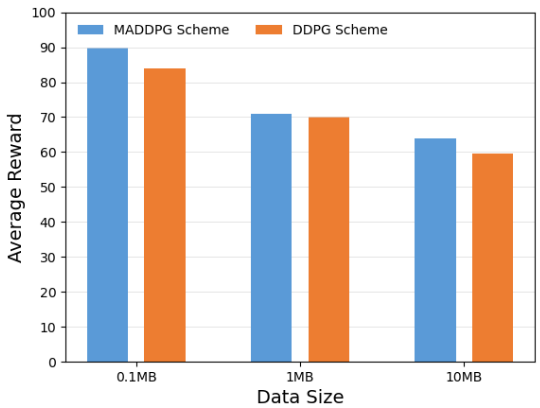

Fig. 5: Comparison of average reward

5 show the average reward by varying the offloaded task's data size. This reward is set based on the weighted sum of the task processing delay and the blockchain's throughput, and the weight of the task processing delay is negative. From Fig. 5, it can be observed that our MADDPG approach achieve the better performance due to its advantages in modeling complex interaction and coordination in vehicular networks.

VI. Conclusion and Future Work

In this paper, we have designed a novel blockchain-based vehicular digital twin architecture with the aim to encourage the resource sharing among nodes using blockchain and guarantee the real-time decision making assisted by digital twin. On basis of this architecture, we have further presented a trusted resource allocation model to meet diverse user demands under secure and reliable networks. Finally, open issues are discussed. For future work, we will investigate connectivity-aware intelligent allocation in the presented model by taking account to the mobility and leveraging distributed learning.

VII. Acknowledgement

This work is supported by the National Key Research and Development Program of China under Grant 2021YFB2700600, the National Natural Science Foundation of China under Grants 62001357, 62102297 and 62132013, the Key Research and Development Programs of Shaanxi under Grant 2021ZDLGY06-03, the Natural Science Foundation of Guangdong Province of China under Grant 2022A1515010988, the Fundamental Research Funds for the Central Universities under Grants ZYTS23180 and ZYTS23178, and the Open Project of Shaanxi Key Laboratory of Information Communication Network and Security under Grant ICNS202005.

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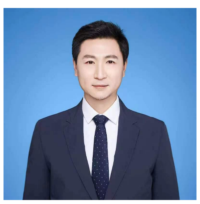

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