Received October 13, 2020, accepted November 1, 2020, date of publication November 6, 2020, date of current version November 18, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3036399

Empowering Blockchain in Vehicular Environments With Decentralized Edges

SU BUDA[1], CELIMUGE WU[2], (Senior Member, IEEE), WUGEDELE BAO[1], SIRI GULENG[1], JIEFANG ZHANG[3], KOK-LIM ALVIN YAU[4], (Senior Member, IEEE), AND YUSHENG JI[5], (Senior Member, IEEE)

[1]School of Computer Science and Information Engineering, Hohhot Minzu College, Hohhot 010051, China
[2]Graduate School of Informatics and Engineering, The University of Electro-Communications, Tokyo 182-8585, Japan
[3]Institute of Intelligent Media Technology, Communication University of Zhejiang, Zhejiang 310018, China
[4]School of Science and Technology, Sunway University, Bandar Sunway 47500, Malaysia
[5]Information Systems Architecture Research Division, National Institute of Informatics, Tokyo 101-8430, Japan

Corresponding author: Celimuge Wu (celimuge@uec.ac.jp)

This work was supported in part by ROIS NII Open Collaborative Research under Grant 2020-20S0502, in part by the Inner Mongolia Natural Science Foundation under Grant 2019MS06035, in part by the Inner Mongolia Science and Technology Major Project, China, in part by the Public Welfare Technology Application Research Project of Zhejiang Province, China, under Grant LGG18F020004, and in part by JSPS KAKENHI, Japan, under Grant 20H00592.

ABSTRACT In order to enable emerging vehicular Internet of Things (IoT) applications, including fully autonomous driving, more efforts should be done in collecting driving experiences in different road situations. This requires the exchange of information between vehicles as each vehicle has very limited experience. Due to the decentralized feature of vehicular environment, an efficient management of collaborative behaviors among the vehicles becomes particularly important. Blockchain has been attracting great interest recently because it provides a way to reach consensus in decentralized systems. However, existing blockchain systems assume high communication capabilities for vehicles, which is difficult to achieve in a decentralized vehicular environment. Existing studies also assume the existence of networking infrastructure, such as roadside units (RSU). In this paper, we propose a scheme to empower blockchain in vehicular environments without depending on the existing networking infrastructure. The proposed scheme uses a distributed clustering approach to select some vehicles as edge nodes, and the edge nodes maintain the blockchain used to record transactions in a decentralized way. The proposed scheme employs a distributed approach that guides vehicle clustering with the consideration of multiple metrics based on a fuzzy logic algorithm. By using the edge nodes, the proposed scheme solves the communication problem of maintaining a blockchain in a totally decentralized vehicular environment. We use computer simulations to clarify the performance of the proposed scheme in terms of communication performance by comparing it with existing baselines.

INDEX TERMS Vehicular IoT, blockchain technology, edge computing, fuzzy logic.

I. INTRODUCTION

Current autonomous vehicles are equipped with sensing and computing technologies to achieve intelligence. However, vehicles are unable to detect events happening behind obstacles, including other vehicles, even when using well-known sensor devices, such as LiDAR (laser imaging detection and ranging) and cameras. Therefore, collaboration among vehicles is becoming more important with the emergence of new vehicular IoT applications, particularly collaborative autonomous driving. By exchanging information among vehicles, the perception capability of each vehicle can be significantly improved, which makes it possible to collect more accurate information and select more appropriate actions in complex road scenarios. While most existing studies widely use vehicle-to-vehicle (V2V) communications to achieve collaborations and improve road safety and driving experience [1], all vehicular nodes have been assumed to be trustable, and so the consensus among the vehicles can be easily achieved. However, the vehicular environment is decentralized in nature, especially in some cases, there is no roadside unit (RSU) or other communication

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

infrastructure available. The problem of how to reach a global consensus in decentralized vehicular environments must be seriously discussed and addressed. A realistic vehicular networking scenario should be considered in the design of a decentralized system.

Blockchain is a technology that can maintain a distributed ledger without depending on an authorized third party. Blockchain is currently widely deployed for supporting cryptocurrencies, including bitcoin [2], Ethereum [3], and so forth. Blockchain is also attracting interest in a wide range of decentralized systems [4], such as healthcare, supply chain management, digital rights management, IoT, etc. As blockchain possess the right characteristics, particularly decentralization, irrevocability, and fault tolerance, it has been proposed for vehicular IoT applications. However, existing studies on the use of blockchain for vehicular IoT have some limitations. First, in these studies, the maintenance of blockchain is conducted by pre-installed infrastructure, such as RSUs or cloud servers. Due to the lack of networking infrastructure in some scenarios, it is important to discuss how to enable blockchain in a decentralized network. Second, while the maintenance of the blockchain requires a high communication bandwidth in a wireless environment, existing studies have yet to address the high overhead issue of blockchain. In other words, most blockchain studies have been focusing on the advantage of using blockchain in designing tamper-resistant and fault-tolerant systems without considering a bandwidth limited vehicular environment.

Various efforts of improving V2V communications have been made. These studies address the communication problem from different perspectives, namely physical layer issues, resource allocation, routing, and applications. Some studies discuss how to efficiently enable different types of communication approaches in multi-access environments in order to improve the spectrum utilization efficiency. Edge computing is one of the important technologies that improves communication performance by performing computing tasks or data caching near the end users. While edge computing is becoming popular, none of existing studies discusses the communication challenges of deploying blockchain in a vehicular environment. It is important to design a communication efficient scheme for exchanging the information related to the distributed ledgers in order to facilitate the blockchain in decentralized environments. This is difficult to achieve by the conventional edge computing framework where the computing tasks are conducted at RSUs or cloud servers. In order to fully support a decentralized and efficient computing, some vehicles can be used as edge computing nodes (edge vehicles) to maintain blockchain and provide blockchain services to other vehicles (ordinary vehicles). However, an efficient selection of edge vehicles is challenging due to the dynamic vehicular environments.

In this paper, we discuss how to enable a blockchain system in a decentralized vehicular network, and propose an edge computing-based scheme to empower blockchain. The main contributions of the paper are summarized as follows:

- We propose an edge computing-based scheme to enable a lightweight blockchain in decentralized vehicular environments. The proposed scheme reduces the communication overhead required for blockchain maintenance by implementing edge computing at selected vehicles.
- We propose a fuzzy logic-based edge node selection approach that takes into account different kinds of factors, specifically the vehicle velocity, vehicle distribution, and the link quality between edge vehicles and ordinary vehicles.
- We generate realistic vehicular networking scenarios to evaluate the proposed scheme in terms of communication overhead incurred in maintaining the blockchain system by comparing its performance with baseline approaches.

The remainder of this article is organized as follows. We first briefly introduce existing studies in Section II. Then, in Section III, the proposed scheme is explained with details. We discuss simulation results in Section IV. Finally, the conclusion of the paper is presented in Section V. The terms ‘‘vehicle’’ and ‘‘node’’ are used interchangeably throughout the paper.

II. RELATED WORK

A. BLOCKCHAIN FOR VEHICULAR IoT

We explain existing research efforts on blockchain for vehicular IoT by classifying related studies according to different IoT layers, namely the *perception* layer that accounts for understanding the environmental status, the *networking* layer for information exchange, and the *application* layer.

1) PERCEPTION LAYER

The complex vehicular environment poses challenges in understanding some information of the environment. By sharing sensor information among vehicles, the cooperation enables a more accurate understanding of the complex environment. However, each vehicle must judge whether the information shared by other vehicles is trustable or not [5]. Recent studies on the perception layer issues are mainly related to trust management. In [6], a blockchain is used to manage the trust of vehicles, whereby RSUs create and validate blocks. The trust of a vehicle is calculated by considering the sensor information received from neighboring vehicles. By using the transparency and irrevocability feature of blockchain, each vehicle is aware of the trust it has placed in other vehicles, which facilitates a more efficient collaboration among vehicles.

Yang *et al.* [7] discuss how to validate a message indicating a traffic event based on the blockchain technology. They use the proof-of-event (PoE) consensus approach to evaluate the trust of each vehicle based on the information received from periodic beacon messages. In [8], a similar blockchain-based trust evaluation scheme is proposed. Each RSU collects messages from multiple vehicles, and reaches a decision about the trust of each vehicle after analyzing the reports (sensor information) from the vehicles. Xie *et al.* [9] discuss the video sharing issue in vehicular networks, whereby RSUs evaluate the trustworthiness of vehicles by checking the video and other information exchanged between vehicles. The trust data are recorded in a blockchain system to maintain the trust values in a transparent and decentralized way. In [10], a blockchain is used to store position errors in order to obtain and share accurate position information among vehicles. All these studies use RSUs to maintain the blockchains, and so the systems must be equipped with networking infrastructure.

2) NETWORKING LAYER

Several studies have employed blockchain to improve the networking performance in vehicular environments. The blockchain is used for different purposes, including achieving decentralization [11], [12], improving security [13]–[17], and incentivizing cooperation [18]. In [11], a blockchain-based scheme is proposed to enable data sharing without a third-party service provider. Zhang *et al.* [12] discuss the use of blockchain in software-defined vehicular networks.

In [13], Zhang *et al.* utilize the irrevocability feature of blockchain to handle the malicious tampering attack in vehicular ad hoc networks (VANETs). Rawat *et al.* [14] discuss the use of blockchain to provide secure data communications in content-centric vehicular networks. In [15], the authors discuss using blockchain to safeguard data delivery by evaluating the trustworthiness of each vehicle based on cooperativeness, honestness, and task completion quality. Chen *et al.* [16] propose a blockchain-based data sharing approach that can detect fake messages by using blockchain to record data sharing histories. In [17], a blockchain is used to mitigate the content poisoning attack in unmanned aerial vehicle (UAV) networks. Li *et al.* [18] discuss the use of blockchain in incentivizing packet forwarding at each vehicle.

3) APPLICATION LAYER

A large portion of application layer studies have put focus on designing a decentralized system using blockchain technologies. Pokhrel and Choi [19] discuss the use of blockchain in improving federated learning (FL), which is a form of distributed machine learning, in vehicular environments. They use blockchain to maintain different versions of learning models (i.e, the parameters for different training steps) in order to verify local updates. In [20], a consortium blockchain is employed to control traffic signals based on VANET technologies. The main purpose of the blockchain is to achieve a resilient decentralized traffic signal control system. A blockchain-based scheme for data sharing in UAV-assisted vehicular networks is proposed by Su *et al.* [21]. A blockchain is used by Shen *et al.* [22] to avoid sending data to a third party while training a support vector machine (SVM). Similarly, [22] uses blockchain to avoid sharing data with the central server. Ma *et al.* [23] use blockchain for security key management in VANETs. Blockchain is used to maintain public keys in a decentralized way, and a smart contract is used to speed up the key registration process.

Blockchain has also been widely used in solving the security or privacy problem of vehicular IoT applications. In [24], Iqbal *et al.* introduce a trust management scheme for VANETs based on blockchain technologies. They consider a task offloading scenario where blockchain is used to record the reputation of each vehicle. Huang *et al.* [25] consider a task offloading scenario where parked vehicles serve as computing servers that offload computation using blockchain in a decentralized manner. Liang *et al.* [26] propose a blockchain-based decentralized intrusion detection system (IDS) where blockchain is used to record intrusion samples and their respective detection approaches. An authentication scheme based on blockchain is proposed in [27]. Liao *et al.* [28] exploit blockchain to facilitate fair and secure task offloading in vehicular fog computing. Zhou *et al.* [29] develop a secure energy trading mechanism for vehicle-to-grid cyber-physical systems based on a consortium blockchain.

There are also many proposals discussing about the deployment of blockchain for audit purpose. Abbade *et al.* [30] use a blockchain system to monitor the vehicle data in order to avoid odometer fraud. Kong *et al.* [31] employ a permissioned blockchain to enable transparent data collection from vehicles to RSUs. Singh *et al.* [32] use a blockchain to manage data processing behaviors in vehicular environments. In [33], a blockchain is used to record vehicle data for the purpose of forensics applications in vehicular IoT.

B. EDGE COMPUTING FOR VEHICULAR IoT

Mobile edge computing (MEC) [34]–[42] is an approach to improve the performance of dynamic and resource limited vehicular networks. By enabling efficient computing and data caching at edge nodes, MEC can achieve a shorter delay and higher throughput. Most studies on edge computing discuss the computation offloading problem to edge nodes. Wang *et al.* [36] discuss the computation offloading issues by using a game theoretic approach. Liu *et al.* [37] conduct computation offloading decisions based on the inter-vehicle distance, application constraints, communication capability, and computing resources.

Many studies discuss about using some vehicles as edge vehicles to perform edge computing. Task offloading problem between different edge vehicles is discussed [38]. In addition to these research efforts on computation offloading, the use of edge computing in data caching is another important research topic. Tan and Hu [39] solve the joint allocation of caching and computing resources using a deep reinforcement learning approach. A similar problem of allocating computing and caching resources in vehicular edge computing is discussed in [40].

Some studies also discuss the use of edge vehicles in improving collaborative packet forwarding in vehicular networks. In [41], a collaborative data transmission scheme for multi-access vehicular networks is proposed to efficiently utilize multiple types of communication resources using edge computing. An integration of licensed and unlicensed spectrum at edge vehicles is discussed in [42].

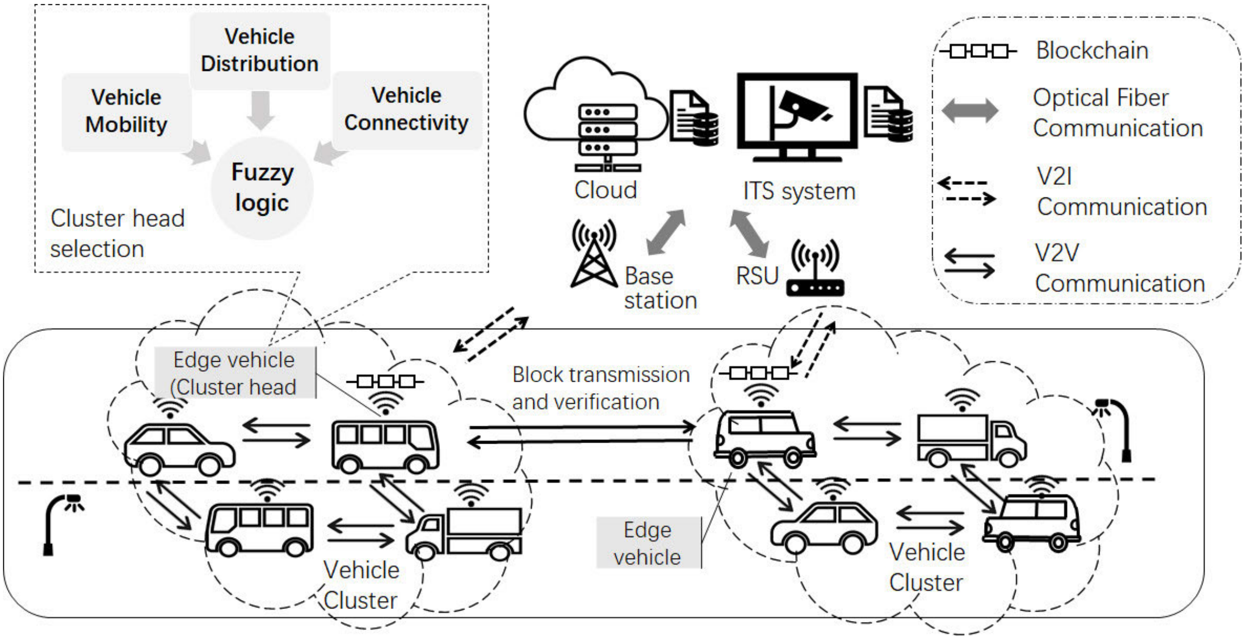


FIGURE 1. Blockchain for vehicular IoT, and the proposed scheme that enables blockchain in V2V decentralized networks.

III. PROPOSED SCHEME

A. OVERVIEW OF THE PROPOSED SCHEME

Figure 1 shows the proposed scheme and its relationship with vehicular IoT. The vehicular IoT includes different types of communications, specifically, V2V communications, vehicle-to-infrastructure (V2I) communications, and the communication between network infrastructure. In this paper, we discuss the challenges of enabling a blockchain system in scenarios with V2V communications only. These scenarios cover the trust management issue for V2V communications, privacy-aware data sharing, collaborative autonomous driving, and so forth. The proposed scheme can be integrated with existing systems without contradicting with them despite sharing the same network infrastructure in order to provide a more advanced vehicular IoT system.

We assume that each vehicle is equipped with a positioning device and a wireless interface that can be used to communicate with other vehicles in the proximity. We consider a totally distributed scenario without RSU. Collaboration among vehicles is achieved by direct communications among vehicles. The proposed scheme consists of two components. The first component is the edge node selection that uses a distributed vehicle clustering algorithm based on fuzzy logic. The second component is the edge-based maintenance of blockchain. We do not assume any particular communication interface for vehicles as the proposed scheme can be applied with any communication standards, including IEEE 802.11p and cellular V2X sidelink interface.

As shown in Figure 1, the proposed scheme first selects edge vehicles by considering the vehicle velocity, vehicle distribution, and connectivity among vehicles. These three metrics are jointly considered using a fuzzy logic algorithm where the information is acquired by exchanging beacon messages among neighbors. The selected edge vehicles work as miners and maintain a blockchain that can be used to save the global consensus in a decentralized approach. All vehicles can be the users of the blockchain system. When a vehicle wants to make a transaction, the vehicle only needs to send a request to a neighboring edge vehicle. The edge vehicles are selected based on a condition that each non-edge vehicle always can directly connect with at least one edge vehicle. By using the edge vehicle-based blockchain maintenance approach, the proposed scheme can reduce the communication overhead incurred in maintaining the blockchain, making the blockchain possible in a decentralized vehicular environments.

B. VEHICLE CLUSTERING AND THE EDGE VEHICLE SELECTION

We conduct a distributed clustering of vehicles based on the one-hop information exchange among neighbors. The cluster head vehicles assume the role of edge vehicles. After selecting the edge vehicles in a decentralized manner, the proposed scheme handles blockchain maintenance based on the collaboration among the edge vehicles. All requests for adding transactions to the blockchain must go through edge vehicles. Therefore, the blockchain system is much more efficient than a purely distributed maintenance system for ledgers without losing the decentralized feature of blockchain. The cluster-based approach is particularly effective in terms of reducing the communication overhead incurred by the maintenance process of blockchain.

The basic rationale behind the use of clustering is to handle mobility and improve the wireless resource utilization efficiency. First, by caching some contents or conducting some computing tasks on cluster head nodes, the end users can retrieve contents or information from the vicinity, which can improve communication efficiency in a mobile environment. Second, the same cluster head nodes can be used for different V2V traffic flows to reduce the number of transmitters significantly, leading to a much higher wireless resource utilization efficiency. The cluster formation algorithm must consider the cluster formation overhead, the lifetime of a cluster, the communication bandwidth between the cluster head and cluster members. Due to the different mobility levels and node densities of vehicles, it is difficult to find a simple mathematical solution to define the clustering criteria.

We use a fuzzy logic-based approach to jointly address the vehicle mobility, vehicle distribution, and the connectivity among vehicles, which are expressed by the stability factor, topology factor, and connectivity factor, respectively.

1) STABILITY FACTOR

For a node x, the stability factor is calculated as follows.

$$SF(x) = 1 - \frac{||\upsilon(x)| - \text{avg}_{y \in N_x} |\upsilon(y)||}{\max_{y \in N_x} |\upsilon(y)|} \tag{1}$$

where $\upsilon(\cdot)$ denotes vehicle velocity and N_x is a set that includes x and all its one-hop neighbors. We use *avg* and *max* to show the average value and the maximal value, respectively. The value of SF shows the stability level, where a higher value means a more stable level. Each node attaches information to beacon messages, including the velocity value $|\upsilon(x)|$ of node x, the average velocity of vehicles $\text{avg}_{y \in N_x} |\upsilon(y)|$ in one-hop region, and the maximal velocity of vehicles $\max_{y \in N_x} |\upsilon(y)|$ in one-hop region. SF is updated at every predefined interval (one second by default) by using a weighted exponential moving average approach with a smooth factor α (0.7 by default) as shown in Eq. (2).

$$SF_i(x) \leftarrow (1 - \alpha) \times SF_{i-1}(x) + \alpha \times SF_i(x). \tag{2}$$

2) TOPOLOGY FACTOR

Topology factor TF indicates the distribution of vehicles as follows:

$$TF(x) = \min\left(1, \frac{c(x)}{|N_x|}\right) \tag{3}$$

where $c(x)$ denotes the number of vehicles moving in the same direction with node x in the one-hop region of node x. A vehicle with a higher $c(x)$ value is more likely to be elected as a cluster head because the vehicle can generate a more stable cluster due to the stability of its relative mobility with other vehicles. Each vehicle sends the number of neighboring vehicles and $c(\cdot)$ to its neighbors by attaching these information to the beacon messages. Similar to SF, TF is updated periodically as shown in Eq. (4).

$$TF_i(x) \leftarrow (1 - \alpha) \times TF_{i-1}(x) + \alpha \times TF_i(x). \tag{4}$$

3) CONNECTIVITY FACTOR

Connectivity factor $CF(x)$ considers the link status between node x and its members. $CF(x)$ is calculated by using the ratio of "the number of beacon messages received from all one-hop neighbors at node x" to "the number of beacon messages sent by all one-hop neighbors" as follows:

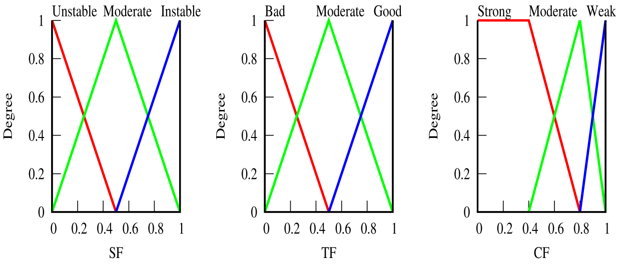


FIGURE 2. Fuzzy membership functions (left: *SF*, middle: *TF*, right: *CF*).

$$CF(x) = \frac{\#\text{ of beacons received at node } x}{\#\text{ of beacons sent by the neighbors of } x}. \tag{5}$$

4) MEMBERSHIP FUNCTIONS

The membership functions are defined in Figure 2. The output membership function for defuzzification is defined as the same as that in [43].

5) FUZZY RULES

The fuzzy rule is defined in Table 1.

TABLE 1. Fuzzy rules.

	Stability	Topology	Connectivity	Rank
Rule1	Stable	Good	Strong	Perfect
Rule2	Stable	Good	Moderate	Good
Rule3	Stable	Good	Weak	Unpreferable
Rule4	Stable	Moderate	Strong	Good
Rule5	Stable	Moderate	Moderate	Acceptable
Rule6	Stable	Moderate	Weak	Bad
Rule7	Stable	Bad	Strong	Unpreferable
Rule8	Stable	Bad	Moderate	Bad
Rule9	Stable	Bad	Weak	VeryBad
Rule10	Moderate	Good	Strong	Good
Rule11	Moderate	Good	Moderate	Acceptable
Rule12	Moderate	Good	Weak	Bad
Rule13	Moderate	Moderate	Strong	Acceptable
Rule14	Moderate	Moderate	Moderate	Unpreferable
Rule15	Moderate	Moderate	Weak	Bad
Rule16	Moderate	Bad	Strong	Bad
Rule17	Moderate	Bad	Moderate	Bad
Rule18	Moderate	Bad	Weak	VeryBad
Rule19	Instable	Good	Strong	Unpreferable
Rule20	Instable	Good	Moderate	Bad
Rule21	Instable	Good	Weak	VeryBad
Rule22	Instable	Moderate	Strong	Bad
Rule23	Instable	Moderate	Moderate	Bad
Rule24	Instable	Moderate	Weak	VeryBad
Rule25	Instable	Bad	Strong	Bad
Rule26	Instable	Bad	Moderate	VeryBad
Rule27	Instable	Bad	Weak	VeryBad

6) CONNECTIVITY BETWEEN EDGE VEHICLES

In the proposed scheme, the edge vehicles collaborate with each other to maintain the blockchain system. The link quality between two neighboring edge nodes is also considered in the edge node selection process. As mentioned before, each

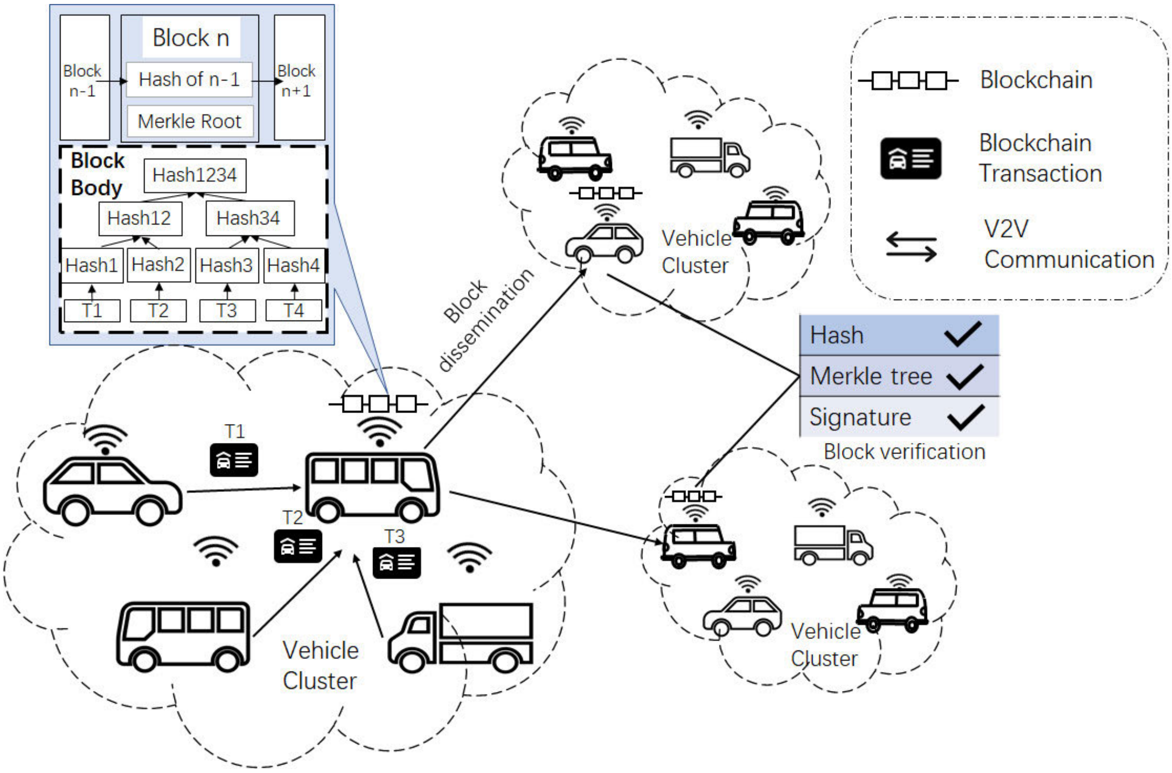


FIGURE 3. Block maintenance in the proposed scheme.

vehicle uses the fuzzy logic-based approach to calculate a competency value that indicates whether it is suitable to serve as an edge vehicle or not. If a vehicle has the largest competency value in its vicinity (i.e., within $\frac{1}{4}R$ region where R is the average communication range), the vehicle declares itself as an edge node. This ensures that the distance between two edge vehicles is smaller than R. If the vehicles are uniformly distributed, then there is at least a single edge vehicle within a $\frac{1}{2}R$ region, resulting in a stable connection between any two neighboring vehicles.

C. MAINTENANCE OF BLOCKCHAIN

The design of a consensus mechanism directly affects the block processing performance of a blockchain system. Proof-of-work (PoW) is the first and widely used consensus approach in blockchain systems. While PoW is effective in reaching consensus, it wastes computing power and time. Therefore, approaches with lower computational overheads, such as proof-of-stake (PoS), have attracted a large degree of attention. IOTA [44] uses a directed acyclic graph (DAG)-based consensus algorithm to achieve a much higher transaction throughput than other consensus algorithms. This paper addresses the communication overhead and designs a network architecture for enabling blockchain in vehicular environments, while the selection of an efficient consensus algorithm is left as a future study.

As shown in Figure 3, vehicles are grouped into different clusters, where each cluster has a cluster head serving as an edge node. When a vehicle wants to conduct transactions, it sends a request to the edge node of the same cluster. Then, the edge node includes the transaction into a block and proceeds with adding the block to the blockchain once the block is verified by other edge nodes based on a certain consensus algorithm. The information of blockchain is shared by all the edge nodes, which are responsible for maintaining the blockchain. As mentioned before, the proposed scheme considers the connectivity between any two neighboring edge nodes during cluster formation, and therefore the proposed scheme is capable of providing efficient communications among blockchain maintainers (edge nodes). Since all users (i.e., vehicles) can find an edge node among its neighbors, each transaction can be sent to the blockchain system quickly with a low communication overhead. In addition, only edge nodes maintain the distributed ledger, contributing to a low communication and storage overhead.

IV. PERFORMANCE ANALYSIS

We generate a realistic vehicular scenario network simulator ns-2 using the same approach in [43]. The proposed scheme is compared with the "Conventional Edge," "Purely Distributed," and "Random Edge" approaches. In the "Conventional Edge" approach, edge vehicles are used to maintain the blockchain, and the edge vehicles are selected one by one among neighboring vehicles starting from the first cluster head, which is also an edge vehicle selected according to a set of predefined rule (e.g., including a random selection as used in this simulation). In the "Purely Distributed" approach, all vehicles participate in the maintenance of

TABLE 2. Simulation Environment.

Road topology	2000m, 6 lanes
Number of vehicles	100-500
Vehicle mobility	Freeway model [43]
Vehicle velocity	60–100 km/h
Data rate	IEEE 802.11p MAC (27 Mbps)
Fading model	Nakagami Model
Simulation time	1000 s

TABLE 3. Parameters of the Nakagami Model.

gamma0_	gamma1_	gamma2_	d0_gamma_	d1_gamma_
1.9	3.8	3.8	200	500
m0_	m1_	m2_	d0_m_	d1_m_
1.5	0.75	0.75	80	200

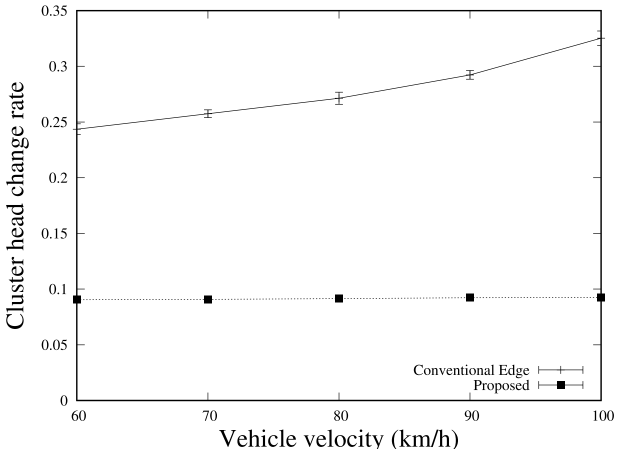


FIGURE 4. Cluster head change rate for different velocities.

the blockchain. In the "Random Edge" approach, vehicles are selected randomly to maintain the blockchain. We consider a freeway road with 3 lanes in each direction, and vehicles have various velocities and densities. The simulation parameters are shown in Table 2. The wireless channel follows the Nakagami model, of which parameters are shown in Table 3. The size of each transaction is 256 bytes, and the block size is 1MB.

A. CLUSTERING EFFICIENCY

First, we evaluate the efficiency of the clustering approach used in the proposed scheme. We introduce a metric called cluster head change rate, which is calculated by $1-\frac{|CH_i \bigcap CH_{i-1}|}{|CH_i \bigcup CH_{i-1}|}$, where CH_i and CH_{i-1} are the current cluster head vehicle set and the previous cluster head vehicle set, respectively [43]. Figure 4 shows the cluster head change rate for different vehicle velocities. The overhead of "Conventional Edge" is sensitive to vehicle velocity because a change of a single cluster head triggers the reselection of all the cluster heads, resulting in a poor performance in a highly mobile environment. In our proposed clustering approach, since fuzzy logic is used to jointly consider the vehicle velocity, vehicle distribution, and the link quality between cluster head and members in the cluster formation, the cluster head change is low for various vehicle velocities. Figure 5 shows the cluster head change rate for different vehicle densities.

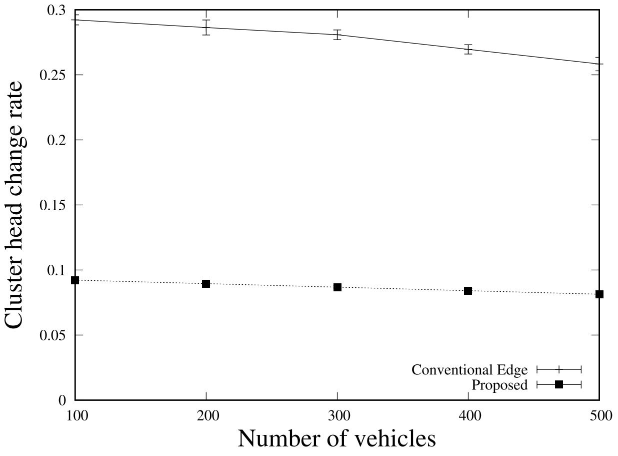


FIGURE 5. Cluster head change rate for different numbers of vehicles.

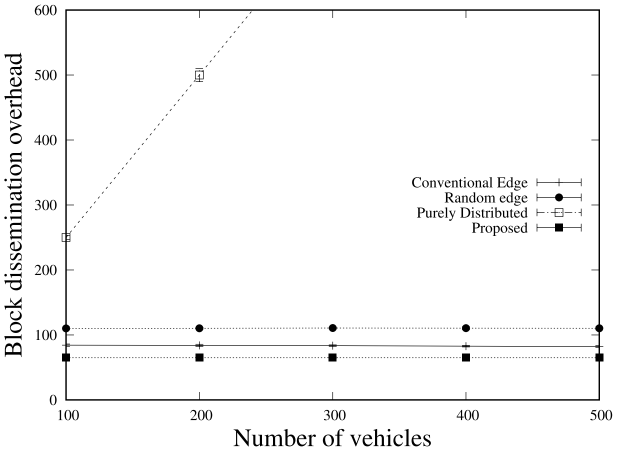


FIGURE 6. Normalized block dissemination overhead for various vehicle densities.

The proposed clustering approach makes decision by observing the information attached in the beacon messages, so the overhead does not increase significantly with node density. Therefore, we observe a stable performance of the proposed scheme in various vehicle densities.

B. BLOCK DISSEMINATION

Figure 6 shows the normalized block dissemination overhead for various vehicle densities. Here, the normalized block dissemination overhead shows the number of transmissions for each block message (message that contains the block information). We observe that "Purely Distributed" incurs a high overhead in disseminating blocks to all nodes. In "Purely Distributed", all vehicles maintain the whole record of the blockchain, which is inefficient and unnecessary. Since the use of edge nodes can reduce the communication overhead in the maintenance of the blockchain, "Random Edge" shows a better performance as compared with "Purely Distributed". However, due to the inefficient random selection of edge nodes, the block transmission may traverse multiple hops before arriving at an edge node. Meanwhile, "Conventional Edge" shows a much better performance than "Purely Distributed" due to fact that the blocks are only transmitted

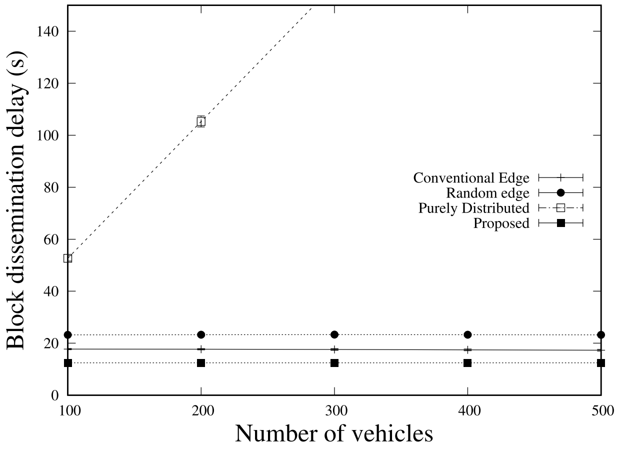


FIGURE 7. Block dissemination delay for various vehicle densities.

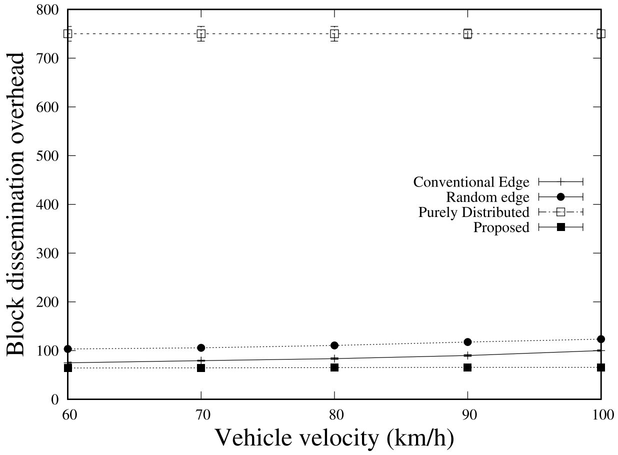


FIGURE 8. Normalized block dissemination overhead for various vehicle velocities.

among different cluster heads. For "Conventional Edge", the change of cluster head nodes increases the number of transmissions. This is because there could be some redundant cluster head nodes resulting from an inefficient cluster head reselection process. By using an edge-based approach, the proposed scheme is more efficient in terms of dissemination of blocks.

Figure 7 shows the block dissemination delay for various vehicle densities. "Purely Distributed" is inefficient as the blocks are disseminated to all vehicles in the network, resulting in an extremely high overhead. This is because all vehicles (as miner nodes) send blocks to all neighboring vehicles, which is unacceptable in vehicular environments where communication bandwidth is limited. "Random Edge" and "Conventional Edge" cannot achieve a satisfactory result because the cluster head selection algorithm is inefficient. The proposed scheme shows the best performance by reducing the cluster head change rate as compared with "Random edge" and "Conventional Edge". With an edge vehicle-based hierarchical approach where the edge vehicles perform the duty of gateways, the proposed scheme can achieve a balanced tradeoff between the volume of transaction records and the transaction delay. Although maintaining all records by all nodes has the shortest transaction delay, it generates a high overhead while distributing the blocks as shown by "Purely Distributed".

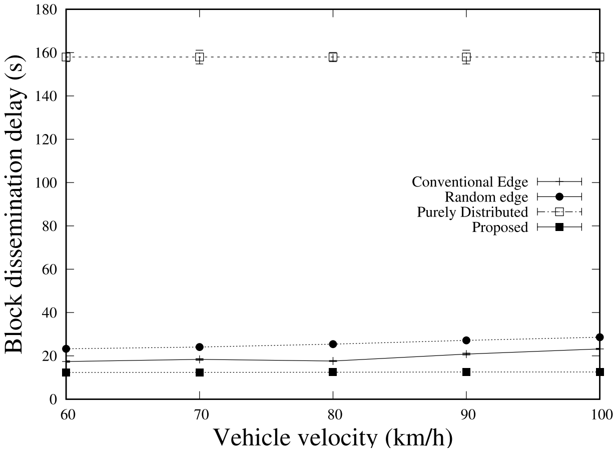


FIGURE 9. Block dissemination delay for various vehicle velocities.

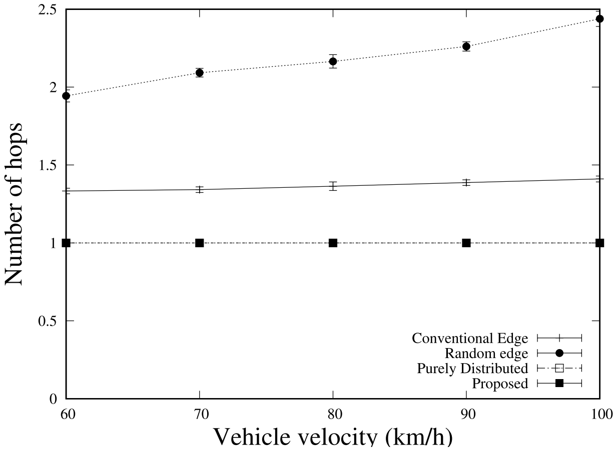


FIGURE 10. Number of hops for transaction requests under various vehicle velocities.

Figure 8 shows the normalized block dissemination overhead for various vehicle velocities. "Purely Distributed" shows the highest overhead in various vehicle velocities. While the performance of "Conventional Edge" is affected by the vehicle velocity, the proposed scheme shows the lowest overhead in various vehicle velocities. The block dissemination overhead directly affects the block dissemination delay. We can observe this in Figure 9 which shows the significance of the proposed scheme in terms of reducing the block dissemination delay in dynamic vehicular environments.

C. TRANSMISSION OVERHEAD FOR TRANSACTION REQUESTS

We also evaluate the performance of transmitting the transaction request messages. In vehicular environments, the users (vehicles) send transaction requests to miners (i.e., edge vehicles in the proposed scheme) to record the transactions in the blockchain. Therefore, it is important to evaluate the overhead incurred in sending the transaction requests. Here, we use the number of hops as the performance metric considering its generality and simplicity in a decentralized network. Figure 10 shows the number of hops traversed by transaction requests under various vehicle velocities. In the proposed scheme, each user is directly connected to an edge vehicle, and so it is possible to reach a miner node within one hop. "Purely Distributed" and the proposed scheme overlap because each vehicle in "Purely Distributed" must transmit transaction requests to its neighbors in order to collect sufficient number of transactions to generate a block with acceptable size.

V. CONCLUSION

We propose an edge computing-based networking scheme for enabling blockchain in decentralized vehicular environments. The proposed scheme selects edge nodes among vehicles by considering the vehicle velocity, vehicle distribution, and the link quality between vehicles. The edge nodes are selected based on a decentralized approach, and the selected edge nodes maintain a blockchain. Realistic computer simulation shows the advantage of the proposed scheme as compared with baseline approaches in terms of communication overhead. The simulation results indicate that the proposed scheme can achieve much efficient block dissemination performance as compared with the baselines, facilitating a blockchain system in decentralized vehicular environments.

REFERENCES

[1] C. Wu, Z. Liu, D. Zhang, T. Yoshinaga, and Y. Ji, "Spatial intelligence toward trustworthy vehicular IoT," *IEEE Commun. Mag.*, vol. 56, no. 10, pp. 22–27, Oct. 2018.

[2] F. Tschorsch and B. Scheuermann, "Bitcoin and beyond: A technical survey on decentralized digital currencies," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 2084–2123, 3rd Quart., 2016.

[3] *Ethereum*. Accessed: Jul. 2020. [Online]. Available: https://ethereum.org/

[4] C. Peng, C. Wu, L. Gao, J. Zhang, K.-L. A. Yau, and Y. Ji, "Blockchain for vehicular Internet of Things: Recent advances and open issues," *Sensors*, vol. 20, no. 18, p. 5079, Sep. 2020.

[5] S. Guleng, C. Wu, X. Chen, X. Wang, T. Yoshinaga, and Y. Ji, "Decentralized trust evaluation in vehicular Internet of Things," *IEEE Access*, vol. 7, pp. 15980–15988, 2019.

[6] Z. Yang, K. Yang, L. Lei, K. Zheng, and V. C. M. Leung, "Blockchain-based decentralized trust management in vehicular networks," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1495–1505, Apr. 2019.

[7] Y.-T. Yang, L.-D. Chou, C.-W. Tseng, F.-H. Tseng, and C.-C. Liu, "Blockchain-based traffic event validation and trust verification for VANETs," *IEEE Access*, vol. 7, pp. 30868–30877, 2019.

[8] X. Liu, H. Huang, F. Xiao, and Z. Ma, "A blockchain-based trust management with conditional privacy-preserving announcement scheme for VANETs," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 4101–4112, May 2020.

[9] L. Xie, Y. Ding, H. Yang, and X. Wang, "Blockchain-based secure and trustworthy Internet of Things in SDN-enabled 5G-VANETs," *IEEE Access*, vol. 7, pp. 56656–56666, 2019.

[10] C. Li, Y. Fu, F. R. Yu, T. H. Luan, and Y. Zhang, "Vehicle position correction: A vehicular blockchain networks-based GPS error sharing framework," *IEEE Trans. Intell. Transp. Syst.*, early access, Jan. 3, 2020, doi: 10.1109/TITS.2019.2961400.

[11] H. Li, L. Pei, D. Liao, S. Chen, M. Zhang, and D. Xu, "FADB: A fine-grained access control scheme for VANET data based on blockchain," *IEEE Access*, vol. 8, pp. 85190–85203, 2020.

[12] D. Zhang, F. R. Yu, and R. Yang, "Blockchain-based distributed software-defined vehicular networks: A dueling deep Q-learning approach," *IEEE Trans. Cognit. Commun. Netw.*, vol. 5, no. 4, pp. 1086–1100, Dec. 2019.

[13] X. Zhang and X. Chen, "Data security sharing and storage based on a consortium blockchain in a vehicular ad-hoc network," *IEEE Access*, vol. 7, pp. 58241–58254, 2019.

[14] D. B. Rawat, R. Doku, A. Adebayo, C. Bajracharya, and C. Kamhoua, "Blockchain enabled named data networking for secure vehicle-to-everything communications," *IEEE Netw.*, vol. 34, no. 5, pp. 185–189, Sep. 2020, doi: 10.1109/MNET.001.1900593.

[15] Y. Wang, Z. Su, K. Zhang, and A. Benslimane, "Challenges and solutions in autonomous driving: A blockchain approach," *IEEE Netw.*, vol. 34, no. 4, pp. 218–226, Jul. 2020, doi: 10.1109/MNET.001.1900504.

[16] C. Chen, C. Wang, T. Qiu, N. Lv, and Q. Pei, "A secure content sharing scheme based on blockchain in vehicular named data networks," *IEEE Trans. Ind. Informat.*, vol. 16, no. 5, pp. 3278–3289, May 2020.

[17] K. Lei, Q. Zhang, J. Lou, B. Bai, and K. Xu, "Securing ICN-based UAV ad hoc networks with blockchain," *IEEE Commun. Mag.*, vol. 57, no. 6, pp. 26–32, Jun. 2019.

[18] L. Li, J. Liu, L. Cheng, S. Qiu, W. Wang, X. Zhang, and Z. Zhang, "CreditCoin: A privacy-preserving blockchain-based incentive announcement network for communications of smart vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 7, pp. 2204–2220, Jul. 2018.

[19] S. R. Pokhrel and J. Choi, "Federated learning with blockchain for autonomous vehicles: Analysis and design challenges," *IEEE Trans. Commun.*, vol. 68, no. 8, pp. 4734–4746, Aug. 2020, doi: 10.1109/TCOMM.2020.2990686.

[20] X. Zhang and D. Wang, "Adaptive traffic signal control mechanism for intelligent transportation based on a consortium blockchain," *IEEE Access*, vol. 7, pp. 97281–97295, 2019.

[21] Z. Su, Y. Wang, Q. Xu, and N. Zhang, "LVBS: Lightweight vehicular blockchain for secure data sharing in disaster rescue," *IEEE Trans. Dependable Secure Comput.*, early access, Mar. 13, 2020, doi: 10.1109/TDSC.2020.2980255.

[22] M. Shen, J. Zhang, L. Zhu, K. Xu, and X. Tang, "Secure SVM training over vertically-partitioned datasets using consortium blockchain for vehicular social networks," *IEEE Trans. Veh. Technol.*, vol. 69, no. 6, pp. 5773–5783, Jun. 2020, doi: 10.1109/TVT.2019.2957425.

[23] Z. Ma, J. Zhang, Y. Guo, Y. Liu, X. Liu, and W. He, "An efficient decentralized key management mechanism for VANET with blockchain," *IEEE Trans. Veh. Technol.*, vol. 69, no. 6, pp. 5836–5849, Jun. 2020, doi: 10.1109/TVT.2020.2972923.

[24] S. Iqbal, A. W. Malik, A. U. Rahman, and R. M. Noor, "Blockchain-based reputation management for task offloading in micro-level vehicular fog network," *IEEE Access*, vol. 8, pp. 52968–52980, 2020.

[25] X. Huang, D. Ye, R. Yu, and L. Shu, "Securing parked vehicle assisted fog computing with blockchain and optimal smart contract design," *IEEE/CAA J. Autom. Sinica*, vol. 7, no. 2, pp. 426–441, Mar. 2020.

[26] H. Liang, J. Wu, S. Mumtaz, J. Li, X. Lin, and M. Wen, "MBID: Micro-blockchain-based geographical dynamic intrusion detection for V2X," *IEEE Commun. Mag.*, vol. 57, no. 10, pp. 77–83, Oct. 2019.

[27] X. Wang, P. Zeng, N. Patterson, F. Jiang, and R. Doss, "An improved authentication scheme for Internet of vehicles based on blockchain technology," *IEEE Access*, vol. 7, pp. 45061–45072, 2019.

[28] H. Liao, Y. Mu, Z. Zhou, M. Sun, Z. Wang, and C. Pan, "Blockchain and learning-based secure and intelligent task offloading for vehicular fog computing," *IEEE Trans. Intell. Transp. Syst.*, early access, Jul. 21, 2020, doi: 10.1109/TITS.2020.3007770.

[29] Z. Zhou, B. Wang, M. Dong, and K. Ota, "Secure and efficient vehicle-to-grid energy trading in cyber physical systems: Integration of blockchain and edge computing," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 50, no. 1, pp. 43–57, Jan. 2020.

[30] L. R. Abbade, F. M. Ribeiro, M. H. D. Silva, A. F. P. Morais, E. S. D. Morais, E. M. Lopes, A. M. Alberti, and J. J. P. C. Rodrigues, "Blockchain applied to vehicular odometers," *IEEE Netw.*, vol. 34, no. 1, pp. 62–68, Jan. 2020.

[31] Q. Kong, L. Su, and M. Ma, "Achieving privacy-preserving and verifiable data sharing in vehicular fog with blockchain," *IEEE Trans. Intell. Transp. Syst.*, early access, Apr. 16, 2020, doi: 10.1109/TITS.2020.2983466.

[32] G. S. Aujla, A. Singh, M. Singh, S. Sharma, N. Kumar, and K.-K.-R. Choo, "BloCkEd: Blockchain-based secure data processing framework in edge envisioned V2X environment," *IEEE Trans. Veh. Technol.*, vol. 69, no. 6, pp. 5850–5863, Jun. 2020, doi: 10.1109/TVT.2020.2972278.

[33] M. Cebe, E. Erdin, K. Akkaya, H. Aksu, and S. Uluagac, "Block4Forensic: An integrated lightweight blockchain framework for forensics applications of connected vehicles," *IEEE Commun. Mag.*, vol. 56, no. 10, pp. 50–57, Oct. 2018.

[34] N. Hassan, K.-L.-A. Yau, and C. Wu, "Edge computing in 5G: A review," *IEEE Access*, vol. 7, pp. 127276–127289, 2019.

[35] X. Chen, H. Zhang, C. Wu, S. Mao, Y. Ji, and M. Bennis, "Optimized computation offloading performance in virtual edge computing systems via deep reinforcement learning," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 4005–4018, Jun. 2019.

[36] Y. Wang, P. Lang, D. Tian, J. Zhou, X. Duan, Y. Cao, and D. Zhao, "A game-based computation offloading method in vehicular multiaccess edge computing networks," *IEEE Internet Things J.*, vol. 7, no. 6, pp. 4987–4996, Jun. 2020, doi: 10.1109/JIOT.2020.2972061.

[37] Y. Liu, S. Wang, Q. Zhao, S. Du, A. Zhou, X. Ma, and F. Yang, "Dependency-aware task scheduling in vehicular edge computing," *IEEE Internet Things J.*, vol. 7, no. 6, pp. 4961–4971, Jun. 2020, doi: 10.1109/JIOT.2020.2972041.

[38] X. Zhang, J. Zhang, Z. Liu, Q. Cui, X. Tao, and S. Wang, "MDP-based task offloading for vehicular edge computing under certain and uncertain transition probabilities," *IEEE Trans. Veh. Technol.*, vol. 69, no. 3, pp. 3296–3309, Mar. 2020, doi: 10.1109/TVT.2020.2965159.

[39] L. T. Tan and R. Q. Hu, "Mobility-aware edge caching and computing in vehicle networks: A deep reinforcement learning," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 10190–10203, Nov. 2018.

[40] Z. Ning, R. Y. K. Kwok, K. Zhang, X. Wang, M. S. Obaidat, L. Guo, X. Hu, B. Hu, Y. Guo, and B. Sadoun, "Joint computing and caching in 5G-envisioned Internet of vehicles: A deep reinforcement learning-based traffic control system," *IEEE Trans. Intell. Transp. Syst.*, early access, Feb. 5, 2020, doi: 10.1109/TITS.2020.2970276.

[41] C. Wu, Z. Liu, F. Liu, T. Yoshinaga, Y. Ji, and J. Li, "Collaborative learning of communication routes in edge-enabled multi-access vehicular environment," *IEEE Trans. Cognit. Commun. Netw.*, early access, Jun. 15, 2020, doi: 10.1109/TCCN.2020.3002253.

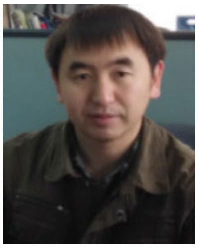
[42] C. Wu, X. Chen, T. Yoshinaga, Y. Ji, and Y. Zhang, "Integrating licensed and unlicensed spectrum in the Internet of vehicles with mobile edge computing," *IEEE Netw.*, vol. 33, no. 4, pp. 48–53, Jul. 2019.

[43] C. Wu, S. Ohzahata, Y. Ji, and T. Kato, "How to utilize interflow network coding in VANETs: A backbone-based approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 8, pp. 2223–2237, Aug. 2016.

[44] *IOTA*. Accessed: Jul. 2020. [Online]. Available: https://www.iota.org/

SU BUDA is currently an Associate Professor with the School of Computer Science and Information Engineering, Hohhot Minzu College, China. Her current research interests include edge computing and wireless networks.

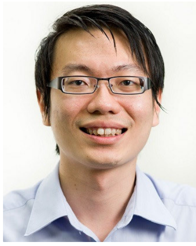
CELIMUGE WU (Senior Member, IEEE) received the Ph.D. degree from The University of Electro-Communications, Japan, in 2010. He is currently an Associate Professor with the Graduate School of Informatics and Engineering, The University of Electro-Communications. His current research interests include vehicular networks, the IoT, big data, and mobile edge computing. He is/has been a TPC Co-Chair of the Wireless Days 2021, the Wireless Days 2019, the ICT-DM 2019, and the ICT-DM 2018, and a Track Co-Chair of many international conferences, including the ICCCN 2019 and the IEEE PIMRC 2016. He is the Chair of the IEEE TCGCC SIG on Green Internet of Vehicles and the IEEE TCBD SIG on Big Data with Computational Intelligence. He is serving as an Associate Editor for the IEEE Transactions on Network Science and Engineering, the IEEE Transactions on Green Communications and Networking, IEEE Access, *Wireless Networks*, *IEICE Transactions on Communications*, the *International Journal of Distributed Sensor Networks*, and *MDPI Sensors*. He is/has been a Guest Editor of the IEEE Transactions on Intelligent Transportation Systems, the IEEE Transactions on Emerging Topics in Computational Intelligence, the *IEEE Computational Intelligence Magazine*, ACM/Springer *MONET*, and so on.



WUGEDELE BAO received the Ph.D. degree from the Minzu University of China, in 2018. He is currently an Associate Professor with the School of Computer Science and Information Engineering, Hohhot Minzu College, China. His current research interests include artificial intelligence and computer systems.

SIRI GULENG is currently a Professor with the School of Computer Science and Information Engineering, Hohhot Minzu College, China. His current research interests include computer networks and cyber security.

JIEFANG ZHANG is currently a Professor with the Institute of Intelligent Media Technology, Communication University of Zhejiang. His current research interests include AI and the IoT for media big data.



KOK-LIM ALVIN YAU (Senior Member, IEEE) received the B.Eng. degree (Hons.) in electrical and electronics engineering from the Universiti Teknologi PETRONAS, Malaysia, in 2005, the M.Sc. degree in electrical engineering from the National University of Singapore, in 2007, and the Ph.D. degree in network engineering from the Victoria University of Wellington, New Zealand, in 2010. He is currently a Professor with the Department of Computing and Information Systems, Sunway University. He is also a Researcher, a Lecturer, and a Consultant in cognitive radio, wireless networks, applied artificial intelligence, applied deep learning, and reinforcement learning. He serves as a TPC Member and a Reviewer for major international conferences, including ICC, VTC, LCN, GLOBECOM, and AINA. He was a recipient of the 2007 Professional Engineer Board of Singapore Gold Medal for being the best graduate of the M.Sc. degree, in 2006 and 2007. He also served as the Vice General Co-Chair for ICOIN'18, the Co-Chair for IET ICFCNA'14, and the Co-Chair (Organizing Committee) for IET ICWCA'12. He serves as an Editor for the *KSII Transactions on Internet and Information Systems*, an Associate Editor for IEEE Access, a Guest Editor for the Special Issues of IEEE Access, *IET Networks*, the *IEEE Computational Intelligence Magazine*, the *Journal of Ambient Intelligence and Humanized Computing* (Springer), and a Regular Reviewer for more than 20 journals, including the IEEE journals and magazines, *Ad Hoc Networks*, *IET Communications*, and others.

YUSHENG JI (Senior Member, IEEE) received the B.E., M.E., and D.E. degrees in electrical engineering from The University of Tokyo. She joined the National Center for Science Information Systems (NACSIS), Japan, in 1990. She is currently a Professor with the National Institute of Informatics (NII) and the Graduate University for Advanced Studies (SOKENDAI). Her research interests include network architecture, resource management, and quality of service provisioning in wired and wireless communication networks. She is/has been an Editor of the IEEE Transactions on Vehicular Technology, a Symposium Co-Chair of the IEEE GLOBECOM 2012, 2014, and a Track Co-Chair of the IEEE VTC2016-Fall, VTC2017-Fall, and so on.

• • •