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ARTICLE

Overcoming Dynamic Connectivity in Internet of Vehicles: A DAG Lattice Blockchain with Reputation-Based Incentive

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ABSTRACT: Blockchain offers a promising solution to the security challenges faced by the Internet of Vehicles (IoV). However, due to the dynamic connectivity of IoV, blockchain based on a single-chain structure or Directed Acyclic Graph (DAG) structure often suffer from performance limitations. The DAG lattice structure is a novel blockchain model in which each node maintains its own account chain, and only the node itself is allowed to update it. This feature makes the DAG lattice structure particularly suitable for addressing the challenges in dynamically connected IoV environment. In this paper, we propose a blockchain architecture based on the DAG lattice structure, specifically designed for dynamically connected IoV. In the proposed system, nodes must obtain authorization from a trusted authority before joining, forming a permissioned blockchain. Each node is assigned an individual account chain, allowing vehicles with limited storage capacity to participate in the blockchain by storing transactions only from nearby vehicles' account chains. Every transmitted message is treated as a transaction and added to the blockchain, enabling more efficient data transmission in a dynamic network environment. A reputation-based incentive mechanism is introduced to encourage nodes to behave normally. Experimental results demonstrate that the proposed architecture achieves better performance compared with traditional single-chain and DAG-based approaches in terms of average transmission delay and storage cost.

KEYWORDS: Blockchain; Internet of vehicles; dynamic connectivity; DAG lattice; incentive

1 Introduction

The blockchain is a distributed technology that can effectively address issues such as the vulnerability of centralized architecture, privacy information leakage, and lack of trust between entities in the traditional Internet of Vehicles (IoV) environment. At present, there have been many studies on blockchain in the IoV, mainly including authentication mechanism [1,2], privacy protection [3,4], trust management [5,6], certificate management [7,8], data sharing [9,10], etc.

In the IoV, the mobility of vehicles leads to high dynamicity, which causes network splits and merging [11]. After network splits, multiple disconnected subnets are formed. When network merging, these disconnected subnets will again form a connected network. Therefore, the connectivity of the network continuously changes in the IoV, and there are no stable routes between nodes. These characteristics of IoV lead to dynamic connectivity issues, which significantly affects the performance of blockchain systems in the IoV. However, blockchain is a decentralized technology that requires consistency in storage among all participating nodes. Currently, the blockchain storage structures used in the IoV mainly include the single-chain structure and the Directed Acyclic Graph (DAG) structure. These two kinds of storage structures need the ledger of nodes to be consistent all the time, which is difficult to achieve this consistency in a dynamically connected IoV.

The IoV applications mainly rely on interactions between nodes and surrounding nodes. For each node, the focus is more on the transactions generated by nearby vehicles, while transactions generated by nodes outside the communication range do not need to be acquired in real-time. This characteristic allows the consideration of a new blockchain structure to meet the demands.

The DAG lattice structure [12,13] is developed from the DAG structure. In the DAG lattice structure, each node has its own account chain, and only the node itself can update its account chain. Transactions from different accounts can reach a consensus parallelly. When two nodes interact, the transaction is added to their respective account chains, without affecting the account chains of other nodes. In the DAG lattice structure, even if transactions are not synchronized in real-time to all nodes in the blockchain network, they will not impact other nodes' processing of transactions. This characteristic perfectly aligns with the local clustering feature in dynamically connected IoV. Moreover, the DAG lattice structure also performs well in terms of transactions per second (TPS). Dong et al. conducted performance evaluations on three popular DAG implementations (IOTA [14], Byteball [15], and Nano) through experiments. The results showed that the Nano system, based on the DAG lattice structure, consistently achieved higher TPS than the other two implementations under varying transaction generation rates [16].

Therefore, this paper adopts a DAG lattice structure to address the issues caused by dynamic connectivity in the IoV, and proposes a security architecture based on DAG lattice blockchain, referred to as DAGL-IoV. In this architecture, all the ledger information is stored in the roadside units (RSUs), while the moving vehicles only need to store transaction information from nearby vehicles. This approach avoids the issue of being unable to synchronize transactions due to network splits, while also better aligning with the characteristics of the IoV. The main contributions of this paper are as follows:

- This paper proposes a security architecture for the IoV based on the DAG lattice blockchain. In this architecture, an account chain is created for each node, and each transmitted message is added as a transaction to the blockchain, ensuring better performance in the dynamic IoV.
- A reputation-based incentive mechanism is introduced, drawing from the slow-start and congestion-avoidance ideas in Transmission Control Protocol (TCP) congestion control, to update the reputation scores of nodes and incentivize nodes to behave normally in the blockchain.
- Experimental results demonstrate that DAGL-IoV outperforms solutions based on single-chain and DAG structures in terms of average transmission delay and storage cost.

The rest of this paper is organized as follows: Section 2 discusses the related works; Section 3 provides a detailed design of the DAG lattice-based secure IoV architecture; Section 4 describes the proposed incentive mechanism. Section 5 describes potential malicious attack scenarios within the architecture and analyzes how to counter these attacks; Section 6 validates the performance of the architecture; and Section 7 concludes the paper.

2 Related Works

Many studies have applied blockchain technology in the IoV. In these studies, the blockchain storage structures include both the single-chain structure and the DAG structure.

2.1 Single-Chain Structure

The single-chain structure is the earliest structure used in the Bitcoin system proposed by Nakamoto [17], where transactions within each block are organized through a Merkle tree. Islam et al. [18] proposed a lightweight blockchain architecture for knowledge sharing, deploying smart contracts within the blockchain to enable automated knowledge sharing, thereby enhancing trustworthiness, verifiability, and non-repudiation in communication processes. Cui et al. [19] used consortium blockchain to provide a trusted environment for secure and efficient data sharing between vehicles. They deployed the blockchain on moving vehicles, enabling data sharing without the participation of RSU. Xu et al. [20] introduced a new framework for secure intelligent vehicle data sharing, where each vehicle can connect to a blockchain platform based on biometric recognition. Kulathunge and Dayarathna [21] proposed a blockchain-based communication framework that stores data in a Hyperledger blockchain. To improve performance and reduce computational costs in message processing within IoV, Zang et al. [22] proposed an efficient vehicle safety communication authentication scheme based on blockchain, introducing smart contracts to restrict malicious vehicles from entering the network.

2.2 DAG Structure

To improve the TPS of blockchain in IoV environments, many researchers have considered using the DAG structure to store blockchain data. Chai et al. [23] proposed a framework for intelligent vehicle knowledge sharing based on adaptive asynchronous distributed learning and blockchain. In this framework, a lightweight Tip selection algorithm was designed for the DAG. Li et al. [24] proposed a decentralized solution based on the DAG structure to address the peer disclosure issue in social IoV. In this solution, a mutual supervision algorithm was designed to deal with untrusted vehicles. Fu et al. [25] designed a blockchain-based architecture for IoV transactions, which integrates the DAG blockchain to record data and bandwidth transactions between vehicles and RSUs, with vehicles and RSUs jointly maintaining the blockchain ledger. Jiang et al. [26] proposed a privacy-preserving computing scheme based on homomorphic encryption and blockchain, where the DAG data structure replaced the chain structure to allow parallel processing and reduce transmission confirmation delay. Liu et al. [27] proposed a reputation management system based on hierarchical blockchain, where vehicles and RSUs jointly maintain and generate local DAG ledgers, utilizing the DAG blockchain structure to design reputation value evaluation.

2.3 Problem Analysis

When a single-chain structure is applied in the IoV, network splits can prevent blocks that reach consensus in separate subnets from being synchronized in real-time across other connected subnets. This can result in new blocks being generated simultaneously in different subnets, causing frequent forks and reducing TPS, which clearly fails to meet the real-time requirements of the IoV. The DAG structure allows the blockchain to fork, enabling parallel consensus. However, when the DAG structure is applied in the IoV, there remains the issue that nodes cannot maintain a unified DAG ledger. When the network splits, the local DAG ledger maintained in a connected subnet cannot be synchronized to other connected subnets in real-time. When the network merges again, conflicts may arise in the DAG structure, making it impossible to merge each local DAG ledger into a global unified DAG ledger. Therefore, maintaining a consistent blockchain ledger between moving nodes is not feasible.

In current research, there is limited exploration of the impact of mobility on blockchain performance, whether in single-chain or DAG-based blockchain systems.

3 Detailed Design of DAGL-IoV

3.1 System Model

In the proposed system, both vehicles and RSUs jointly constitute the blockchain network. This architecture not only capitalizes on the stable connectivity and rapid data dissemination capabilities of RSUs but also extends network coverage to areas with limited RSU deployment through vehicular participation. Wireless communication between vehicles, as well as between vehicles and RSUs, is realized using technologies such as Dedicated Short-Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X). In contrast, communication among RSUs is conducted via wired links, wherein the Gossip protocol is employed to ensure the consistency and synchronization of the distributed ledger. The overall system model is depicted in Fig. 1, where the main entities include the Trust Center (TC), vehicles, and RSUs.

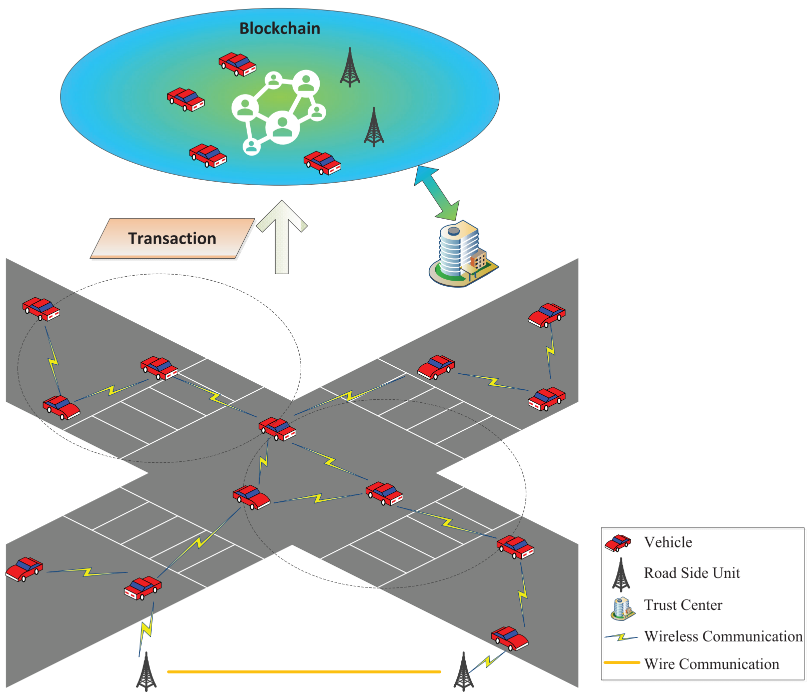


Figure 1: The system model

- TC: Serving as a fully trusted authority, the TC is responsible for generating public-private key pairs for both vehicles and RSUs. It further assists RSUs in the verification of account information and credentials generated by blockchain nodes, thereby ensuring the integrity and authenticity of network identities.
- Vehicles: As lightweight nodes with limited storage, vehicles maintain a pruned version of the blockchain to reduce computational and storage overhead. Depending on their storage capacity, the system considers three storage methods: 1) For nodes with larger storage, they store all transactions generated by surrounding nodes; 2) When storage space is insufficient, they send a pruning request to save the pruned transactions; 3) To enable vehicles to validate transactions and participate in consensus, they store only the minimum number of transactions necessary for blockchain operation, including the latest transaction information for the vehicle itself and other nearby vehicles. To enhance blockchain security, vehicles are encouraged to store more transactions and only prune locally stored transactions when storage space is insufficient.

- RSUs: As full nodes with substantial storage capacity and computing power, RSUs are capable of performing all blockchain-related functions, including data storage, transaction validation, and block generation. To prevent data loss, RSUs must store the entire blockchain data to ensure data integrity. Newly added nodes can retrieve the entire blockchain data from RSUs, eliminating issues related to guiding new nodes. Transactions that reach consensus on vehicles must be quickly synchronized with the RSUs. To encourage nodes to maintain normal behavior, a reputation-based incentive mechanism is introduced, where each node's reputation score is maintained by the RSUs.

Due to the high dynamics of the IoV, a fully decentralized public blockchain is not suitable for large-scale IoV applications [28]. Moreover, many applications in IoV are related to road traffic safety, and allowing any node to freely join the blockchain network would inevitably increase the risk of IoV attacks. The permissioned blockchain [29] requires institutional authorization to join the blockchain and can control the addition of unrelated or malicious entities, making it highly effective in privacy or security-sensitive scenarios. Therefore, this architecture constructs a permissioned blockchain on both vehicles and RSUs.

3.2 Component Model

This section defines the basic components of DAGL-IoV from four aspects: nodes, accounts, transactions, and ledger.

3.2.1 Nodes

Each node can perform full or partial blockchain operations, including transaction generation, verification, consensus, and storage. In DAGL-IoV, both vehicles and RSUs act as blockchain nodes, collaboratively maintaining the distributed ledger. Vehicle nodes are denoted as $VNode_i \in \{VNode_1, VNode_2, \ldots, VNode_N\}$, where N is the total number of vehicles. RSU nodes are denoted as $RNode_i \in \{RNode_1, RNode_2, \ldots, RNode_M\}$, where M is the total number of RSUs.

3.2.2 Accounts

An account represents the unique identity of a blockchain node in the system. For management efficiency, each node is assigned a single account consisting of a public-private key pair $\{P_r, S_r\}$. All key pairs are generated by the TC. The system comprises vehicle accounts and RSU accounts, corresponding to vehicle and RSU nodes, respectively. Vehicle accounts are denoted as $VNode_i \in \{VNode_1, VNode_2, \ldots, VNode_N\}$, where N is the total number of vehicles. RSU accounts are denoted as $RAC_i \in \{RAC_1, RAC_2, \ldots, RAC_M\}$, where M is the total number of RSUs.

3.2.3 Transactions

In the DAG lattice blockchain structure, each account maintains its own account chain. To minimize coupling among account chains and enable parallel transaction processing, a traditional blockchain transaction is divided into sending and receiving transactions, which are stored separately in the corresponding account chains. Each transaction is treated as an independent block and appended individually to the blockchain. The system defines four types of transactions: account creation ($T_{account\_create}$), message sending ($T_{message\_send}$), reputation sending ($T_{reputation\_send}$), and receiving ($T_{receive}$). The $T_{account\_create}$ is used to create a node account. The $T_{message\_send}$ and $T_{receive}$ occur in pairs to complete message transmission, while $T_{reputation\_send}$ and $T_{receive}$ occur in pairs to complete reputation updates. Notably, $T_{account\_create}$ involves only one account and does not require a corresponding receiving transaction.

3.2.4 Ledger

For each account, the transactions on its account chain include both message-related and reputation-related records. To enhance processing efficiency, facilitate transaction queries, and enable parallel execution, the account chain is divided into a message chain and a reputation chain for separate storage. The ledger adopts a DAG lattice structure, as illustrated in Fig. 2. The genesis block is generated during system initialization and serves as the parent block for all account creation transactions. Each account creation transaction acts as the genesis transaction of its respective account chain, to which the message and reputation chains are linked through $T_{account\_create}$. Changes in node reputation scores are driven by node behavior—specifically, whether a node transmits correct messages. Consequently, each reputation sending transaction must reference the corresponding message sending transaction that triggered the reputation update.

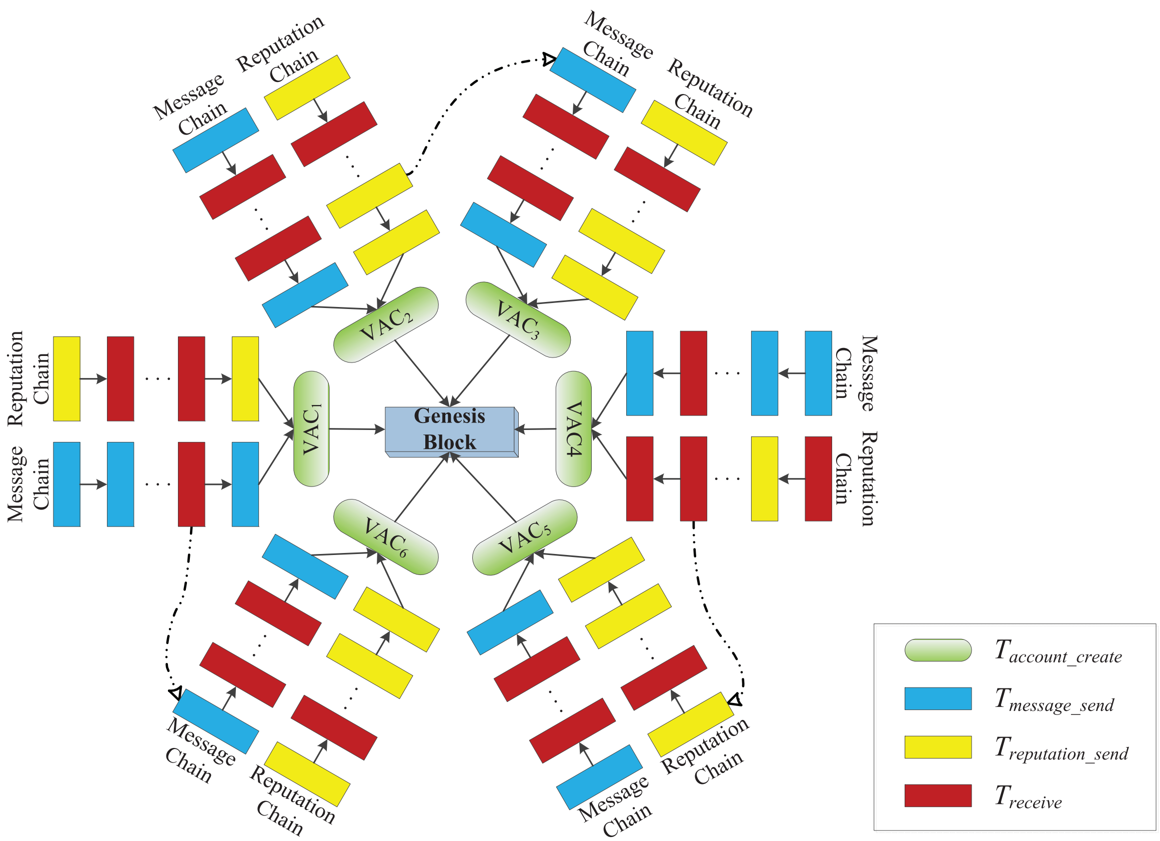


Figure 2: DAG lattice structure

In practical IoV applications, nodes typically interact with surrounding nodes and are more focused on the messages from nearby nodes, without the need to access messages generated by nodes in other connected subnets in real-time. Additionally, in different connected subnets, nodes can implement related applications in parallel. Using the DAG lattice structure shown in Fig. 2, transactions between different accounts can be processed in parallel. Within the same account, transactions in the message chain and reputation chain can also be processed in parallel. Each node can independently operate its own account chain, needing only to synchronize with the account chains of nearby nodes to complete the blockchain functionality. This approach aligns well with the characteristics of the IoV application scenario.

3.3 Synchronize Transactions

To enable nodes to access the account chains of other nodes or participate in consensus for transactions, they need to synchronize the account chain data from neighboring nodes. In the DAGL-IoV, transaction synchronization primarily occurs in two scenarios: when a new node joins the blockchain or when a node moves into the communication range of another node.

3.3.1 New Node Joining the Blockchain

When a new node joins, it synchronizes the blockchain ledger from the RSUs. Considering the limited storage resources of vehicles, new vehicles can synchronize only partial blockchain data, such as the transactions needed to verify transactions and participate in consensus, as well as transactions of interest generated by other nodes.

When a new node synchronizes transactions, it first synchronizes the genesis block to its local ledger, then determines which nodes to synchronize transaction information from, and synchronizes the account creation transactions of these nodes. Lastly, depending on its local storage capacity, it synchronizes transactions from the node account chain. To ensure that the newly joined node can verify transactions and participate in consensus, it must synchronize the latest message-related and reputation-related transactions from the node account chain.

3.3.2 Node Moving into the Communication Range of Another Node

As vehicles on the road are in moving, each vehicle's account chain moves along with the vehicle. The nodes near vehicle A always store the latest transactions of that vehicle, whereas nodes farther away may not need to or cannot store its most recent transactions. During the vehicle's movement, when it enters the communication range of A, its local ledger may not have stored the latest transactions of A, preventing it from verifying or participating in consensus for transactions generated by A. In such cases, synchronization of the A's latest transactions is necessary.

The process begins by determining whether A is a newly joined node to the blockchain. If so, the account creation transaction of A must first be synchronized, followed by the synchronization of the latest message-related and reputation-related transactions from its account chain.

3.4 Generate Transaction

In the DAGL-IoV framework, the types of transactions that can be generated include account creation transactions, message sending transactions, reputation score sending transactions, and receive transactions.

3.4.1 Account Creation Transaction

To create an account, a blockchain node initiates an account creation transaction defined as $T_{account\_create} = \{type, account, nonce, difficulty, timestamp, signature\}$. The $type$ field specifies the transaction type ("account_create"), and $account$ denotes the address of the new account. $difficulty$ defines the PoW difficulty, and $nonce$ is a random value satisfying this difficulty. $timestamp$ records the transaction creation time. $signature$ ensures authenticity and data integrity by preventing denial or tampering. It is generated by encrypting the hash of the transaction content excluding the $signature$ field) using the sender's private key G^{S_r}, as expressed in Eq. (1), where $hash(\cdot)$ denotes the hashing algorithm.

$$signature = E_{G^{S_r}}\{hash(type, account, nonce, difficulty, timestamp)\}. \tag{1}$$

3.4.2 Message Sending Transactions

When a node sends a message, it generates a message sending transaction defined as $T_{message\_send} = \{type, previous, source, destination, nonce, difficulty, timestamp, msg\{desc, content\{plaintext\_cont, ciphertext\_cont\}\}, signature\}$. The *type* field specifies the transaction type ("message_send"), and *previous* stores the hash of the previous block. *source* and *destination* represent the sender and receiver account addresses, respectively. The *msg* field includes *desc*, a brief description, and *content*, which contains public content *plaintext_cont* and encrypted content *ciphertext_cont*. Both *desc* and *plaintext_cont* are stored in plaintext, while *ciphertext_cont* is encrypted and accessible only to the intended receiver. The *signature* is produced by encrypting the hash of the transaction content (excluding the *signature* field) with the sender's private key G^{S_r}, as shown in Eq. (2).

$$signature = E_{G^{S_r}}\{hash(type, previous, source, destination, nonce, difficulty, timestamp, msg)\}. \tag{2}$$

3.4.3 Reputation Sending Transaction

When an RSU updates a node's reputation score, it issues a reputation sending transaction defined as $T_{reputation\_send} = \{type, previous, source, destination, associate, nonce, difficulty, timestamp, timestamp_{dest}, reputation\{desc, score\}, signature, signature_{dest}\}$. The *type* field specifies the transaction type ("reputation_send"). *destination* identifies the account whose reputation is being updated, and *associate* points to the hash of the related message transaction that triggered the reputation change. The *reputation* field contains the update description *desc* and the new score *score*. The $timestamp_{dest}$ records when the updated node signs the transaction. *signature* and $signature_{dest}$ are the digital signatures of the RSU and the updated node, respectively, ensuring mutual verification. The update is valid only when both parties co-sign the transaction, preventing unauthorized modifications. The *signature* is generated by encrypting the hash of the transaction content (excluding the *signature*, $timestamp_{dest}$, and $signature_{dest}$ fields) with the RSU's private key G^{S_r}, as given in Eq. (3). The $signature_{dest}$ is generated similarly using the updated node's private key D^{S_r}, as expressed in Eq. (4).

$$\begin{aligned} signature = E_{G^{S_r}}\{hash(&type, previous, source, destination, associate, nonce, difficulty, \\ &timestamp, reputation)\}. \end{aligned} \tag{3}$$

$$\begin{aligned} signature_{dest} = E_{D^{S_r}}\{hash(&type, previous, source, destination, associate, nonce, difficulty, \\ &timestamp, reputation, timestamp_{dest})\}. \end{aligned} \tag{4}$$

3.4.4 Receive Transaction

When a node receives either a message sending or a reputation sending transaction, it generates a receive transaction defined as $T_{receive} = \{type, previous, source, destination, associate, nonce, difficulty, timestamp, signature\}$. The *type* field specifies the transaction type:"message_receive" for message transactions and "reputation_receive" for reputation updates. *destination* identifies the receiving account, and *associate* links the transaction to its corresponding sending transaction. The *signature* is generated by encrypting the hash of the transaction content (excluding the *signature* field) using the sender's private key G^{S_r}, as shown in Eq. (5). The operation is completed only when both the sending and receiving transactions reach consensus and are appended to the blockchain.

$$signature = E_{G^{S_r}}\{hash(type, previous, source, destination, associate, nonce, difficulty, timestamp)\}. \tag{5}$$

3.5 Validate Transaction

When a node in the blockchain network receives a transaction T generated by node K ($K \in VNode_i \parallel RNode_i$), the transaction must undergo validation. The process includes verifying: 1) the nonce value, 2) the timestamp, 3) the transaction signature, and 4) associated transactions. The detailed validation steps are described as follows.

(1) Nonce value

The correctness of the nonce value determines whether node K has successfully completed the corresponding PoW. Only nodes that have completed PoW are permitted to broadcast transactions to the blockchain network; thus, nonce validation is essential. The verification process checks whether *hash(type, difficulty, timestamp, nonce)* meets the specified PoW difficulty. If the nonce satisfies the difficulty condition, node K is deemed to have completed the required PoW; otherwise, the transaction is discarded.

(2) Timestamp

The purpose of timestamp validation is to ensure that node K transmits the transaction immediately after its creation, thereby preventing malicious nodes from performing pre-computation PoW attacks (as discussed in Section 5). The timestamp is validated by checking whether the time interval $\Delta t = |Time - timestamp||timestamp_{dest}|$ between the transaction timestamp and the reception time $Time$ satisfies the condition $\Delta t < Thr$. If Δt exceeds this threshold, the transaction is considered invalid. For reputation sending transactions, both *timestamp* and $timestamp_{dest}$ are included. When the transaction is generated by an RSU, the $timestamp$ field is verified; when it is generated by the node whose reputation score is being updated, the $timestamp_{dest}$ field is verified.

(3) Signature of transaction

Validating a transaction's signature ensures that it is generated by the legitimate creator rather than a malicious node. The verification process computes the hash of the transaction (excluding the $signature$ or $timestamp_{dest}$ fields) denoted as $hash_1$ = *hash(type, account, nonce, difficulty, timestamp)*, using the same hash function $hash(\cdot)$ as in the signing phase (taking account creation transactions as an example). The generator's public key G^{P_r} is then used to decrypt the signature, obtaining $hash_2 = D_{G^{P_r}}\{signature\}$. If $hash_1 = hash_2$, the signature is considered valid; otherwise, the transaction is discarded.

It is noteworthy that for reputation sending transactions, if the transaction is generated by an RSU, only the *signature* requires verification. However, if it is generated by the node whose reputation score is being updated, both the *signature* and $timestamp_{dest}$ must be verified.

(4) Associated transactions

For account creation and message sending transactions, no associated transactions require verification. However, reputation sending transactions must be linked to the corresponding transaction that triggers the reputation change, and receive transactions must verify their associated message sending or reputation sending transactions. Upon receiving a reputation sending or receive transaction, the system checks whether the related transactions already exist on the blockchain. If they do, validation succeeds; otherwise, the transaction is discarded.

Transactions that pass the above validation steps are subsequently finalized through the consensus process and appended to the blockchain.

4 Incentive Mechanism

Due to the high dynamic nature of the network, nodes in a blockchain are typically unfamiliar with each other, making it difficult to establish trust. Therefore, it is essential to implement an incentive mechanism to encourage nodes to join the blockchain and maintain normal behavior. The DAGL-IoV framework adopts a reputation-based incentive mechanism, assigning a reputation score to each node. By dynamically updating reputation scores, the system incentivizes well-behaved nodes while penalizing malicious ones. Nodes with higher reputation scores have more opportunities to generate transactions, and their transactions are prioritized for processing. This incentive mechanism helps to encourage nodes to maintain high reputation scores, allowing trust to be established even when communicating with unfamiliar nodes.

4.1 PoW for Spam Prevention

Before sending a transaction, a node must first complete a PoW process (it should be noted that, unlike Bitcoin's PoW, the PoW in the DAGL-IoV is solely used for spam prevention). The node calculates a random number that meets a specific difficulty, filling in the *difficulty* and *nonce* fields. Only after completing the PoW can the transaction be sent. Other nodes, upon receiving the transaction, will first verify whether the nonce value is correct. Since PoW consumes computational resources, it prevents malicious nodes from flooding the network with spam messages, thus avoiding Denial of Service (DoS) attacks. The lower the PoW difficulty, the fewer computational resources are required, and the faster the transaction can be generated. Conversely, the higher the PoW difficulty, the more computational resources are needed, which slows down the transaction generation speed.

In this architecture, the PoW difficulty is dynamically adjusted according to the node's reputation score. Nodes with higher reputation scores are assigned lower PoW difficulty, while those with lower scores face higher difficulty. This mechanism incentivizes nodes to maintain a high reputation to increase their chances of generating transactions. Since the node's reputation score is dynamic, the difficulty is also dynamic. The specific calculation methods are given by the equations Eqs. (6) and (7).

$$N_{zero} = \left\lfloor e^{-(\vartheta \cdot Score+\mu)} * N_{hash} \right\rfloor. \tag{6}$$

$$difficulty \Leftarrow \underbrace{0\ldots0}_{N_{zero}} + \left(2^{N_{hash}-N_{zero}} - 1\right) B. \tag{7}$$

Here, N_{hash} denotes the length of the hash value, which depends on the selected hashing algorithm (e.g., MD5: 128 bits; SHA-1: 160 bits; SHA-256: 256 bits). The choice of algorithm is determined by application requirements. N_{zero} represents the number of leading zeros defining the PoW difficulty. *Score* denotes the node's reputation value, while ϑ and μ are preset parameters controlling the adjustment rate and upper bound of PoW difficulty. $\lfloor \cdot \rfloor$ indicates the floor operation, and $(\cdot)\,B$ denotes the conversion of a decimal number into binary form.

Once the difficulty is determined, the node attempts to find a nonce that satisfies the PoW. This is done by repeatedly trying different nonce values until one is found that meets the difficulty requirement, that is, *Hash(type, difficulty, timestamp, nonce)* $\leq difficulty$.

4.2 Updating Reputation Score

In traditional reputation score updating methods, nodes are rewarded with a fixed score for sending truthful messages and penalized with a fixed deduction for sending false messages [30,31]. However, this method only updates a node's reputation score based on current behavior and does not consider the influence of the node's historical actions. For instance, a malicious node may send false messages to lower its score, but then send truthful messages to recover its score, engaging in On-Off attacks [32] by periodically alternating between false and true messages. Traditional reputation score updating methods do not account for historical behavior and thus cannot prevent On-Off attacks.

Therefore, this framework draws inspiration from the ideas of "slow start" and "congestion avoidance" from TCP congestion control to update nodes' reputation scores, introducing a reputation score threshold S_{thr}. This threshold reflects the node's historical behavior. Different updating methods are applied when a node's reputation score is below or above S_{thr}. Given that the trust level of newly joined nodes is unknown, all nodes initially have a reputation score of 1. To enable normal nodes to gain higher reputation scores more quickly, the initial reputation score threshold S_{thr} is set to 100. The specific updating process is outlined in Algorithm 1.

Algorithm 1: Algorithm for updating node's reputation scores

Input: Message *msg* sent by the node, reputation score threshold S_{thr}, current reputation score *Score*, frequency of sending false messages *f*.

Output: Updated reputation score $Score'$.

Verify the authenticity of the *msg*;
if *msg* is *True* **then**
    if $core < S_{thr}$ **then**
        Update $Score'$: $Score' \leftarrow Score * 2\Delta\eta$;
    else
        Update $Score'$: $Score' \leftarrow Score + \Delta\zeta(1 - f)$;
    end if
else
    Update S_{thr}: $S_{thr} \leftarrow \left\lfloor \frac{Score'}{2} \times (1 - f) \right\rfloor$;
    Set $Score' \leftarrow 1$;
end if

In this algorithm, the first step is to verify the authenticity of the message sent by the node. The authenticity of messages can be determined by combining salient object detection methods, which is not the focus of this paper. For specific information, please refer to references [33,34]. If the message is truthful, the reputation score is increased. The method of increasing the reputation score is determined by the reputation score threshold S_{thr}. If the node's reputation score is below S_{thr}, the score increases exponentially, i.e., it is multiplied by $2\Delta\eta$ (Where $\Delta\eta \in (0.5, 1]$ controls the speed of exponential growth). If the reputation score is above or equal to S_{thr}, the score increases linearly by $\Delta\zeta(1 - f)$ (Where $\Delta\zeta \in (0, 1]$ controls the speed of linear growth). The maximum reputation score is capped at 100. If the message is false, the reputation score threshold S_{thr} is updated using equation Eq. (8), and the reputation score is reset to 1.

$$S_{thr} = \left\lfloor \frac{Score'}{2} \times (1 - f) \right\rfloor \tag{8}$$

where $f \in [0, 1]$ is the frequency of false messages sent by the node, calculated based on the ratio of false messages to truthful messages sent within a recent time period. Nodes with a higher frequency of false messages will experience a faster decline in their reputation score threshold, thus slowing the recovery of their reputation score.

As illustrated in Algorithm 1, the calculation and updating of a node's reputation score are influenced by its historical behavior. Specifically, a higher frequency of sending false messages in the past results in a longer time required for the node to achieve a high reputation score. Additionally, the reputation score is directly linked to the PoW difficulty for the node's transactions: a higher reputation score corresponds to a lower PoW difficulty. To ensure that a node's transactions are prioritized for inclusion on the blockchain, it must consistently maintain a high reputation score over time. In this way, this system effectively incentivizes nodes to behave honestly.

5 Security Analysis

This section describes the potential security issues that may arise in the proposed DAGL-IoV and analyzes how to address these problems. Malicious or attacked nodes in the blockchain may initiate the following types of network attacks.

5.1 Sybil Attack

Malicious nodes may create multiple accounts to launch a Sybil attack. In the DAGL-IoV, both the public and private keys of vehicles and RSUs are issued by a trusted center. Additionally, when creating accounts, RSUs are validated through the trusted center, ensuring that each node creates a genuine, valid, and unique account. Therefore, under this architecture, malicious nodes cannot create numerous accounts to launch a Sybil attack.

5.2 Transaction Flooding Attack

Malicious nodes may send a large number of valid but meaningless transactions to the blockchain, consuming substantial network bandwidth and wasting node resources in the transaction validation and consensus process. In the DAGL-IoV, before sending a transaction, a node must complete a PoW process, making it impossible for nodes to generate large numbers of transactions simultaneously. Moreover, PoW difficulty is related to the node's reputation score. If transaction flooding attacks are detected, the node's reputation score will be reduced, making it harder to generate transactions. When the computational resources consumed by PoW exceed the benefits obtained from launching the attack, the node will proactively abandon the attack.

5.3 On-Off Attack

Malicious nodes may initiate an On-Off attack by alternating between sending false and truthful messages. During the reputation score update process, the rate of increase in a node's reputation score is much lower than the rate of decrease. Therefore, after a malicious node performs an attack, it takes a long time to recover its reputation score before it can launch another attack. Furthermore, for nodes that frequently send malicious messages, the reputation score threshold controls the speed of their reputation score recovery, making it even more difficult for such nodes to carry out On-Off attacks.

5.4 Integrity of the Blockchain

An attacker could target vehicles or RSUs within the blockchain to tamper with the data stored on the blockchain, thereby compromising the integrity of the ledger. In the DAGL-IoV, vehicles, due to their limited storage capacity, only store recent transactions, while RSUs store the full blockchain ledger. For recent transactions, both vehicles and RSUs store them, and an attacker would need to control 51% of the nodes in the network to alter the transactions, which is very difficult to achieve. For older transactions, they are only stored on RSUs. As time passes, older transactions become more difficult to tamper with. Additionally, RSUs are typically deployed and maintained by government agencies, making them less likely to be attacked. Therefore, while vehicles only store recent transaction information, it remains very difficult for attackers to compromise the integrity of the blockchain ledger.

5.5 Double-Spending Attack

A malicious node may attempt to conduct a double-spending attack by simultaneously issuing two transactions. Within a connected network, such attacks can be prevented through transaction validation and consensus mechanisms. However, due to the dynamic connectivity of the IoV, partitions may occur, allowing the malicious node to disseminate the two transactions to different connected regions, thereby launching a double-spending attack. In DAGL-IoV, nodes serve as the carriers of their ledgers, and the surrounding nodes remain synchronized with them in real time. Consequently, even if a malicious node sends transactions to different regions, a double-spending attack cannot be successfully executed.

6 Experiments and Analysis

This section focuses on experimentally simulating the proposed DAGL-IoV for IoV. The goal is to validate the performance of the architecture in terms of average transmission delay and storage cost, as well as assess the feasibility of the incentive mechanism.

6.1 Experimental Setup

6.1.1 Experimental Environment

The experimental simulations were implemented using the traffic flow simulation tool VanetMobiSim (version 1.1) and the network simulation platform OPNET (version 14.5) to model vehicular mobility and network communication behaviors, respectively. The DAG lattice-based blockchain is implemented using OPNET, where the related operations of the DAG lattice structure and blockchain are executed on vehicles and RSUs. Initially, the traffic scenario is modeled using VanetMobiSim. A simulation area of 4500 m was created, and node trajectories were generated within this area and imported into the OPNET environment to simulate node mobility. Nodes communicated with neighbors using a log-normal connection model, with a communication range of 450 m, consistent with C-V2X technology [35].

6.1.2 Experimental Parameters

The simulation parameters used in the experiment are shown in Table 1.

6.1.3 Performance Metrics

(1) Average Propagation Delay (Avg_{delay})

The average propagation delay refers to the average time taken for a block, after consensus completion, to propagate to other nodes in the network. This metric reflects the time required to synchronize the block to other nodes once consensus is completed. The calculation method for Avg_{delay} is given by Eq. (9):

$$Avg_{delay} = \frac{\sum_{i=1}^{N} Time_{rece} - Time_{cons}}{N} \tag{9}$$

where $Time_{rece}$ is the time when the node receives the transaction. $Time_{cons}$ is the time when the transaction consensus is completed. N is the number of nodes in the network that receive the block.

(2) Storage Cost

Storage cost refers to the storage space required by a node to store the blockchain ledger. This metric reflects the lightweight nature of the architecture. For a blockchain system, the more ledger data a node stores, the more secure the system becomes. However, for nodes with limited storage resources, the goal is to store as little ledger data as possible without affecting the blockchain.

Table 1: Simulation parameters

Parameters	Values
Simulation time	1800 s
Communication range	450 m
Communication protocol	802.11
Number of nodes	20, 40, 60, 80, 100, 120
Transaction generation interval	3 s
Data rate	11 mbps
Transaction size (bytes)	Exponential (250)
Transmit power	0.000654
Packet reception-power threshold (dBm)	−95
Physical characteristics	DirectSequence
ϑ	0.01
μ	1.9
N_{hash}	160
$\Delta\eta, \Delta\zeta$	1

6.2 Experimental Analysis

This section analyzes the performance of the architecture proposed in this paper and the feasibility of the incentive mechanism. When evaluating the performance of the architecture, comparisons are made with blockchain systems using a single-chain structure and a DAG structure in the IoV. In the figure, the single-chain structure is labeled as "Single Chain", the DAG structure is labeled as "DAG", and the DAG lattice structure is labeled as "DAG lattice".

(1) Average transmission delay under different numbers of nodes

Fig. 3 presents a comparison of the average transmission delay under different numbers of nodes. The x-coordinate represents the number of nodes (20, 40, 60, 80, 100, 120), while the y-coordinate shows the average transmission delay under different structures. As can be seen from Fig. 3, regardless of the number of nodes, the average transmission delay using the DAG lattice structure blockchain is the lowest, while the single-chain structure exhibits the highest average transmission delay. This is because, under the single-chain structure, multiple transactions need to be packaged into blocks, resulting in larger block sizes and higher transmission delays. Both the DAG and DAG lattice structures achieve consensus on a per-transaction basis, leading to lower transmission delays. However, the average transmission delay in the DAG lattice structure is lower than in the DAG structure, as the former only requires consensus among neighboring nodes, while the latter necessitates the transmission of transactions to all nodes in the network.

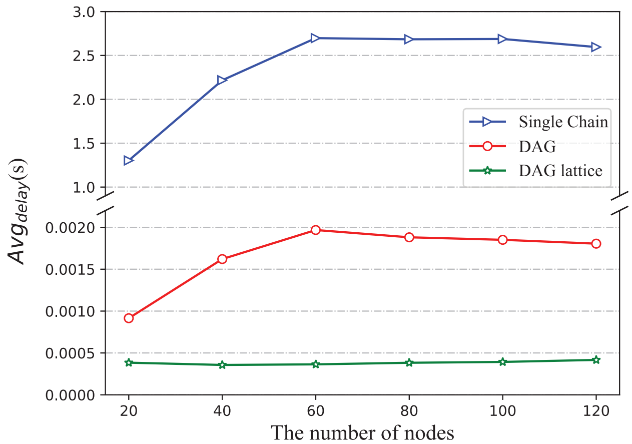


Figure 3: The comparison of Avg_{delay} different number of nodes

(2) Storage cost of nodes

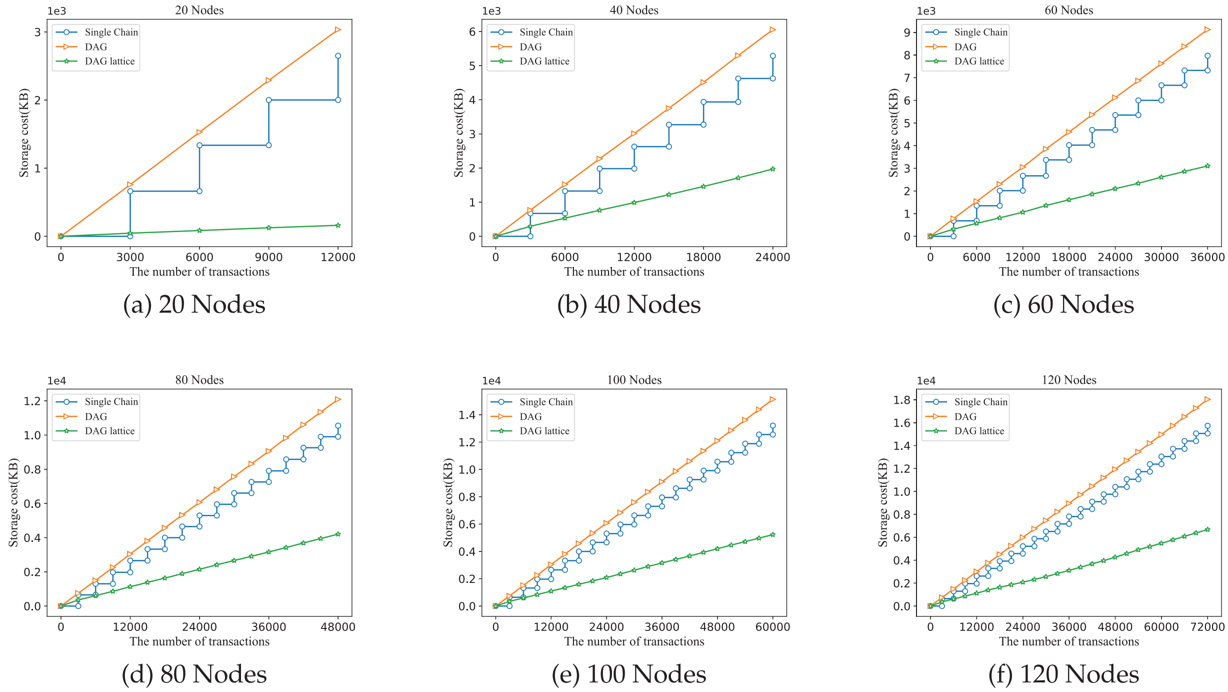
1) Storage cost of nodes under different structures

Fig. 4 presents a comparison of the storage cost of nodes under different structures as the number of system transactions increases. The x-coordinate represents the number of transactions generated by the system, while the y-coordinate shows the storage cost of the nodes. Fig. 4a–f respectively describes the storage costs in scenarios with 20, 40, 60, 80, 100, and 120 nodes. In both the DAG and DAG lattice structures, the storage is updated with each new transaction, while in the single-chain structure, the storage is updated with each new block. As can be seen from Fig. 4, regardless of the scenario, the storage cost of nodes in the DAG lattice structure is always lower than that of the other two structures. This is because, in the DAG lattice structure, nodes only store the account chain data of neighboring nodes. In the DAG structure, each transaction includes information about its parent node, whereas in the single-chain structure, each block (with 3000 transactions per block in this experiment) only contains the block header. Therefore, the storage cost in the single-chain structure is lower than in the DAG structure.

2) Storage cost of RSU and vehicles under different numbers of nodes

Fig. 5 presents a comparison of the storage costs of different types of nodes in the DAGL-IoV system as the number of nodes increases. The x-coordinate represents the number of nodes (20, 40, 60, 80, 100, 120), while the y-coordinate shows the storage costs for different types of nodes. In this experiment, the storage costs of RSU nodes (labeled as "RSU") and vehicle nodes are compared. For the vehicle nodes, three different storage methods are considered based on their storage capacity, namely: (1) storing all transactions generated by surrounding nodes (labeled as "Vehicle_All"), (2) storing pruned transactions (labeled as "Vehicle_Pru"), and (3) storing only the minimal number of transactions that do not affect blockchain operation (labeled as "Vehicle_Min").

As shown in Fig. 5, as the number of nodes increases, the storage costs for different types of nodes also increase. The RSU, which stores the entire blockchain ledger, incurs the highest storage cost. The storage cost for vehicles is lower than that for RSU, with the "Vehicle_Min" storage method having the lowest cost. When the number of nodes is small (20, 40, 60, 80), fewer transactions are generated, so there is no need to prune transactions. However, when the number of nodes is large (100, 120), more transactions are generated. Due to insufficient storage space, vehicles prune partial transactions, thus the storage cost of the "Vehicle_All" method is higher than that of "Vehicle_Pru".



(a) 20 Nodes (b) 40 Nodes (c) 60 Nodes

(d) 80 Nodes (e) 100 Nodes (f) 120 Nodes

Figure 4: The comparison of storage cost under different structures

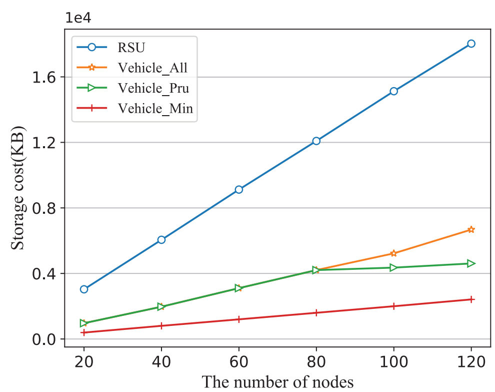


Figure 5: The storage cost of RSU and vehicle under different number of nodes

Discussion: As the blockchain operates, the storage space required for maintaining the DAG lattice ledger grows continuously, which imposes heavy storage burden and maintenance costs on RSUs. To address this, a layered ledger design can be adopted, where RSUs only maintain chain data related to their geographic regions, while cross-regional queries are handled through communication among different RSUs. However, this goes beyond the scope of this paper, and we will focus on addressing this issue in our future work.

3) Storage cost of a single vehicle node under different storage methods

Fig. 6 shows the variation in the storage cost of a single vehicle node in the DAGL-IoV system under different storage methods. The data in the figure are from randomly selected nodes in a scenario with 120 nodes. The x-coordinate represents the system runtime, while the y-coordinate shows the storage costs for the vehicle node under three different storage methods. These three methods are: (1) storing all transactions generated by surrounding nodes (labeled as “Vehicle_All”), (2) storing pruned transactions (labeled as

"Vehicle_Pru"), and (3) storing only the minimal number of transactions that do not affect blockchain operation (labeled as "Vehicle_Min").

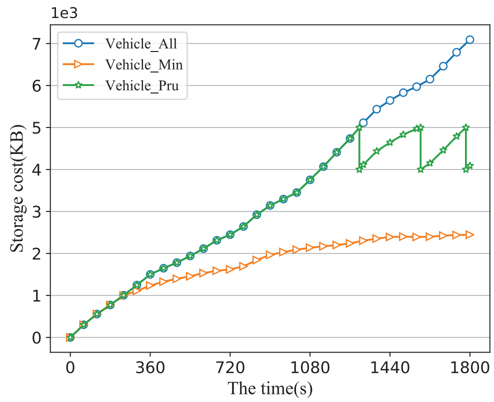


Figure 6: The storage cost of a single vehicle node under different storage methods

As shown in Fig. 6, the storage cost is lowest when using the "Vehicle_Min" method. As the system runs, when the storage cost of the vehicle exceeds a certain threshold, the "Vehicle_Pru" method will prune transactions locally, keeping the storage cost consistently below that threshold.

(3) The impact of different false message sending frequencies f on updating reputation score

Fig. 7 illustrates the impact of different false message sending frequency f on updating nod's reputation score. The x-coordinate represents the number of reputation score update rounds, while the y-coordinate shows the node's reputation score. As shown in Fig. 7, with an increase in the frequency f of false message transmissions, the number of update rounds required for a node to recover its reputation score to 100 also increases. This is because a higher frequency of sending false messages f results in a lower reputation score threshold S_{thr}, causing nodes to require more rounds to increase their reputation scores linearly, while each incremental increase becomes smaller. Therefore, it can be concluded that the reputation score update method proposed in this paper effectively incentivizes nodes to maintain normal behavior.

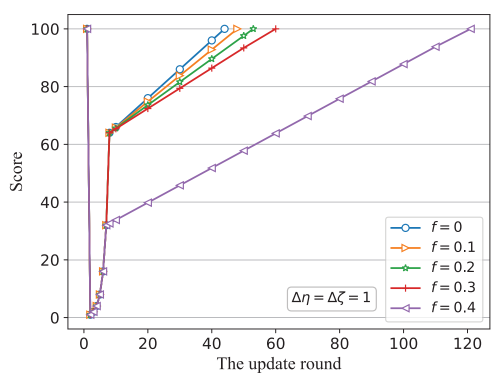


Figure 7: The impact of f on updating node's reputation score

7 Conclusion and Future Work

This paper adopts a DAG lattice structure to address the issues caused by dynamic connectivity in the IoV, and proposes a security architecture based on DAG lattice blockchain. This architecture avoids the issue of being unable to synchronize transactions due to network splits, while also better aligning with the characteristics of the IoV. The experimental results show that the blockchain based on the DAG lattice structure performs better in terms of average propagation delay compared to the singlechain structure and DAG structure. At the same time, while ensuring the normal operation of the blockchain, the storage space required by the DAG lattice structure is smaller than that of the single-chain structure and DAG structure. In future work, we plan to design a layered ledger to reduce the storage burden and maintenance costs of RSUs and deploy the proposed scheme in a real-world setting to verify its effectiveness.

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Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest regarding the present study.

Key Abbreviations

IoV	Internet of Vehicles
DAG	Directed Acyclic Graph
DAG lattice	Directed Acyclic Graph lattice
RSU	Roadside Units
TPS	Transactions Per Second
TCP	Transmission Control Protocol
DSRC	Dedicated Short Range Communication
C-V2X	Cellular Vehicle-to-Everything
TC	Trust Center
DoS	Denial of Service

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