Blockchain Dividing Based on Node Community Clustering in Intelligent Manufacturing CPS

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***Abstract*—The blockchain technology becomes a key facilitator for *Intelligent Manufacturing* as it enables intelligent nodes to participate in global manufacturing networks with secure ledgers and smart contracts features. However, Traditional centralized storage cannot meet performance and security requirements and fully distributed storage consumes a large amount of computing, storage and network resources, which is inefficient and difficult to implement. In this paper, we propose a clustering strategy on node community clustering by constructing a trust model based on the decentralization of blockchain technology. We introduce a multi-chain storage structure. Our experiments show that the proposed strategy reduces data synchronization time and storage space, improves system performance by enabling efficient parallel processing.**

***Keywords*-Intelligent Manufacturing, Blockchain, Multi-chain, Strategy of Blockchain Dividing**

I. INTRODUCTION

Cyber-Physical System (CPS) is the unification of computer and physical process, and it is an intelligent system that integrates calculation, communication and control. They are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet [1]. CPS has an integrated relationship with technologies such as Internet of Things, Industrial Control Systems, and Industrial Internet [2]. CPS shows great promise in factories of the future in the areas of future trends [3]. Today, the manufacturing industry is aiming to improve competitiveness through the convergence with cutting-edge ICT technologies in order to secure a new growth engine [4]. However, in the traditional intelligent manufacturing production mode, the operation, production and maintenance records of equipment are stored in a single and isolated third-party database system. When the data need to be transmitted and communicated between devices, the equipment needs to send data request to the third-party database system first, then the database system receives the requests and transmits the target data to the requesting equipment. The equipment have to do this long and complex process to ask for data from the database, which brings great storage pressure to the third-party database system, and slow down the speed for data query. The huge amount of data requests and provisions among many devices in the intelligent manufacturing system brings great challenges to the centralized database storage system in terms of data storage, data processing capabilities, and energy consumption. In addition, there are security problems in this storage method to varying degrees. Firstly, in the absence of a powerful data protection framework, the possibility of data loss and tampering exists in the transmission of digital parameters of information. Secondly, the centralized data storage method also has serious security risks. Once the centralized database system encounters failures, malicious attacks or production equipment safety and production accidents, it is difficult for equipment owners, users, manufacturers and production safety departments to ensure the authenticity and consistency of records, and it could hinder the prevention of future accidents and improvements on the equipment.

Blockchain has the features of unalterable data entries, data encryption and traceability. We propose to use the important feature of decentralized ledgers of the blockchain technology to connect control modules, nodes, subsystems and ERP systems in the manufacturing network. Through the unified ledger, we can monitor every link of production and manufacturing continuously and reliably.

In this paper, our main contributions is that we proposed a strategy of blockchain dividing based on node community clustering. It is a method for dividing nodes into different groups in a CPS system. Each group is a chain and contains some nodes maintaining the same data. A node can be added to different chains according to the strategy. For data synchronization, the nodes on the same chain only need to synchronize the data of the nodes that have joined this chain. Our strategy produces less cross-link communication data, reduces the network pressure in the system, and helps improve the efficiency of system communication. At the same time, it reduces the storage of irrelevant data by nodes and improves the speed of data query. Moreover, the data synchronization of nodes on different chains do not affect each other, which improves the concurrency of the system.

Our theoretical analysis and experimental results show that the proposed strategy can effectively reduce the time and storage space of data synchronization, and improve the system performance by enabling efficient parallel processing.

II. Related Work

Currently, blockchains mostly use single-chain scheme to store data and all nodes participate in consensus. With the increase of communication, the amount of data will become increasingly larger, and each node will synchronize and store some unnecessary data. In order to reduce the consumption of storage space, most of the existing blockchain data storage schemes choose to store large data outside the chain. By means of hash encryption of data on the chain, the data can be prevented from being tampered with, and only the hash value of the stored data can be quoted on the blockchain in order to meet the storage requirement of the business.

There are a few studies on the storage methods of intelligent manufacturing. Wang [5] proposed that intelligent manufacturing has the characteristics of large data scale and complex data structure and the optimal design of data storage structure. Based on the big data technology, he has analyzed the data relationship in the textile industry of intelligent manufacturing industry. However, this design scheme uses non-relational database, which has insufficient data association and fusion, and the data storage efficiency is not satisfactory. For traditional enterprise databases, open source relational databases lacking efficient data processing and analysis capabilities are often used, such as MySQL, postgresql and Oracle. Wang et al. [6] proposed using cloud platform technology to reconstruct hardware into resource pool and software layer to dynamically perceive resource requirements and reconstruct resources.

With the existing blockchain storage schemes, such as Bitcoin-NG [7], the performance of blockchain can be improved slightly, but the performance of blockchain consensus will be seriously reduced when a large number of nodes are confronted with single-chain hybrid processing. Factom [8] supports classification processing, but it can not meet the needs of rapid data validation. Xu et al. [9] proposed a master-multi-chain model based on hash anchoring, which takes the main chain verification block as the index block of the slave chain block, and constructs the master-multi-chain model with multiple slave links. But the model does not propose a relevant strategy of blockchain dividing. Yang [10] proposed a consensus mechanism based on queuing theory and an on-demand routing algorithm to improve the applicability of blockchain technology in power system. Ding et al. [11] proposed that they divided nodes into core nodes and light nodes in order to solve the problem that the storage space of nodes in the information physical fusion system, which is difficult to carry with the increase of data volume. Zhang et al. [12] proposed a data storage strategy of trust decentralization strategy. They divided the original data into dynamic data and static data. The dynamic data belongs to the part re-encrypted when the revocation algorithm occurs, while the static data belongs to the algorithm that does not need to be re-encrypted every time when the revocation occurs. Tian [13] proposed a secure storage architecture based on cloud platform, in which the cloud platform integrates control services, operation services and guidance services, and uses different databases to store the linear data and metadata of nodes. Wang et al. [14] proposed a new Dependable Exchange Protocol. With proper convertible signature scheme and message logging method, the exchange protocol provides a recovery method for network and local system failures. Cheng et al. [15] proposed a semicentralized mode with attribute-based blockchain in Internet of Vehicles to balance the tradeoff between the availability and the privacy preservation. In this mode, a method of control-by-vehicles is used to control signals of communication lights to increase communication efficiency. The mode not only achieves the aim of privacy preservation but also supports responsibility investigation for historical agreements via ciphertext-policy attribute-based encryption (CP-ABE) and blockchain technology. Zyskind et al. [16] proposed that they describe a decentralized personal data management system that ensures users own and control their data. They implement a protocol that turns a blockchain into an automated access-control manager that does not require trust in a third party.

Wang et al. [17] proposed locking and unlocking algorithms for smart contracts and design a digital account model for the transfer of assets between centralized and decentralized ledgers. Ma et al. [18] proposed a new blockchain-based data privacy management framework. The framework consists of three components: a data privacy classification method according to the characteristics of financial data and a new collaborative-filtering-based model and a confirmation data disclosure scheme for customer strategies based on the Nudge Theory. Ao et al. [19] proposed a framework for providing secure key management within the heterogeneous network. Zhao et al. [20] proposed that a new architecture called secure pub-sub (SPS) without middle ware, i.e., blockchain-based fair payment with reputation.

In SPS, publishers publish a topic on the blockchain and subscribers specify an interest message by making a deposit to subscribing the topic. Imbault et al. [21] proposed that they explore the use of blockchain technology implemented on an Industrial operating system (Predix) for a use case of green certificates, demonstrated within an eco-district. Asaph et al. [22] proposed MedRec: a novel, decentralized record management system to handle EMRs, using blockchain technology.

From the above-mentioned studies, we can see that the existing storage algorithms need the computing power of complex encryption and decryption algorithms, and data storage needs to rely on trusted third parties or a centralized core control. However, the core parts of data centralized storage that are vulnerable to attacks and have no effective scheme to prevent attacks. In addition, these data storage schemes and architectures can not solve the problem of data centralized storage. The efficiency of data processing and analysis is low. Also, the ability of data concurrent processing is weak. In summary, existing methods are not satisfactory for the practical application of intelligent manufacturing CPS.

In the intelligent manufacturing CPS system, there are many nodes and frequent interactions. From the aspects of function and performance, the single-chain storage structure of blockchain system, which is widely used at present, can not satisfy the requirements of high concurrency and large amount of data for many manufacturing equipments in intelligent manufacturing CPS system. It is mainly manifested in the following two aspects. Firstly, the feature of unalterable data entries of blockchain will make the nodes in the intelligent manufacturing CPS system with huge data volume bulky and bulky, and consume the storage space of the equipment extremely. Secondly, because of the serious homogenization of node types and slow execution speed, the communication speed between nodes can not meet the requirements of high concurrency and high response speed of manufacturing industry. In intelligent manufacturing CPS system, the interaction between nodes must meet the real-time requirements to meet the characteristics of flexible manufacturing process. Therefore, data storage structure and processing efficiency become the key factors to optimize system performance.

With the characteristics of intelligent manufacturing system, we should adopt multi-chain structure in the research of integration of blockchain technology and intelligent manufacturing CPS system. The multi-chain structure achieves the data isolation of the system. At the same time, the multi-chain structure can handle the high concurrent communication requirements of devices belonging to different chains. In addition, in the process of data storage, the ledger data needed by devices in different chains is no longer the data of all nodes, but only the data belonging to the device nodes in the chain, which reduces the storage space required by the devices and improves the execution speed of the system.

Aiming at the storage performance problem of blockchain technology in intelligent manufacturing and considering the community structure among intelligent manufacturing nodes, we propose a blockchain-dividing strategy based on cluster of node communities.

III. Strategy of Blockchain Dividing Based on Clustering of Node Societies

A. Node Communication Trust Relation Model

In actual production, there are differences in communications between nodes, which can be used as a basis for data chaining. Based on this, we propose a trust model of undirected weighted graph. In this model, we abstract the device as a node in an undirected graph. The edge strength represents a certain communication relationship between two connected nodes, and the degree of communication tightness represents the communication between one node and the other joint nodes, which is a variable to measure the degree of trust relationship between devices. Establishing the undirected-weighted-graph-based trust model is helpful for us to quantitatively analyze the trust relationships among the participating nodes in the network. Relevant variables in the model are defined as follows:

edge strength, edge strength ω_{ij} is the strength on the joint edge l_{ij} of the node v_i and the node v_j, which represents the communication between the node and the node.

communication tightness, tightness of communication between devices is defined here as the amount of communication between two nodes v_i and v_j in a unit time. That is, the greater the edge strength, the higher the tightness of communication between nodes.

B. Blockchain-dividing strategy based on node community structure partition

In order to store the data of many intelligent manufacturing nodes in multi-chains, the nodes in the system must be divided first. We divide the equipment in the system into different groups according to the communication tightness between the equipment, so that the equipment with close communication relationships can be divided into groups as far as possible, so as to form a data chain in the blockchain system with a multi-chain structure. Therefore, when data changes occur due to communications between devices, and if two nodes are on the same chain, all nodes in the chain need to synchronize data. If two nodes are not in the same chain, then all nodes in the two chains need to synchronize the changed data because of the cross-chain communication.

By analyzing the community structure of complex network relations, we propose a blockchain-dividing strategy to store and process device data. Community is a set of nodes with similar function. For a graph G, if one of the complete subgraphs (with edges between any two nodes) has k nodes, then the complete subgraph can be called a k-clique. If there are $k-1$ common nodes between two k-cliques, then the two cliques are adjacent and such a series of cliques adjacent to each other constitute the largest set, which is called a community. Clubs can overlap and nodes can be allowed to belong to multiple communities at the same time. As shown in Figure 1, there are four associations, three of which contain common nodes with other associations. The algorithm is as follows.

Algorithm 1 algorithm of nodes divided into community

Input:
The threshold of the tightness of communication between devices, T;
The set of edge strengths between nodes, S_n;
Output:
The set of nodes and communities, C_k ;

repeat
  while W_i **in** S_n **do**
    if $W_i \geq T$ **then**
      continue
    else
      Delete(W_i)
    end if
  end while
until all nodes are connected and $W_i \geq T$. If not, T need to be reset a new value
$k = 3$
repeat
  if all nodes can divide in k communities **then**
    $C_k \leftarrow k$
  else
    $k = k + 1$
  end if
until all nodes in the network can not be divided into communities
return C_k;

- Step 1. According to the tightness of communication between devices in intelligent manufacturing system, a threshold is set, and the communication relationship between nodes is divided into two categories. One is that the communication relationship is relatively close and the edge strengths between nodes are larger than the set threshold. The other is less communication and the edge weights between nodes are less than the threshold or there are no edges. According to the classification results, the nodes with close communication relationship are divided into the same group.
- step 2. In all the groups in step 1, check whether all nodes have edges and their strengths are greater than the threshold. If it is not, adjust the threshold and repeat the step 1 until all nodes have edges whose edge strength are greater than the threshold connected to them (except for individual special devices in the actual production environment).
- Step 3. Delete the edges whose strengths are lower than the threshold value, and take the edges whose strengths are larger than the threshold value as the research object. According to the communication tightness between nodes, the nodes in the system are divided into communities.
- Step 4. In the process of community partition, we first set 3 nodes in a community. Then increase the number of community containing nodes in turn and record the results of the number of communities that can be divided by all nodes in each trip until all nodes in the network can not be divided into communities. At this time, all the cases of dividing the associations have been listed, and the process of dividing the associations has been completed.
- Step 5. Count the results of each community partition including all the nodes in the system, and point out the common nodes between communities.

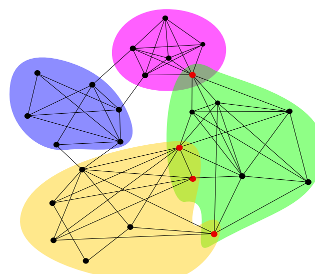

Figure 1. Community Structure

IV. Experimental Results and Analysis

A. Experimental Settings and Data Set Processing

In this paper, the data communication between nodes in an intelligent manufacturing CPS system is taken as the data acquisition object. Considering a device port as a node in a blockchain network, the communications between device ports are used to simulate the communications between nodes in intelligent manufacturing CPS system, and the monitoring port is used to count the communications between nodes, obtain and analyze the data.

The experimental simulation environment represents an intelligent manufacturing system with 44 nodes. The number of nodes is from '01' - '44'. According to the actual production situation, the communications between nodes generating the communications based on different configurations. In terms of the tightness of communication, some nodes have heavier communication loads while some nodes have lighter communication loads. In terms of node degree, some nodes do not have interconnection and interoperability. Furthermore, some nodes communicate with many nodes in the system, while some nodes only communicate with a few nodes in the system.

In the experimental simulation process, we randomly select a part of the nodes from 44 nodes, and there is no communication relationships between these nodes. We then randomly select a part of the nodes in these nodes: the communication intervals between these nodes are short and the communication volumes are high; the rest of the nodes have long communication time intervals and the communication volumes are low. The experiment produced 48667 communication records.

B. Classification of node edge weight relations generated by simulation

In order to implement the multi-chain storage structure in the blockchain system, it is necessary to classify all nodes in the system according to the communication tightness set as a threshold. During the process of classification, in order to differentiate the edges connected between nodes according to different classifications, the edges whose communication tightness is higher than the threshold are represented by solid yellow lines and the edges whose communication tightness is lower than the threshold are represented by blue dotted lines. The undirected weighted graph constructed by the model is depicted in Figure 2.

In Figure 2, all the nodes of the experimental model set the thresholds according to the tightness of communication. Among them, the first group and the second group have high internal communication tightness, while the nodes in the two groups have very little communication with other nodes. In contrast, the third group of nodes is more complex than the first two. Node 3023 and node 5022 are at the intersection of two groups respectively. We use k-clique penetration algorithm to divide the nodes into communities, taking the solid line in the graph as the research object. Firstly, we take out the edges of solid lines (edge weights greater than thresholds) between nodes in the model.

After removing all edges whose edge weights are below the threshold, we use the k-clique infiltration algorithm to divide nodes into different communities. In the process of partitioning, the first step is to start with $k = 3$ nodes in the community. When each partition is completed, the value of k is added 1 in turn until all nodes in the network can not be divided into communities. That is to say, all cases of the division of associations have been enumerated. In the simulation experiment set up in this paper, the results of 44 nodes dividing communities are as Table 1 shown.

From the results of community division, we can see that when the number of communities is 5, all the nodes in the experiment are divided into at least one community, and the rest of the partition results have different number of nodes not divided into communities. Therefore, in this experiment, when all nodes are divided into 5 communities according to the community structure, the dividing method is effective. Other dividing methods are ineffective because of the existence of nodes that are not classified into the community.

C. Data Storage Space Analysis

After dividing the nodes in the experiment, it is necessary to analyze the space occupied by the data storage, so we can see the improvement due to the storage optimization by the data chaining strategy. In order to facilitate statistical analysis, a block contains only one piece of data generated by communication between nodes. We assume that the size of each piece of data is the same, so each block size is the same. A block with a piece of data is the basic unit of storage. Then, the number of blocks generated by all nodes is the total number of communications. The size of the space occupied by storing data in the experiment is only related to the communication of nodes in each chain in the experiment. For four strategies, namely, non-dividing, random blockchain-dividing, blockchain dividing base on edge strengths, and node-based community dividing, we respectively calculate the storage space occupied by various chains and the storage space occupied by cross-chain communication under the blockchain-dividing strategy. The total communication of the system can be calculated according to the following formula.

$$count = insid + cross = \sum i_{cj} * n_{cj} + \sum n_{c2} * i_{c2} \quad (1)$$

Among them, $count$ is the total communication, $insid$ is the intra-chain communication, $cross$ is the inter-chain communication under cross-chain communication. The statistical results are shown in Figure 3.

From the comparison results in Figure 3, we find that the data occupies the most storage space when the nodes are ungrouped. Random blockchain-dividing can effectively reduce the space occupied by data storage, but it can not improve the efficiency of data processing and system concurrency. Random blockchain-dividing makes the data storage between nodes irregular, which may not synchronize the data between nodes with high communication density. It results in that the nodes in other chains need to query data across chains many times in order to get the data of the related nodes, which slow down the speed of data query in the system and affects the efficiency of the system. In addition, using the random blockchain-dividing method, the data of different tasks need to be maintained in one chain, which makes the data records maintained by the nodes confused. As a result, the nodes often have cross-chain communication when synchronizing the data, and the synchronized data between the nodes is more frequent, resulting in redundant data that multiple chains maintain the same data and increasing the system overhead. Clustering nodes base on community structure can effectively reduce the space

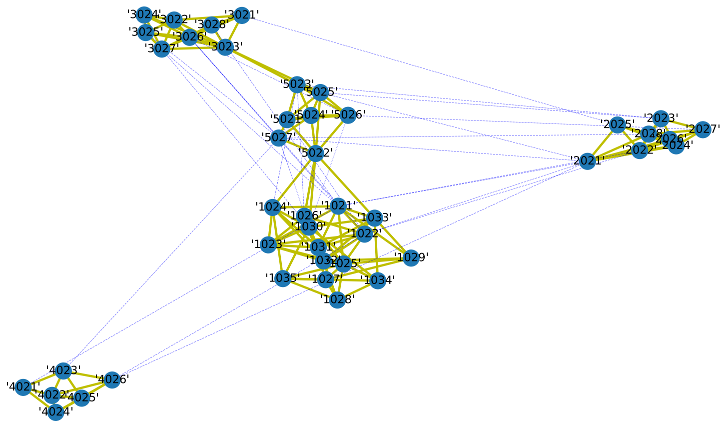

Figure 2. Trust Relation Model Graph Based on Communication Tightness Classification

Table I
STATISTICAL TABLE OF THE RESULTS OF THE DIVISION OF ASSOCIATIONS

Grouping method		**Interchain node**	**count**	**cross**
Ungrouped		Null	2141348	0
Random grouping	dividing into 3 groups No.1	Null	834634	231041
	dividing into 3 groups No.2	Null	1399677	944376
	dividing into 4 groups No.1	Null	697724	275052
	dividing into 4 groups No.2	Null	958928	731827
	dividing into 5 groups No.1	Null	510002	126346
	dividing into 5 groups No.2	Null	835004	678367
Grouping by edge strength(3 groups)		Null	1068800	8798
Grouping by Community Structure(5 groups)		2	509960	84444

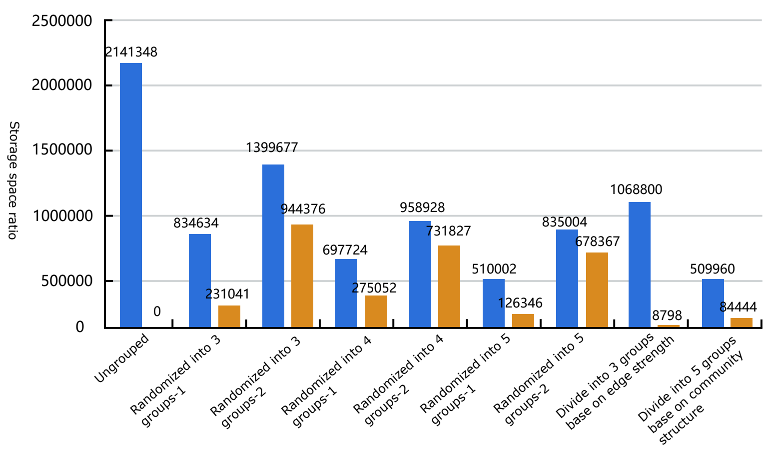

Figure 3. Spatial statistics of different classification methods

occupied by data storage, speed up data processing, and improve the concurrency of the system.

According to the different grouping combinations of nodes (randomly divided into three groups, four groups and five groups, each group has two different ways of grouping nodes), the space occupied by communication data storage between nodes fluctuates with the different grouping methods. If only the nodes are grouped by the weights between nodes, the nodes in the system are divided into three groups. The occupy space of nodes divided into three groups is not the least one in all methods. So it is necessary to divide the nodes into community structure in the next step to achieve a more reasonable partition of nodes. When the nodes are divided into regular communities using community structure algorithm, the storage space of communication data between nodes is better than other random grouping, and there is no obvious advantage with the first method of random grouping (”random grouping 5-1”).

We considers the storage space occupied by the data volume storage of system cross-link communication (represented by cross). As can be seen from the above figure, the first method (”Random Five Groups-1”) which is randomly divided into five groups has the storage space of 510002 to 509960 of the community structure partition method. However, in the random grouping method, the cross-chain communication is much larger than the cross-chain communication of the community partitioning method. That is to say, the first distribution which is randomly divided into five groups is similar to the result of community partition in the total storage space, but there are a lot of data generated by cross-chain communication in the random group. These cross-chain communication data consume a lot of resources and make the nodes on the chain have a lot of redundant data, which makes the nodes in the system look up the corresponding data when they query it. The speed of inquiry decreases, which affects the efficiency of the system. In addition, because the nodes on a chain in a random grouping may not have a large communication relationship, the nodes synchronize more irrelevant data, which affects the concurrent processing of communication data between nodes in the system. It is difficult to achieve the goal of multi-chain storage to improve the concurrency of the system. The comparative results of the effects of blockchain-dividing method, random dividing method and community dividing method on system performance are shown in the table below.

In summary, comparative analysis shows that the system space occupied by storage can be significantly reduced by using multi-chain storage structure. By using the strategy of community clustering and blockchain-dividing strategy, the storage space of the system can be optimized and the concurrency of the system can be improved.

Table II
PERFORMANCE COMPARISON OF DIFFERENT BLOCKCHAIN-DIVIDING METHODS

Methods	**Storage space occupancy**	**Query speed**	**Concurrency**
Non-dividing chain	1	Slow	Sequential processing
Random dividing chain	0.33	Fast	Concurrent
dividing on community construct	0.23	Fast	Good Concurrent

V. CONCLUSION

In this paper, we focus on the performance problems caused by centralized storage in the current intelligent manufacturing system CPS. In intelligent manufacturing, the data storage space in manufacturing equipment is limited. With the increase of the number of devices and the accumulation of communication data, the limited storage space of manufacturing equipment can not suffer the pressure from the storage of large amounts of data. In order to address this problem, we first construct a trust relationship model according to the equipment communication characteristics of intelligent manufacturing CPS system, so that we can make statistical analysis of the communication data in the system. Second, we propose and analyze a blockchain dividing strategy based on community structure clustering method. Finally, we test the proposed blockchain dividing strategy by simulate comparative experiments with strategies including undividing, random dividing, and dividing with the community structure clustering method. The experimental results show that multi-chain storage can greatly reduce the consumption of data storage space. Compared with random dividing, the method of community structure division can reduce the number of cross-chain communication, effectively reduce the communication load in the system, and help to improve the communication efficiency of the system. At the same time, the strategy of blockchain dividing can reduce the storage of irrelevant data, so the data processing efficiency is improved. The multi-chain structure enables that the synchronization data of nodes in different chains will not affect each other, in this way, we improve the concurrency of the system.

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