IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 4 October 2022, accepted 25 October 2022, date of publication 1 November 2022, date of current version 8 November 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3218660

RESEARCH ARTICLE

Intelligent Terminal Computation Offloading Method Based on the Incentive of Reputation Value

HUI ZHI[1,2], YINLIANG WU[1,2], XINYU ZHANG[3], AND LIXIA YANG[2], (Member, IEEE)
[1]Key Laboratory of Intelligent Computing and Signal Processing of Ministry of Education, Anhui University, Hefei 230601, China
[2]School of Electronic and Information Engineering, Anhui University, Hefei 230601, China
[3]School of Computer Science and Technology, Anhui University, Hefei 230601, China

Corresponding author: Hui Zhi (zhihui_0902@163.com)

This work was supported by the National Natural Science Foundation of China under Grant 62001001, Grant U21A20457, Grant 62071003, Grant 41874174, and Grant 61901004; by the Natural Science Foundation of Anhui Province under Grant 2008085MF186; by the University Collaborative Innovation Project of Anhui Province under Grant GXXT-2020-050; by the Key Basic Research Program of the State Administration of Science; and by the Technology for Nation Defense and Collaborative Innovation Program of Colleges in Anhui Province under Grant GXXT-2021-028.

ABSTRACT Existing researches that apply blockchain into computation offloading do not consider the enthusiasm of terminals to participate in computation offloading, the fairness of terminals to obtain bookkeeping right and the consensus mechanism that applicable to computation offloading between terminals. So, in this paper, a computation offloading method based on reputation value incentive is proposed, and the detailed workflow of this method is designed. In the workflow, a computation resource allocation method based on dynamic adjustment auction, a mining difficulty setting method based on intelligent terminal devices (ITDs) clustering and an improved POW consensus mechanism based on reputation value (RVPOW) are proposed to ensure the fairness of ITDs to obtain bookkeeping right and improve the enthusiasm of ITDs to participate in computation offloading and blockchain consensus. Simulation results show that the proposed computation offloading method can encourage ITDs to participate in computation offloading, and the RVPOW consensus mechanism can achieve fast consensus.

INDEX TERMS Computation offloading, blockchain, K-means clustering, reputation value.

I. INTRODUCTION

In recent years, with the rapid development of mobile internet technology, the number of intelligent terminal devices (ITDs) increased explosively, which leads to the uses of various applications on ITDs and the needs of high computation power on ITDs [1]. However, ITD has limited computation resources, so it is difficult to complete computation intensive tasks in limited time. Therefore, many researchers have studied the method of offloading terminals' computation tasks to edge server [2]. But when ITD is far away from edge server and cannot connect to edge server, or when edge server is too busy with computation tasks and there are idle terminals' computation resources around the ITD that cannot be effectively utilized, the method of computation offloading to edge server is no longer applicable. So, researchers began to discuss the method of computation offloading to other ITDs with idle resources [3], [4], and this paper also discusses the method of computation offloading to other ITDs.

Many methods of computation offloading to other ITDs are studied, such as the methods in [5] and [6]. Although the methods in [5] and [6] can solve the problem of processing intensive computation tasks in time, they have the data security problem caused by central node failure. Blockchain (BC) is decentralized and its data cannot be tampered with, so blockchain can solve the data security problem in computation offloading [7]. Therefore, some researchers apply BC into computation offloading.

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

But existing researches that apply blockchain into computation offloading only discuss how to improve the data security in computation offloading without considering the enthusiasm of IDTs to participate in computation offloading and block consensus, the fairness of IDTs to obtain bookkeeping right, and the consensus mechanism that applicable to computation offloading between terminals.

ITDs are selfish, due to the mutual distrust, they are not willing to participate in computation offloading or sharing computing resources. Thus, in the network, the ITDs' computing tasks cannot be effectively configured and ITDs' idle computing resources cannot be fully utilized. On the other hand, if ITDs are not willing to participate in block consensus or they are cheating in block consensus, it is difficult to guarantee the security of the blockchain system. Therefore, we introduce reputation value as an incentive to encourage ITDs to honestly participate in computation offloading and block consensus. First, ITDs can obtain reputation value through honest cooperative computation and honest generating blocks. If an ITD cheats when participating cooperative computation and block consensus, it will be blacklisted and cannot participate in cooperative computation and blockchain consensus anymore. The higher the reputation value of an ITD, the more the rewards it gets, so ITDs are encouraged to honestly participate in cooperative computation and block consensus. Thus, ITDs' computing tasks can be effectively configured, ITDs' idle computing resources can be fully utilized and the security of blockchain system can be improved. Second, ITD reputation values are recorded in blockchain, which is open, transparent and cannot be tampered with. So, ITDs can trust each other, actively and honestly participate in computation offloading and block consensus, and the system security can be improved.

On the fairness of ITDs to obtain bookkeeping right, literatures [8], [9] use the decentralized characteristics of BC to build the trust foundation between ITDs and improve the data security in computation offloading. Literatures [10], [11] take reputation value as an evaluation standard, which is directly proportional to the reward and can improve ITDs' enthusiasm. However, in [8], [9], [10], and [11], only the ITDs with highest reputation value can obtain bookkeeping right, ITDs with low reputation value cannot obtain bookkeeping right, so the consensus mechanism designs in [8], [9], [10], and [11] are unfair to all ITDs, and ITDs with low reputation value will lose their enthusiasm to participate in consensus. To improve the fairness of ITDs to access bookkeeping right, this paper proposes a mining difficulty setting method based on ITDs clustering, which can dynamically adjust the mining difficulty value of each ITD, so that ITDs can obtain bookkeeping right more fairly.

On the consensus mechanism that applicable to computation offloading, the blockchain consensus mechanisms adopted in [8], [9], [10], [11], and [12] need long time to generate block and achieve consensus. For example, The POW used in [8] and [9] needs long time to generate block, and the consensus mechanisms in [10] and [11] also need long time to generate block. Reference [12] uses blockchain and smart contract to promote task offloading and mitigate various security attacks, designs a trust index to improve the possibility of successful offloading, and develops a trust evaluation mechanism to improve the safety of computation offloading. Although the consensus mechanism in [12] improves the success rate of computation offloading, it has high computational complexity and long block generation time, which affects the timeliness of the whole system. Consensus mechanisms in [13], [14], and [15] only focus on the data security of BC computation offloading. T-PBFT consensus mechanism in [16] constructs a trusted consensus group based on the delegation model, which can effectively reduce the number of consensus nodes. T-PBFT evaluates the trust value of each node and prevents dishonest nodes from obtaining bookkeeping right. RTChain in [17] is a reputation-based consensus mechanism. First, leader is randomly selected from all nodes and some nodes with high reputation value are selected as consensus nodes. Then, dishonest nodes are punished by reducing their reputations. To sum up, all the consensus mechanisms in [8], [9], [10], [11], [12], [13], [14], [15], [16], and [17] focus on the data security of BC computation offloading, do not optimize the block generation delay in BC computation offloading. However, in the scenario of terminal computation offloading, blockchain needs to record transactions and update the reputation values of terminals in time, so the consensus mechanisms in [8], [9], [10], [11], [12], [13], [14], [15], [16], and [17] with long time delay are not applicable to the computation offloading between terminals, we need to design a blockchain consensus mechanism that can generate blocks fast and achieve rapid consensus.

In this paper, in order to encourage terminals to participate in computation offloading and achieve rapid consensus, a computation offloading method based on reputation value incentive is proposed. When designing the computation offloading method based on reputation value incentive, there are three aspects need to be considered: the computation resource allocation scheme to incentive ITDs, the mining difficulty design to incentive ITDs, and the consensus mechanism design that is suitable for the computation offloading between terminals.

In the aspects of computation resource allocation scheme and mining difficulty design to motivate ITDs, literatures [18], [19], [20] focus on the application of different types of auction algorithms in computing offloading. But the auction algorithms in [18], [19], and [20] are all static auction algorithms, and cannot improved the enthusiasm of ITDs to participate in computing offloading. Literature [21] uses two-stage auction algorithm to allocate computation resources. The first stage is selecting primary users and secondary users, and providing auction strategies to maximize the utility. The second stage is proposing an auction algorithm to realize the stable matching between primary users and secondary users and ensure the security of transactions. Although [21] improves the throughput of the ITDs that are participation in the computation offloading, it cannot encourage ITDs to participate in computation offloading. While in our work, we consider a dynamic adjustment of auction price to encourage ITDs to participate in computation offloading. In addition, reference [22] adopts the incentive system combined with reputation value. Although the incentive system can effectively improve the efficiency of ITDs participating in computation offloading, it does not consider the dynamic adjustment of mining difficulty, so ITDs with high reputation value frequently obtain bookkeeping right, this leads to the centralization of bookkeeping right and violates the decentralized idea of BC. In order to encourage ITDs to participate in computing offloading, we propose a computation resource allocation scheme based on dynamic adjustment auction, and add the dynamic adjustment of auction price in each round of auction to facilitate CRP to obtain greater revenue. Therefore, the dynamic adjustment of auction price can encourage CPRs to participate in computation offloading. In addition, in order to ensure that ITDs have fair bookkeeping right, we design a dynamically adjusting mechanism of mining difficulty, ITDs are divided into L clusters based on reputation value K-Means clustering, and different clusters are set with different mining difficulties. Therefore, the mining difficulty can be dynamically adjusted with the change of reputation value. Then, the reputation value threshold and dynamically adjusting of reputation value are set to improve the fairness of ITDs to achieve bookkeeping right.

In the aspect of the blockchain consensus mechanism design, some researches have applied blockchain into computation offloading, but these researches only consider the data security of computation offloading, without considering how to achieve fast consensus, such as previously described literatures [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. In addition, some literatures propose consensus mechanisms that can achieve fast consensus, such as improved Raft in [23] and Consensus Resource Slicing Model (CRSM) in [24], but these consensus mechanisms are also not suitable for terminal computation offloading. In order to improve ITDs' enthusiasm and reduce the block generation delay, this paper proposes a RVPOW consensus mechanism, which can encourage terminals to participate in computation offloading and achieve rapid consensus on the premise of ensuring data security.

The contribution of this paper is summarized as follows:

1. Computation offloading method based on reputation value incentive is proposed, and the detailed workflow of this method is designed, including system initialization, computation resource allocation based on dynamic adjustment auction algorithm (DAAA), computation offloading, E-money transaction and reputation value update, blockchain consensus based on RVPOW.
2. A computation resource allocation method based on DAAA is proposed, which considers the ITDs' computing resource, computing task size and reputation value, selects the optimal one by one pairing of computation task owners (CTOs) and computation resource providers (CRPs), and obtains the corresponding transaction price for each pair. This computation resource allocation method can encourage ITDs to participate in computation offloading.
3. A mining difficulty setting method based on ITDs clustering is proposed. ITDs are divided into L clusters based on reputation value K-Means clustering, and their mining difficulty values are set according to the clusters, then the reputation value threshold and dynamically adjusting of reputation value are introduced to improve the fairness of ITDs in obtaining bookkeeping right.
4. A RVPOW consensus mechanism is proposed to encourage ITDs to participate in computation offloading and achieve fast consensus.

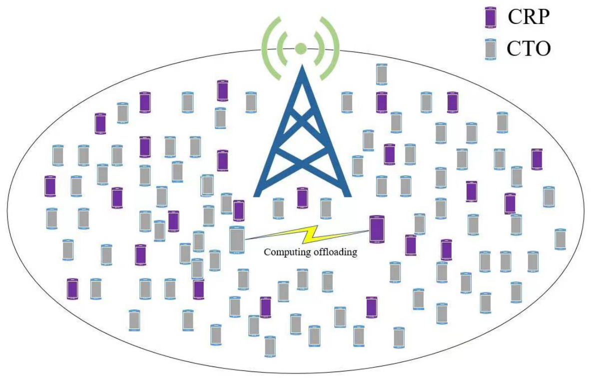


FIGURE 1. System model.

II. SYSTEM MODEL AND WORKING PROCESS

A. SYSTEM MODEL

The system model of computation offloading is given in Fig. 1. There are Q ITDs recorded as $U_1, U_2, \ldots, U_Q$ and one base station (BS). All ITDs are divided into M computation task owners (CTOs) that have computing tasks to be offloaded and N computation resource providers (CRPs) that have idle computing resources. M CTOs are written as $T_1, T_2, \ldots, T_M$ respectively, and N CRPs are written as $R_1, R_2, \ldots, R_N$ respectively. According to the size of computing task in each CTO and the size of the computation resources in each CRP, BS solves the resource allocation problem between CTOs and CRPs using a dynamic adjustment auction algorithm, and obtains the one-by-one pairing of CTOs and CRPs. Then, for each pair of CTO and CRP, CTO uses Device-to-Device (D2D) mode to offloading its computation tasks to its corresponding CRP. The local computing delay of T_i is the time delay of T_i completing its own computing task [10], that is

$$T_{T_i} = \frac{D_{T_i}}{V_{T_i}} \tag{1}$$

where $i \in \{1, 2, \cdots, M\}$, D_{T_i} represents the size of the computing task that T_i needs to offload. V_{T_i} represents the computing ability of T_i, i.e., the number of bits calculated by T_i per second.

The offloading computing delay is the time delay of T_i offloading computing task to R_j and the computing task is completed on R_j, that is

$$T_{T_i,R_j} = \frac{D_{T_i}}{B_{T_i,R_j} \times log_2(1 + \frac{P_{T_i} \times \xi}{N_{T_i,R_j}})} + \frac{D_{T_i}}{V_{R_j}} \tag{2}$$

where $j = \{1, 2, \cdots, N\}$. B_{T_i,R_j} represents the channel bandwidth that T_i transmits computing task D_{T_i} to R_j, P_{T_i} is the offloading transmit power of T_i. $\xi = \frac{1}{d^4_{T_i,R_j}}$, and $d_{T_i,R_j}$is the distance between T_i and R_j. N_{T_i,R_j} represents the additive white Gaussian noise (AWGN) power between T_i and R_j, V_{R_j} represents the computing ability of R_j.

B. WORKING PROCESS OF THE COMPUTATION OFFLOADING METHOD BASED ON REPUTATION VALUE INCENTIVE

The working process of computation offloading method based on reputation value incentive can be divided into following four steps. The working processes can be written into smart contract and executed automatically. Smart contract is executable code that can automatically run under certain conditions, BC smart contract does not require a trusted third party to manage, and it is an open and transparent contract recognized by all terminals [12].

(1) system initialization: Each ITD needs to register at BS as a legitimate user, BS records the ID of each ITD. Each ITD initializes its wallet address and reputation value.

(2) computation resource allocation based on dynamic adjustment auction algorithm (DAAA): Each CRP uploads its computation resource size to BS, BS uses the DAAA to obtain the one-by-one pairing of CTOs and CRPs and the corresponding transaction price for each pair. For the detailed description of computation resource allocation method based on DAAA, please refer to section III. A.

(3) computation offloading, E-money transaction and reputation value update: According to the one-to-one pairing results, for each pair of CTO and CRP, CTO offloads computing task to CRP and CRP completes the computing task. CRP sends the computation result back to CTO, and CTO verifies whether the calculation result is correct. Then, for each pair of CTO and CRP, if the calculation result is correct, CTO pays E-money to CRP according to the corresponding transaction price in step (2), and CTO and CRP broadcast their transaction information, other ITDs record this transaction information. After that, each CRP's reputation value is updated according to the its honest cooperative computation (expression (6) in the following).

(4) blockchain consensus based on RVPOW: ITDs are divided into L clusters based on K-Means clustering, and their mining difficulty values are set according to the clusters. For detailed ITDs grouping and mining difficulty value setting, see section III.B. When the block generation time comes, a new block is generated, then the new block is broadcasted and verified by other ITDs to reached a consensus according to RVPOW consensus mechanism. For the detailed description of RVPOW consensus mechanism, see section III.C. Each ITD's reputation value is updated according to its honest generation block (expression (6) in the following). If the new block reaches a consensus, it will be added into blockchain in the order of timestamp. If the new block does not reach a consensus, return to step (4) to regenerate a new block until consensus is reached.

In the above computation offloading method based on reputation value incentive, ITDs can obtain reputation value through honest cooperative computation and honest generating blocks. If an ITD cheats when participating cooperative computation and block consensus, it will be blacklisted and cannot participate in computation offloading and blockchain consensus anymore. The higher the reputation value of an ITD, the more the rewards it gets (expression (5) in the following), so ITDs are encouraged to honestly participate in computation offloading and block consensus.

III. COMPUTATION RESOURCE ALLOCATION METHOD AND CONSENSUS MECHANISM

A. COMPUTATION RESOURCE ALLOCATION METHOD BASED ON DAAA

In this paper, we apply auction algorithm into computation resource allocation scenario, computation task owners (CTOs) are buyers, computation resource providers (CRPs) are sellers, CRPs sell their idle computation resource to CTOs and help CTOs to complete computation tasks, so the dynamic adjustment auction algorithm (DAAA) is also a computation resource allocation method. Each CRP uploads its computation resource size to the BS, BS uses the DAAA given in Algorithm 1 to obtain the one-by-one pairing of CTOs and CRPs and the corresponding transaction price for each pair. The auction price $P^l_{T_i,R_j}$ is

$$P^l_{T_i,R_j} = \frac{1}{T_{T_i,R_j}} + \delta \frac{P^{l-1}_{R_j,max}}{T_{T_i,R_j} + T_{T_i}} \tag{3}$$

where $P^l_{T_i,R_j}$represents the auction price of T_i to R_j in the lth round auction. δ represents the auction price coefficient. $P^{l-1}_{R_j,max}$ is the largest auction price of R_j in the l-1th round auction. After the BS obtains local computing delay T_{T_i} for all $i \in \{1, 2, \cdots, M\}$ and offloading computing delay T_{T_i,R_j} for all $i \in \{1, 2, \cdots, M\}, j = \{1, 2, \cdots, N\}$, the DAAA is executed.

In the whole process of the DAAA, for each CRP in turn, CTOs conduct ten rounds price competitive auctions. In order to maximize the benefits of CRP R_j, in the first round of price competitive auction for R_j, K CTOs are selected from $T = \{T_1, T_2, \ldots, T_M\}$ randomly to bid for R_j's idle computing resource, and the CTO with highest auction price is chosen from selected K CTOs. In the next round of auction for R_j, the last chosen CTO is excluded from $T = \{T_1, T_2, \ldots, T_M\}$, and the rest CTOs bid for R_j, and the auction prices of all CTOs are dynamic adjust according to expression (3), that's to say, the auction prices in the next round is affected by the highest auction price in the previous round. After ten rounds of auctions for R_j, the highest auction price and its corresponding CTO are chosen as the final transaction price and the pairing of R_j respectively.

Algorithm 1 Dynamic Adjustment Auction Algorithm (DAAA)

1: Set$P^0_{R_j,max} = 0$ for all j={1, 2, ..., N}, and set $T = \{T_1, T_2, \ldots, T_M\}$
2: Set $j = 1$. // searching for the CTO that match to R_j.
3: Set $l = 1$, set$\Delta^l_{R_j} = T$, calculate the auction price $P^l_{T_i,R_j}$ according to expression (3) for R_j and all CTOs in set $\Delta^l_{R_j}$.
4: Select K CTOs randomly from set $\Delta^l_{R_j}$, where $K < M$.
5: Among the selected K CTOs, find the CTO with largest auction price for R_j (i.e., find the maximum value of $P^l_{T_i,R_j}$ from selected K CTOs), then write the CTO with largest auction price as $T^l_{R_j}$and write the largest auction price as $P^l_{R_j,max}$.
6: $l = l$+1
7: Judge whether $l = 11$ is satisfied, if it's satisfied, turn to step 10; if it's not satisfied, turn to step 8
8: Delete$T^{l-1}_{R_j}$ from set $\Delta^{l-1}_{R_j}$ to obtain set$\Delta^l_{R_j}$, i.e., $\Delta^l_{R_j} = \Delta^{l-1}_{R_j} - \{T^{l-1}_{R_j}\}$
9: All CTOs in set$\Delta^l_{R_j}$update their auction price $P^l_{T_i,R_j}$for R_j according to formula (3), then return to step 4.
10: Find the largest auction price in$P^1_{R_j,max}, P^2_{R_j,max}, \ldots, P^{10}_{R_j,max}$, and write the largest auction price as $P^{12}_{R_j,max}$, write the corresponding CTO as $T^{12}_{R_j}$.
11: Delete $T^{12}_{R_j}$ from set T to obtain new set T.
12: $j = j + 1$, judge whether j = N + 1 is satisfied, if it's satisfied, end this algorithm; if it's not satisfied, return to step 3.

According to formula (3), we can see that if the highest auction price in round l-1 is higher than that in round l-2 and the calculation delay is the same, the auction price in round l will increase. That's to say, the auction price increases with the number of auction rounds. When compared with other auction algorithms with only one round and no dynamic price adjustment [25], [26], DAAA can obtain a higher price due to the auction price increase caused by dynamic adjustment. The higher the auction price, the more revenue CRP gets. So CPRs are encouraged to participate in computation offloading to get more revenue. That's to say, the dynamic adjustment of auction price can encourage CPRs to participate in computation offloading.

B. MINING DIFFICULTY SETTING METHOD BASED ON ITDS CLUSTERING

First, using K-means clustering algorithm [27], all ITDs are divided into L clusters based on their reputation values. In this K-means clustering algorithm, we select L ITDs as cluster centers from Q ITDs, remaining ITDs are divided into L clusters according to the smallest reputation value difference to the selected L cluster centers. In the next round of cycle, each cluster center is recomputed according to the average computation method in [28] and remaining ITDs are redivided. This cycle is repeated until L cluster centers are not change.

Then, L clusters are sorted according to their reputation values from large to small. The index numbers of the sorted clusters are 1,2, ..., L, respectively, i.e., the cluster with largest reputation value is cluster 1. In each cluster, ITDs are sorted according to their reputation values from large to small. The index numbers of the sorted ITDs in cluster l are 1,2, ..., Q_l respectively. The mining difficulty values of different ITDs are different. The higher the reputation value, the lower the mining difficulty. The mining difficulty value of an ITD is set as

$$D = l \times D_0 \times e^{\lambda \times (1+\frac{q+l}{Q_l})}, \quad \lambda = 1 - \sigma \tag{4}$$

where l represents the index number of cluster that the ITD belongs to, $l \in \{1, 2, \ldots, L\}$; D_0represents the initial difficulty value of mining; λ represents the difficulty value coefficient; σ is the reputation value coefficient, $\sigma = \lfloor Rep_t/10 \rfloor / 10$, and Rep_t is the reputation value of the ITD; q represents the index number of the ITD in its cluster, and $q \in \{1, 2, \ldots, Q_l\}$, where Q_l is the number of ITDs in the cluster l. In [10], only the ITDs with highest reputation value can obtain bookkeeping rights and ITDs with low reputation value will lose their enthusiasm to participate in blockchain consensus. From expression (4), we can see that the higher the reputation value, the lower the mining difficulty, the easier to obtain bookkeeping rights, but not always the ITD with highest reputation value gets bookkeeping right. This reputation value setting can improve the fairness of ITDs to obtain bookkeeping right and encourage ITDs to participate in blockchain consensus.

C. RVPOW CONSENSUS MECHANISM

RVPOW consensus mechanism is an improvement of the traditional POW consensus mechanism. The purpose of the improvement is to improve the fairness of bookkeeping right, encourage ITDs to participate in computation offloading, and achieve fast consensus.

RVPOW combines the traditional POW mechanism with reputation value incentive mechanism. The traditional POW consensus mechanism is used to ensure that each ITD has equal mining difficulty and fairness. Combined with the reputation value incentive mechanism, ITDs are encouraged to participate in computing offloading. The specific process of RVPOW is as follows:

(i) After each transaction, both participants (the pairing of CRP and CTO) broadcast transaction information and their reputation values to other ITDs and BS. Other ITDs and BS record the information.

(ii) For each ITD, the mining difficulty value is set according to expression (4).

(iii) When the block generation time comes, all ITDs compete to calculate random numbers and generate a new block according to their own mining difficulty value.

(iiii) When one of the ITDs finds the random numbers and generates a new block, it will broadcast the new block to other ITDs. After more than 2 / 3 of all ITDs verify that the new block is correct, the new blocks will be put into the blockchain in the order of time stamps; If less than 2 / 3 ITDs verify that the block is correct, return to step (ii) to regenerate new block.

In POW, all ITDs has the same mining difficulty value, and fairness can be guaranteed by increasing the mining difficulty value. While in RVPOW, ITDs have different mining difficulty values, we can set lower mining difficulty values to improve fairness and achieve fast consensus.

In the scenario of computing offloading based on BC, each ITD has a reputation value, which is related to the incentive mechanism. For example, ITDs can obtain rewards from honest cooperative computation and generation block (expression (5)), and their reputation value can also be accumulated from honest cooperative computation and generation block (expression (6)). The reward of an ITD is:

$$R = \eta \times R_{fix} + r \times P^{12}_{R_j,max} \tag{5}$$

Among them: R_{fix} represents the reward obtained by honest generating block; η represents the reward coefficient when the ITD honestly generates block; r represents the reward coefficient of honest cooperative computation; Since ITDs can get wards from honest cooperative computation and honest generation blocks, all ITDs are encouraged to participate in computation offloading and blockchain consensus.

However, in order to prevent the ITD reputation value from being too high and maintain the fairness of ITDs' getting bookkeeping right, a reputation value threshold Rep_{max} is set. For an ITD with reputation value reaching Rep_{max}, its reputation value will be reduced to 20% of itself. The dynamically adjusting of reputation value is

$$Rep_t = \begin{cases} Rep_{t-1} + \sigma_1 \times log_{10}^{Rep_{t-1}} & Rep_t < Rep_{max} \\ Rep_t \times 20\% & Rep_t \geq Rep_{max} \end{cases} \tag{6}$$

where Rep_{t-1} is the reputation value of a ITD at last time, Rep_t is the reputation value at this time, $\sigma_1 = \lfloor Rep/10 \rfloor /10$ represents the accumulated reputation value coefficient of each ITD, and Rep is the accumulated reputation value of ITD due to honest cooperative computation and honest generation blocks at this time. 20% is the optimal percentage that is set according to the simulation results in Figure 2. If a ITD has dishonest behavior and is verified by other ITDs, this ITD will be blacklisted according to its ID, and cannot participate in the computation offloading and blockchain consensus anymore.

So, according to expression (6), after adding the dynamically adjusting of reputation value, ITDs with high reputation value cannot frequently obtain bookkeeping right, this can improve the fairness of ITDs and encourage ITDs to participate in blockchain consensus.

The fairness of ITDs is reflected in the scenario that ITDs are competing to obtain bookkeeping right. So, we write the fairness of ITDs in formula (7).

$$F_{air} = \sum_i (C_i - C_{aver})^2, \quad i \in \{1, 2, \ldots, Q\} \tag{7}$$

where C_i is the bookkeeping times of the ith ITD. C_{aver} is the average bookkeeping times of all ITDs. F_{air} represents the fairness of ITDs to obtain bookkeeping right, the smaller the F_{air}, the better the fairness of ITDs to obtain bookkeeping right.

According to expressions (5) and (6), it can be seen that both the reputation value and the reward are proportional to the number of honest cooperative computation and honest generation block. So, the reward is also proportional to the reputation value. That's to say, the higher an ITD's reputation value, the higher its reward. Therefore, an incentive mechanism based on reputation value is set through formulas (5) and (6), and RVPOW can encourage ITDs to participate in computation offloading and blockchain consensus.

Reputation value incentive and consensus algorithm performance improvement are mutually reinforcing relationship due to the following two reasons.

First, ITDs can improve their reputation values and get rewards from honest cooperative computation and honest generating blocks, so all ITDs are encouraged to participate in computation offloading and blockchain consensus due to the reputation value incentive. The higher the enthusiasm of ITDs to participate in consensus, the faster the block generation speed, which further promotes the improvement of consensus performance.

Second, when the consensus algorithm performance is improved, blocks can be generated faster, and ITD can obtain more reputation values from honest generation blocks. More reputation values mean more rewards, so ITDs are wanting to participate in consensus to get rewards, this leads to reputation value incentive.

The performance improvement of consensus algorithm is based on the incentive of reputation value, so we call the new consensus mechanism as improved POW consensus mechanism based on reputation value (RVPOW).

IV. SIMULATION RESULTS AND ANALYSIS

In this section, we simulate the computation offloading method based on reputation value incentive and compare it with other methods. In simulations, the number of ITDs is $Q = 500$, the ITDs' reputation values are accumulated by honest cooperative computation and honest generation block according to expression (6), and the reputation value obtained by honest generation blocks is randomly selected between (0, 45). Other parameters are shown in table 1.

TABLE 1. Simulation parameters.

Symbol	Value
B	5 MHz
D_0	2^{32}
V_{T_i}, V_{R_j}	1.5 ∼2.5 Gbit/s
η	0.2
D_{T_i}	1000 ∼5000 kb
r	0.1
P_{T_i}	0.6 W
ξ	50^{-4}
N_{T_i, R_j}	10^{-10}

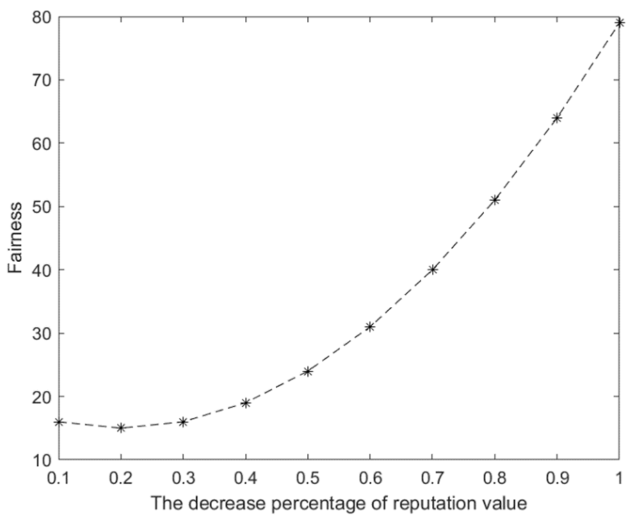


FIGURE 2. Optimal decrease percentage of reputation value.

A. SIMULATION RESULTS OF OPTIMAL DECREASE PERCENTAGE OF REPUTATION VALUE

In expression (6), it may be not optimal to directly halve the reputation value of ITDs that exceed the threshold. The decrease percentage of reputation value is set to prevent some ITDs from obtaining bookkeeping rights frequently due to their high reputation value, and to maintain the fairness of ITDs to obtain bookkeeping right. Therefore, we simulate the system fairness (expression (7)) when reputation value decreases to different percentages. Figure 2 shows the simulation results. From Figure 2, it can be seen that when reputation value decreases to 0.2 of itself, the system fairness is the best. Therefore, in following simulations, we always set this decrease percentage as 20%.

B. SIMULATION RESULTS OF THE COMPUTATION RESOURCE ALLOCATION METHOD BASED ON DAAA

Figure 3 shows the simulation results of the total auction price of DAAA in this paper, Competition Auction (CA) in [18], Real Random Auction (RAA) in [19] and Two Ways Auction (TWA) in [20]. It can be seen that, by running DAAA, CA, RAA and TWA auction algorithms in the computation offloading scenario, DAAA can achieve a higher total auction price than CA, RAA and TWA. The higher the auction price, the more revenue CRP gets. So DAAA can encourage CPRs with idle computing resources to participate in computation offloading, thus the idle computing resources in the network can be effectively utilized. On the other hand, according to the definition of the auction price in formula (3), it can be seen that the auction price is inversely proportional to computation delay. That is to say, the higher the auction price, the shorter the computation delay. So DAAA can obtain shorter computation delay than other three auction algorithms.

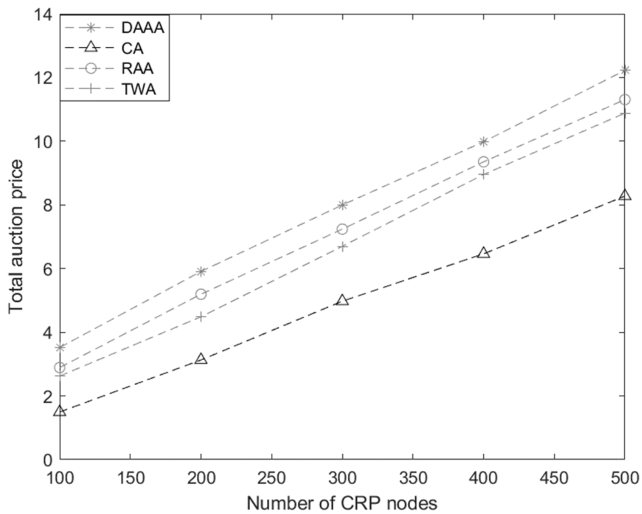


FIGURE 3. Comparisons of different computing resource allocation methods.

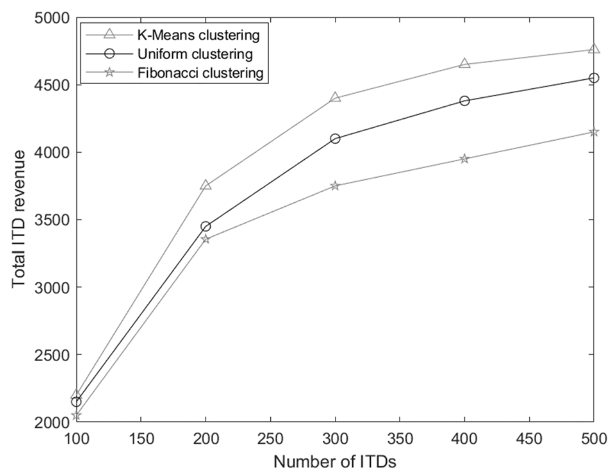


FIGURE 4. Comparison of different mining difficulty setting methods.

C. SIMULATION RESULTS OF THE MINING DIFFICULTY SETTING METHOD BASED ON ITDS CLUSTRING

Figure 4 shows the comparison of Uniform clustering, Fibonacci clustering [28], and K-Means clustering in this paper in terms of total ITD revenue. We can see that, due to the different mining difficulty setting, the K-Means clustering can achieve higher ITD revenue than Uniform clustering and Fibonacci clustering. With the increase of the number of ITDs, the total ITD revenue for K-Means clustering and Uniform clustering increases. Fibonacci clustering has the lowest ITD revenue, and with the increase of the number of ITDs, its total ITD revenue becomes flat. The higher the ITD revenue, the higher the enthusiasm that ITD participates in computation offloading and blockchain consensus. So, the mining difficulty setting method based on ITDs K-Means clustering can encourage ITDs to participate in computation offloading and blockchain consensus.

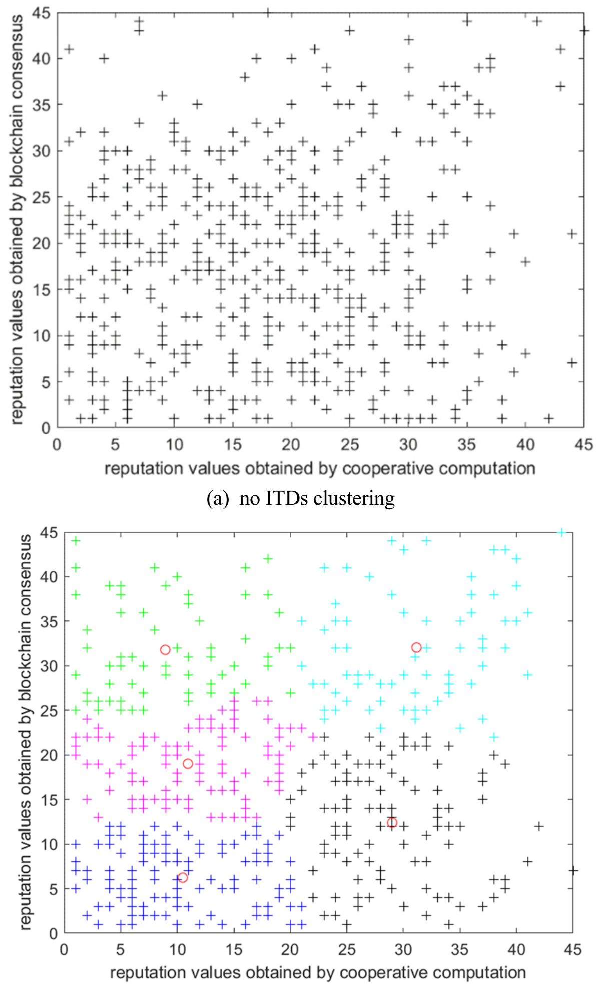
Figure 5 shows the comparison of ITDs reputation value distribution between no ITDs clustering in [29] and ITDs K-Means clustering in this paper. In figure 5 (a), the reputation values obtained by honest cooperative computation and blockchain consensus are randomly distributed, so the mining difficulty values of ITDs are also randomly distributed. Through K-Means clustering, in figure 5 (b), ITDs with closer reputation values are placed in the same cluster, different ITD reputation values are set with different mining difficulty. The distribution of reputation values in figure 5 (b) is more uniform than that in figure 5(a), so the introduction of reputation value threshold and dynamically adjusting of reputation value can improve the fairness of ITDs in obtaining bookkeeping right.

D. SIMULATION RESULTS OF FAIRNESS

Figure 6 shows the fairness of ITDs in the computation offloading scenario, where the initial reputation value is $Rep_0 = 50$, there are ten clusters and 100 ITDs in each cluster. It can be seen from the figure 6 that in the computation offloading scenario of 10 clusters, the bookkeeping times of ITDs in each cluster is consistent. Compared with the PoCaC consensus mechanism in literature [10], the fairness of ITDs in RVPOW consensus mechanism is better than that in PoCaC. That's to say, in RVPOW consensus mechanism, the bookkeeping times of each ITD is closer to the average bookkeeping times.

E. SIMULATION RESULTS OF RVPOW CONSENSUS MECHANISM

In order to show that the proposed RVPOW can achieve fast consensus, we compare it with traditional POW, improved POW based on user benefits (UBPOW) [30], T-PBFT [16] and RTChain [17] in terms of average block generation and verification delay. The simulation results in figure 7 are the average value of 500 experimental results. The simulation results show that RTChain and T-PBFT are superior to other consensus mechanisms in terms of delay when the number of ITDs is small. However, with the increase of the ITDs, RTChain and T-PBFT have higher delays than other consensus mechanisms. When the number of ITDs is large, up to several hundreds, the delay of RTChain and T-PBFT is very large. Among the five consensus mechanisms, RPVOW has the shortest delay when the number of ITDs is large. That's to say, when comparing with other consensus mechanisms,



(a) no ITDs clustering

(b) ITDs K-Means clustering

FIGURE 5. Comparison of no ITDs clustering and ITDs K-Means clustering.

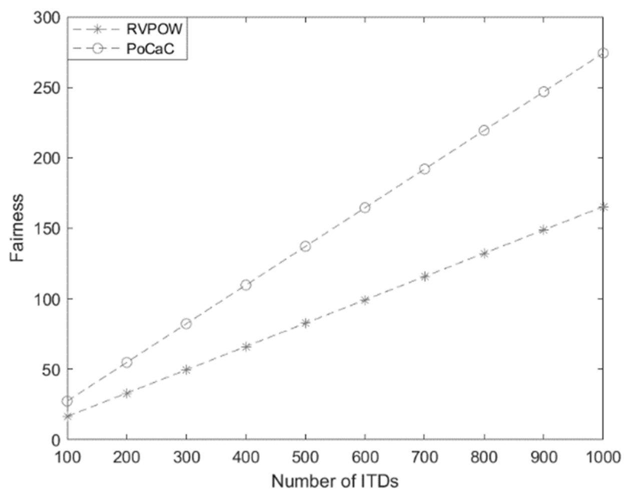


FIGURE 6. The fairness of ITDs to obtain bookkeeping right.

RPVOW can reduce average block generation and verification delay, achieve fast consensus.

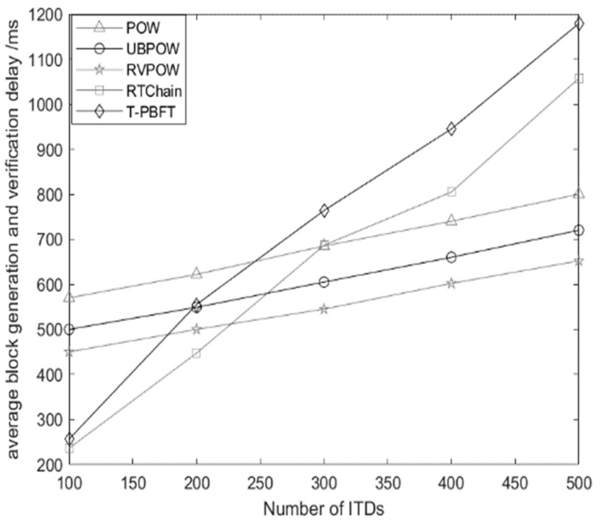


FIGURE 7. **Comparison of different consensus mechanisms.**

V. CONCLUSION

A computation offloading method based on reputation value incentive is proposed, and the detailed workflow of this method is designed. In the workflow, a computation resource allocation method based on DAAA is proposed to improve the enthusiasm of CRPs to participate in computation offloading. In order to improve the fairness of ITDs in getting bookkeeping right, a mining difficulty setting method based on ITDs clustering is proposed. In order to prevent the ITD's reputation value from being too high and improve the fairness of ITDs, threshold and dynamically adjusting are set for ITDs' reputation value. In addition, RVPOW consensus mechanism is proposed to achieve fast consensus. The higher the ITD's reputation value, the more rewards it gets. So RVPOW can improve the enthusiasm of ITDs to participate in computation offloading and blockchain consensus. Simulation results show that the proposed computation offloading method can improve the fairness of ITDs to obtain bookkeeping right, encourage ITDs to participate in computation offloading and achieve fast consensus.

REFERENCES

[1] L. Nadeem, M. A. Azam, Y. Amin, M. A. Al-Ghamdi, K. K. Chai, M. F. N. Khan, and M. A. Khan, ''Integration of D2D, network slicing, and MEC in 5G cellular networks: Survey and challenges,'' *IEEE Access*, vol. 9, pp. 37590–37612, 2021.

[2] L. Zhao, W. Tan, B. Li, Q. He, L. Huang, Y. Sun, L. Xu, and Y. Yang, ''Joint shareability and interference for multiple edge application deployment in mobile-edge computing environment,'' *IEEE Internet Things J.*, vol. 9, no. 3, pp. 1762–1774, Feb. 2022.

[3] M. Chen, H. Wang, D. Han, and X. Chu, ''Signaling-based incentive mechanism for D2D computation offloading,'' *IEEE Internet Things J.*, vol. 9, no. 6, pp. 4639–4649, Mar. 2022.

[4] J. Lee and J. H. Lee, ''Performance analysis and resource allocation for cooperative D2D communication in cellular networks with multiple D2D pairs,'' *IEEE Commun. Lett.*, vol. 23, no. 5, pp. 909–912, May 2019.

[5] S. Guo, Y. Dai, S. Guo, X. Qiu, and F. Qi, ''Blockchain meets edge computing: Stackelberg game and double auction based task offloading for mobile blockchain,'' *IEEE Trans. Veh. Technol.*, vol. 69, no. 5, pp. 5549–5561, May 2020.

[6] R. Zhang, F. R. Yu, J. Liu, T. Huang, and Y. Liu, ''Deep reinforcement learning (DRL)-based device-to-device (D2D) caching with blockchain and mobile edge computing,'' *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6469–6485, Oct. 2020.

[7] X. Shen, Q. Pei, and X. Liu, ''Overview of blockchain technology,'' *Chin. J. Netw. Inf. Secur.*, vol. 2, pp. 11–20, Apr. 2016.

[8] D. Nguyen, M. Ding, P. Pathirana, A. Seneviratne, J. Li, and V. Poor, ''Cooperative task offloading and block mining in blockchain-based edge computing with multi-agent deep reinforcement learning,'' *IEEE Trans. Mobile Comput.*, early access, Oct. 14, 2021, doi: 10.1109/TMC.2021.3120050.

[9] J. Shi, J. Du, Y. Shen, J. Wang, J. Yuan, and Z. Han, ''DRL-based V2V computation offloading for blockchain-enabled vehicular networks,'' *IEEE Trans. Mobile Comput.*, early access, Feb. 23, 2022, doi: 10.1109/TMC.2022.3153346.

[10] D. Pan, G. Zhu, and Q. Yang, ''Blockchain consensus mechanism based on contribution value and reputation,'' *J. Comput. Appl.*, vol. 42, no. s1, pp. 1–7, Aug. 2021.

[11] 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.*, vol. 22, no. 7, pp. 4051–4063, Jul. 2021.

[12] X. Qiu, L. Liu, W. Chen, Z. Hong, and Z. Zheng, ''Online deep reinforcement learning for computation offloading in blockchain-empowered mobile edge computing,'' *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 8050–8062, Aug. 2019.

[13] X. Zheng, M. Li, Y. Chen, J. Guo, M. Alam, and W. Hu, ''Blockchain-based secure computation offloading in vehicular networks,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 7, pp. 4073–4087, Jul. 2021.

[14] D. Wei, N. Xi, J. Ma, and J. Li, ''Protecting your offloading preference: Privacy-aware online computation offloading in mobile blockchain,'' in *Proc. IEEE/ACM 29th Int. Symp. Quality Service (IWQOS)*, Jun. 2021, pp. 1–10.

[15] D. Wu and N. Ansari, ''A cooperative computing strategy for blockchain-secured fog computing,'' *IEEE Internet Things J.*, vol. 7, no. 7, pp. 6603–6609, Jul. 2020.

[16] S. Gao, T. Yu, J. Zhu, and W. Cai, ''T-PBFT: An EigenTrust-based practical Byzantine fault tolerance consensus algorithm,'' *China Commun.*, vol. 16, no. 12, pp. 111–123, Dec. 2019.

[17] Y. Sun, R. Xue, R. Zhang, Q. Su, and S. Gao, ''RTChain: A reputation system with transaction and consensus incentives for E-commerce blockchain,'' *ACM Trans. Internet Technol.*, vol. 21, no. 1, pp. 1–24, Feb. 2020.

[18] J. Huang, Z. Han, M. Chiang, and H. Vincent Poor, ''Auction-based resource allocation for cooperative communications,'' *IEEE J. Sel. Areas Commun.*, vol. 26, no. 7, pp. 1226–1237, Sep. 2008.

[19] B. Wu, X. Chen, Y. Chen, and Y. Lu, ''A truthful auction mechanism for resource allocation in mobile edge computing,'' in *Proc. IEEE 22nd Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2021, pp. 21–30.

[20] A. M. Rocchi, S. Fernández, and J. R. Vega, ''A double auction mechanism for distribution of electrical supply capacities among enterprises of an industrial park,'' *IEEE Latin America Trans.*, vol. 19, no. 2, pp. 269–279, Feb. 2021.

[21] R. Zhu, H. Liu, L. Liu, X. Liu, W. Hu, and B. Yuan, ''A blockchain-based two-stage secure spectrum intelligent sensing and sharing auction mechanism,'' *IEEE Trans. Ind. Informat.*, vol. 18, no. 4, pp. 2773–2783, Apr. 2022.

[22] Y. Zha, H. Zhi, and X. Fang, ''Blockchain-based cooperative computing scheme for IoT intelligent terminals,'' *J. Beijing Univ. Posts Telecommun.*, vol. 44, no. 2, pp. 89–94, 2021.

[23] D. Huang, X. Ma, and S. Zhang, ''Performance analysis of the raft consensus algorithm for private blockchains,'' *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 50, no. 1, pp. 172–181, Jan. 2020.

[24] M. Hu, T. Shen, J. Men, Z. Yu, and Y. Liu, ''CRSM: An effective blockchain consensus resource slicing model for real-time distributed energy trading,'' *IEEE Access*, vol. 8, pp. 206876–206887, 2020.

[25] Y. Jiao, P. Wang, D. Niyato, and K. Suankaewmanee, ''Auction mechanisms in cloud/fog computing resource allocation for public blockchain networks,'' *IEEE Trans. Parallel Distrib. Syst.*, vol. 30, no. 9, pp. 1975–1989, Sep. 2019.

[26] Q. Li, H. Yao, T. Mai, C. Jiang, and Y. Zhang, "Reinforcement-learning- and belief-learning-based double auction mechanism for edge computing resource allocation," *IEEE Internet Things J.*, vol. 7, no. 7, pp. 5976–5985, Jul. 2020.
[27] J. Qi, Y. Yu, L. Wang, and J. Liu, "K-means: An effective and efficient K-means clustering algorithm," in *Proc. IEEE Int. Conf. Big Data Cloud Comput. (BDCloud), Social Comput. Netw. (SocialCom), Sustain. Comput. Commun. (SustainCom) (BDCloud-SocialCom-SustainCom)*, Oct. 2016, pp. 242–249.
[28] J. He, K. Zhang, R. Xue, N. Zhu, P. He, and H. Son, "High reliability blockchain consensus mechanism based on contribution value and difficulty value," *Chin. J. Comput.*, vol. 44, no. 1, pp. 162–176, Jan. 2021.
[29] X. Du, Y. He, and J. Z. Huang, "Random sample partition-based clustering ensemble algorithm for big data," in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2021, pp. 5885–5887.
[30] Z. Gao, B. Lin, K. Xiao, Q. Wang, Z. Mo, and Y. Yang, "A dynamic resource allocation algorithm based on auction model in mobile blockchain network," in *Proc. 3rd Int. Conf. Electron. Inf. Technol. Comput. Eng. (EITCE)*, Oct. 2019, pp. 1605–1610.

HUI ZHI received the Ph.D. degree in communication and information systems from the Nanjing University of Posts and Telecommunications, in July 2013.

She is currently a Researcher with the Key Laboratory of Computational Intelligence and Signal Processing, Ministry of Education of China. She is also an Associate Professor and a Master Tutor with Anhui University. Her current research interests include blockchain, cooperative communication, network coding, and massive MIMO.

YINLIANG WU received the bachelor's degree in communication engineering from the Hefei University of Economics, in 2020. He is currently pursuing the master's degree in electronics and communication engineering with Anhui University, China.

Since 2020, he has been engaged in wireless communication research at the Key Laboratory of Computational Intelligence and Signal Processing, Ministry of Education of China. His research interests include blockchain, computation offloading, and mobile edge computing.

Mr. Wu's awards and honors include the Anhui University Academic Scholarship and the Class Scholarship of Hefei University of Economics.

XINYU ZHANG is currently pursuing the bachelor's degree in computer and technology with Anhui University, China.

Since 2021, she has been engaged in the information technology talent class jointly organized by Anhui University and Deakin University. In 2022, she has been engaged in the Baidu pinecone talent training elite class. Her research interests include recommended algorithm, blockchain, and data mining.

Miss. Zhang's awards and honors include the Anhui University Academic Scholarship.

LIXIA YANG (Member, IEEE) is currently a Professor, a Doctoral/Master's Supervisor with Anhui University, the Deputy Director of the School of Electronic and Information Engineering, Anhui University, and the Deputy Director of the Anhui Provincial Laboratory of Information Materials and Intelligent Perception. He is also the Director of technical committee of Jiangsu Passive Microwave Device Engineering Technology Center, the Executive director of Jiangsu Electronics Society, a Senior Member of China Electronics Society, a member of National Expert Committee on Electromagnetic Scattering and Inverse Scattering, the Deputy Director of Radio Propagation Branch of China Electronics Society, and the Director of Anhui Key Laboratory of Space Electromagnetic Perception.