RBT: A Distributed Reputation System for Blockchain-Based Peer-to-Peer Energy Trading with Fairness Consideration[⋆]

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ABSTRACT

In order to improve the efficiency of blockchain and fairness of energy trading market, many recent works choose to involve reputation into their systems. Implementing a reputation system in a distributed way is a difficult problem. Distributed reputation and its application in the energy field have not been fully studied yet. In this paper, we design a distributed reputation system, called RBT, that relies on blockchain, especially the smart contract technology, to achieve distributed and automatic reputation management. We then use RBT to implement delegated consensus for the blockchain system and reputation-based k-double auction for the peer-to-peer (P2P) energy trading system. Our simulation results show that RBT can effectively improve the scalability and fault tolerance capability of the blockchain system. In addition, we define a fairness indicator to capture the reputation-based average benefits and costs when considering reputation as the contribution to the P2P energy trading system. Our experiment also demonstrate balanced fairness indicators of reputation-based k-double auction, indicating that reputation can well serve as an incentive in P2P energy trading.

Nomenclature

χ_{CN}	Characteristic coefficient for R_{CN} when calculating R
χ_{EB}	Characteristic coefficient for R_{EB} when calculating R
χ_{ES}	Characteristic coefficient for R_{ES} when calculating R
ℓ	Leader node in consensus
BFI	Buyler fairness indicator
bp	Bidding price of a demand order
$C(r)$	Voting committee for request r
$cost$	Total cost during a trading period
E_{buy}	Total amount of energy purchased during a trading period
E_{sell}	Total amount of energy sold during a trading period
$income$	Total income during a trading period
op	Offering price of a supply order
R	The comprehensive reputation score
r	Consensus request
R_C	Average reputation score of committee C
$R_{\min}$	Trust lower bound for R
R_{CN}	The consensus node reputation score
R_{CN}	The energy buyer reputation score
R_{CN}^{+}	Reputation increase of consensus nodes
R_{CN}^{-}	Reputation decrease of consensus nodes
$R_{CN}^{L,+}$	Additional reputation reward of leader
$R_{CN}^{L,-}$	Additional reputation penalty of leader
R_{EB}^{+}	Reputation increase of the buyer for a successful transaction execution
R_{EB}^{-}	Reputation decrease of the buyer due to the failed consumption of a transaction
R_{ES}	The energy seller reputation score
R_{ES}^{+}	Reputation increase of the seller for a successful transaction execution
R_{ES}^{-}	Reputation decrease of the seller due to the failed supply of a transaction
$rank_{buy}$	Buying rank of a demand order

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$rank_{sell}$	Selling rank of a supply order
SFI	Seller fairness indicator
tp	Trade price of a transaction
w_{CN}	Weight factor for R_{CN} when calculating R
w_{EB}	Weight factor for R_{EB} when calculating R
w_{ES}	Weight factor for R_{ES} when calculating R
CN-x	Rule x for consensus nodes
EB-x	Rule x for energy buyers
ES-x	Rule x for energy sellers

1. Introduction

There have been a large number of research works and practical projects on blockchain-based energy trading since the advent of the blockchain technology in 2008 [1]. A blockchain system maintains a linked list of blocks with data, and any modification to the blockchain needs to be approved by participants, or nodes for simplicity, via a distributed consensus algorithm before it takes effect [2]. As a significant improvement of Blockchain 2.0 compared with Blockchain 1.0, smart contracts are a kind of programmable scripts that can run automatically once the predefined execution conditions are satisfied [3], which further expands the application scope of blockchain. In the field of energy, with the help of blockchain technology, distributed energy systems in various scenarios have been widely promoted, for example, peer-to-peer (P2P) energy trading [4], energy cryptocurrency [5], automatic metering and billing [6], green certificate trading [7] and carbon emission trading [8], and automatic energy management. Among them, P2P energy trading is the most used scenario of blockchain. With the extensive deployment of renewable energy power generation devices, more and more energy systems are implemented in distributed ways [9]. The decentralized nature of blockchain can be applied to remove centralized parties and avoid additional intermediate cost during distributed energy trading [10].

In blockchain, consensus is used as a subprotocol to prevent the behavior of consensus nodes from deviating from the prescribed protocols in a decentralized environment [11]. Although consensus is a classical problem in distributed computing, improving the scalability of consensus algorithms has always been a very difficult problem [12]. As a result, many existing blockchain systems are difficult to be applied on a large scale in practice [13]. In essence, consensus is a way to distributedly establish oblivious trust. Without the access to the history of previous consensus instances, this oblivious trust needs to be established for every new consensus instance, resulting in the heavy burden of computing or information transmission.

In recent years, more and more research works start to introduce reputation (or credit) to resemble real-world trust that is generally recordable, cumulative, and dynamic. A general reputation system records a reputation value that evaluates the trustworthiness of each node based on historical record [14]. One of the major uses of reputation in distributed systems is to enhance the efficiency of blockchain via delegated consensus. By delegating consensus decisions to nodes with higher reputation values, consensus can be reached much faster because the number of message transmissions required is reduced, with only a little sacrifice in decentralization [15]. Since low-reputation members are less likely to get involved into the consensus process, reputation mechanisms are also helpful in regulating the behavior of consensus participants [16].

In the meanwhile, reputation also plays an important role in the scenario of energy trading. With the promotion of distributed energy trading, the uncertain, untrusted, or selfish behavior of sellers or buyers makes the violation of trading contracts more common [17, 18]. Using reputation mechanisms to evaluate the behavior of transaction users can effectively improve the reliability and fairness of energy trading [19].

1.1. Motivations

Although many works have introduced reputation in consensus, blockchain, or energy trading, most implementation manners of their reputation mechanism are either omitted or centralized (e.g., [20, 21, 22]). As a matter of fact, implementing a reputation system in a distributed way is a difficult problem. For one thing, the recording and management of user reputation should not depend on a centralized authority. For another, the results provided by the distributed reputation system should be admitted by users.

Similar to energy trading, distributed reputation systems can also benefit from the decentralization provided by blockchain. In fact, there are other scholars studying distributed reputation management based on blockchain. The traceability and immutability of blockchain can improve the reliability of a distributed reputation system, and any update occurs to reputation can be tracked and cannot take effect unless it is approved by the majority. Blockchain-based reputation management has been applied to many different fields, for example, supply chain [23], vehicular network [24], intelligent transportation [25], and machine-to-machine application service [26].

In the energy field, reputation can be applied in many ways. The simplest way of applying reputation in the energy field is to improve the efficiency of the consensus subprotocol of energy blockchain [27]. Beyond that, reputation can also become a factor for transaction matchmaking [22] or an incentive for demand response [28]. However, as far as we are concerned, the application of distributed reputation in energy systems has not been fully explored yet. With the popularization of distributed energy systems, how to purposefully design and implement distributed reputation is worth studying.

Moreover, many works claim to bring fairness to energy trading. However, there is no consensus on what "fairness" is, and how fairness is assessed is rather vague. Some works believe that fairness eliminates the discrimination in benefit allocation among prosumers [29] or demand response among consumers [30]. On the contrary, Khaqqi *et al.* [22] literally interpret fairness as "equity", i.e., distributing permit, compliance cost, and reduction responsibility based on reputation. Still, there is a lack of a scientific method to evaluate this equity.

1.2. Related Works

In recent years, there have been a lot of works using reputation to improve the efficiency and scalability of consensus and blockchain. Proof-of-Reputation (PoR) [31] is a consensus for blockchain where the node with the highest reputation value becomes the block generator, and top 20% nodes become the verifiers of blocks. It stores reputation values in sub-blocks integrated into normal blocks that hold transaction information. In [32], a scheme called Proof-of-Reputation-X (PoRX) is proposed. It includes a reputation module to improve PoX, i.e., consensus algorithms similar to Proof-of-Work (PoW) and Proof-of-Stake (PoS). The basic idea derives from [33] that different difficulty levels of solving consensus puzzles are assigned to different nodes according to their reputation values.

In spite of this, most existing works focus more on applying reputation to distributed systems than specifying implementation details of their reputation mechanisms. As a result, their implementation nanners are either omitted or centralized. ReCon [20] is a reputation module that can be integrated with any consensus algorithm. A public committee that makes consensus decisions is probabilistically selected based on the reputation values of nodes. However, how reputation values are maintained and how the selection of the committee is admitted by noncommittee members are not explained. Dynamic-reputation Practical Byzantine Fault Tolerance (DBFT) is a consensus algorithm similar to PoR, which only allows the first 60% nodes to participate in consensus according to the ranking of credit values [27]. To complete multiple critical tasks including calculating credit values and selecting leader nodes, a centralized monitoring node is nonetheless indispensable.

Similar to many other distributed systems, distributed reputation management system can also be accomplished by blockchain. Tang *et al.* [34] carry out a trust-based framework to enable cross-platform collaboration in Internet-of-Things (IoT) scenarios. In this framework, the trust information is shared between different domains through a global blockchain. The trust-based credits can also serve as incentives to IoT collaboration engagement. Similarly, Shala *et al.* [26] shows that the machine-to-machine application services provided by peers can also be evaluated by blockchain which stores credibility information. They also provides an elaborate and comprehensive trust evaluation framework. In addition, [35] provides a systematic assessment of literatures on blockchain-based trust and reputation management.

In the energy field, reputation mechanisms have also been applied in different energy scenarios. Khaqqi *et al.* [22] first consider the impact of reputation on trading prices in their emission trading system. The system will calculate a priority value based on both seller/buyer reputation and offering/bidding price for each order, which decides the visibility of the order during the matchmaking process. In the demand response mechanism provided by [28], the blockchain-based reputation system evaluates the quality of end-users and load aggregators, which affects the priority when matching with a user or aggregator in a similar way. With the help of smart contract, this reputation system accomplishes automatic reputation calculation.

1.3. Contributions

In this paper, we design RBT, a distributed reputation system for blockchain-based P2P energy trading. This reputation system has the following features:

1. Its design relies on the blockchain technology. Reputation scores are stored in blockchain, making reputation traceable and tamper-proof. In addition, smart contract is used to achieve automatic reputation management. Although there is a reciprocal relationship between reputation and blockchain, existing researches mainly focus on improving the efficiency of blockchain through reputation or achieving distributed reputation management through blockchain, but few of them have both.
2. This reputation system analogize the universality of real-world trust in the sense that it is used in both blockchain consensus and energy trading. On the one hand, reputation improves the efficiency of blockchain by implementing delegated consensus, and it also improves the fairness of energy trading by involving the reputation scores of both sellers and buyers in matchmaking. On the other hand, the behavior of users during blockchain consensus or energy trading will be reflected in their future reputation scores.
3. In particular, the P2P energy trading system uses a reputation-based k-double auction matchmaking strategy. Different from the original k-double auction in [36], our reputation-based k-double auction decides trade prices that are more beneficial to buyers and sellers with higher reputation scores. The purpose is to balance the fairness indicator among participants, which is defined as the average income by reputation for sellers and the average cost by reputation for buyers. This intuitively makes reputation an incentives in P2P energy trading.
4. We simulate a comprehensive system consisting of a reputation system, a blockchain system, and a P2P energy trading system. The simulation shows the improvement in the efficiency in blockchain and the fairness of the trading strategy.

The rest of this paper is organized as follows: Section 2 describes the framework of our blockchain-based distributed reputation system; Section 3 provides details of designing delegated consensus based on our reputation system; Sec-

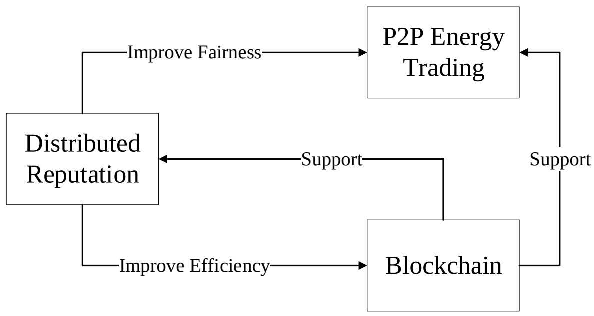


Figure 1: The relationship between distributed reputation, blockchain, and P2P energy trading.

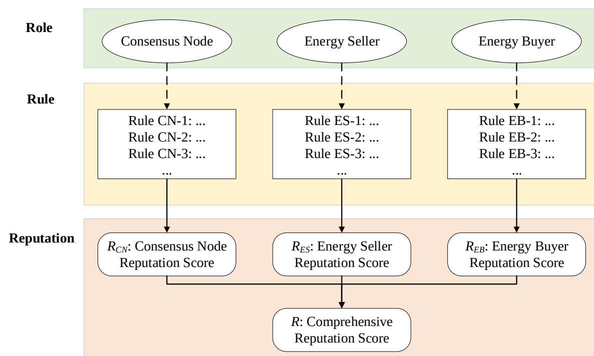


Figure 2: Framework of RBT.

tion 4 explains a P2P energy trading strategy that also considers seller/buyer reputation; Section 5 evaluates the performance of the entire system by simulation; Section 6 concludes this paper.

2. RBT: A Distributed Reputation System

In this section, we describe RBT, a blockchain-based distributed reputation system that can be applied in the scenario of blockchain-based P2P energy trading. Specifically, the reputation system is comprehensive in the sense that it can improve the efficiency of blockchain and the fairness of energy trading. The relationship between reputation, blockchain, and P2P energy trading is depicted in Figure 1.

2.1. Reputation Framework

The most direct purpose of RBT is to maintain a reputation score that comprehensively evaluates the behavior of each participant as different roles according to the prescribed rules. As shown in Figure 2, the framework of RBT consists of three modules: role, rule, and reputation. We will explain each module in detail.

2.1.1. Role

The role module defines three different roles that each participant can play:

- **Consensus Node.** The energy trading system uses blockchain to record transactions (see more details in Section 3). Participants can choose to become a consensus node and join the process of transaction validation to receive extra reward.
- **Energy Seller.** Energy users with power generation devices, e.g., household rooftop photovoltaic panels, can play the roles of energy sellers (or prosumers). They can make a profit by releasing surplus energy on the P2P trading platform for sale.
- **Energy Buyer.** Any participant can be an energy buyer (or consumer) during energy trading. Energy buyers can purchase energy on demand from the P2P trading platform.

New members are energy buyer by default, and they can choose to do the job of consensus nodes or energy sellers at the same time.

2.1.2. Rule

Real-world trust systems usually have rules to regulate people's behavior. Similarly, RBT also has a rule module that defines rules for each role to regulate the behavior of participants. These rules are implemented as the criteria to calculate and update reputation scores. Following these rules helps to build up the reputation scores while violating these rules could result in a deduction in reputation scores.

As shown in Fig. 2, rules for consensus nodes (CN) are represented by CN-1, CN-2, ..., rules for energy sellers (ES) are represented by ES-1, ES-2, ..., and rules for energy buyers (EB) are represented by EB-1, EB-2, ... The rules for different roles are independent. For example, CNs only contain rules for consensus activities and will not affect the energy buyer reputation or the energy seller reputation.

2.1.3. Reputation

In RBT, reputation scores are stored as a 4-tuple:

$$\langle R, R_{CN}, R_{ES}, R_{EB} \rangle.$$

Among them, $R \in [0, 1]$ is called the comprehensive reputation score. This reputation score is calculated based on:

- R_{CN}: the consensus node reputation score;
- R_{ES}: the energy seller reputation score;
- R_{EB}: the energy buyer reputation score.

Note that R_{CN}, R_{ES}, and R_{EB} are also numbers from $[0, 1]$ that are calculated based on the rules prescribed in the rule module (see Section ...). For new participants, $R_{CN} = R_{ES} = R_{EB} = 0.5$ by default.

In more detail, the comprehensive reputation score R is calculated as follows:

$$R = \frac{w_{CN}\chi_{CN}R_{CN} + w_{ES}\chi_{ES}R_{ES} + w_{EB}\chi_{EB}R_{EB}}{w_{CN}\chi_{CN} + w_{ES}\chi_{ES} + w_{EB}\chi_{EB}}, \quad (1)$$

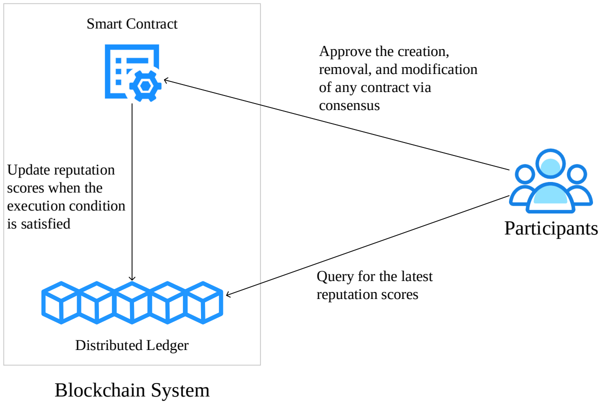


Figure 3: Implementation of RBT.

where w_{CN}, w_{ES}, $w_{EB} > 0$ are weights, and χ_{CN}, χ_{ES}, χ_{EB} are characteristic coefficients defined as:

$$\chi_{CN} = \begin{cases} 1 & \text{participant is a consensus node;} \\ 0 & \text{otherwise;} \end{cases}$$
$$\chi_{ES} = \begin{cases} 1 & \text{participant is an energy seller;} \\ 0 & \text{otherwise;} \end{cases}$$
$$\chi_{EB} = \begin{cases} 1 & \text{participant is an energy buyer;} \\ 0 & \text{otherwise.} \end{cases}$$

There is no worry about the divide-by-zero case because each participant is an energy buyer by default and $\chi_{EB} = 1$. Here we take $w_{CN} = w_{ES} = w_{EB} = 1/3$ for simplicity. Note that real-world systems may have different emphasis on different roles. This can be easily achieved by adjusting these weights.

We also define a trust lower bound $R_{\min}$. The participant with a comprehensive reputation score under $R_{\min}$ is seen as untrusted. Here we set $R_{\min} = 0.2$.

2.2. Distributed Implementation

There are several essential points in implementing a reputation mechanism in a distributed way. First, the reputation system should not be owned, maintained, or manipulated by any minority. This helps to regulate the behavior of participants if everyone has the competence to monitor the good and bad behavior of others. Second, any update in reputation scores should be seen, admitted, and shared by all participants. This could effectively prevent possible tampering with reputation scores. Third, the problem of data redundancy of the distributed system will be more serious as the number of participants increases. There is an urgent need for an effective way to store these reputation scores.

As shown in Fig. 3, the implementation of RBT includes three main components:

- **Distributed Ledger**. Reputation scores are stored in a distributed ledger maintained by the blockchain system. Any update of the reputation scores can be viewed by all participants. This makes the reputation system more transparent and more robust to malicious tampering with reputation scores. Moreover, the linked list structure of blockchain makes reputation changes more traceable.
- **Smart Contract.** The rules in the rule module of the reputation framework are implemented as the scripts in smart contracts supported by the blockchain system. Once some execution condition is satisfied, the scripts will automatically update the reputation scores stored in the database. Any creation, deletion, and modification of smart contracts will be broadcast to all participants.
- **Participants.** Participants can query the distributed database for reputation lookup. In addition, when a change of the smart contracts is received, participants will run a distributed consensus protocol to decide whether to approve or deny the change.

3. Reputation-Based Blockchain

In a blockchain-based energy trading system, blockchain is integrated to remove centralized transaction intermediaries and store transaction records in a transparent and immutable way. We use RBT to improve the efficiency of the blockchain by implementing delegated consensus. Delegated consensus is an effective way to reduce the client-side latency and improve server throughput of a consensus algorithm by reducing the number of consensus nodes.

When a new block containing transaction records is generated, it needs to be approved by distributed nodes in the peer-to-peer network through consensus before it can be added to the chain. The consensus algorithm is used to prevent double-spending transactions, where the same assets are spent in multiple transactions. Different from common consensus algorithms, an instance of delegated consensus will not involve all consensus nodes. Usually, delegated consensus will form a voting committee that contains consensus nodes with higher reputation scores, and the consensus process to approve transactions is only reached among committee members. Similar to [27], we use our reputation framework to implement delegated Practical Byzantine Fault Tolerance (PBFT) for the blockchain system. Non-committee nodes only participate in the consensus to approve changes in smart contracts.

3.1. Delegated PBFT

Each consensus instance begins with a client submitting a request to consensus nodes. In the blockchain-based energy trading system, adding energy transactions to the blockchain can be seen a consensus request. The original PBFT consensus completes in three main stages: pre-prepare, prepare, and commit [37].

1. In the pre-prepare stage, if the request is valid, then a pre-selected consensus node, called the leader, will broadcast a pre-prepare message that contains the request to all the other nodes. This stage makes sure the request received by all nodes are the same.

2. In the prepare stage, the nodes that have received a valid pre-prepare message broadcast a prepare message, which shares the pre-prepare message received from the leader. This stage makes sure that all nodes are participating the same consensus instance.
3. In the commit message, each node votes for the valid request by broadcasting a commit message. The commit message is also sent to the client. The request is committed and consensus is achieved if the commit messages from more than 2/3 nodes are received.

PBFT has a quadratic message complexity because three stages require message broadcasting. In other words, if the total number of consensus nodes is n, then the number of message transmission to complete a consensus instance has the order of n^2. This brings significant workload to the system as the number of consensus nodes increases. As illustrated by Figure 4, with the help of the reputation mechanism, delegated PBFT can effectively reduce its message complexity. We will describe the details of delegated PBFT in the next.

Delegated PBFT also has a distinguished leader node ℓ. Suppose leader node ℓ receives a request r. Leader ℓ need to generate a pre-prepare message as long as request r is valid. Different from the pre-prepare message of PBFT, the pre-prepare message of delegated PBFT need to specify a voting committee $C(r)$ which includes the information of the consensus nodes that will participate the prepare and commit stage.

In theory, any node other than ℓ with a comprehensive reputation score $R \geq R_{\min}$ may be selected as a committee member. Although we do not require the reputation scores of committee members to be at the top, it is recommended that committee $C(r)$ has a high average reputation (see Section 3.3). In order to effectively enhance the efficiency of delegated PBFT, the size of the committee should be much smaller than n when n is very large, and at least 4 nodes are needed to reach consensus.

After receiving the pre-prepare message, committee members in $C(r)$ as well as ℓ will continue with the prepare and commit stages as the original PBFT, which excludes non-committee nodes (or secondary nodes). Non-committee nodes only receive the pre-prepare message and the commit message passively. The consensus is successful if more than 2/3 committee members approve the request by broadcasting commit messages.

3.2. Offline Verification

Delegated consensus is a means to quickly respond to the client. It delegates the consensus tasks to participants with higher reputation scores. However, consensus decisions of the committee are not necessarily correct. Therefore, offline verification carried out by non-committee members is needed to ensure the final correct of the blockchain. Offline verification will also provide evidence for subsequent reputation updates. The offline verification is to prevent double spending and conspiracy.

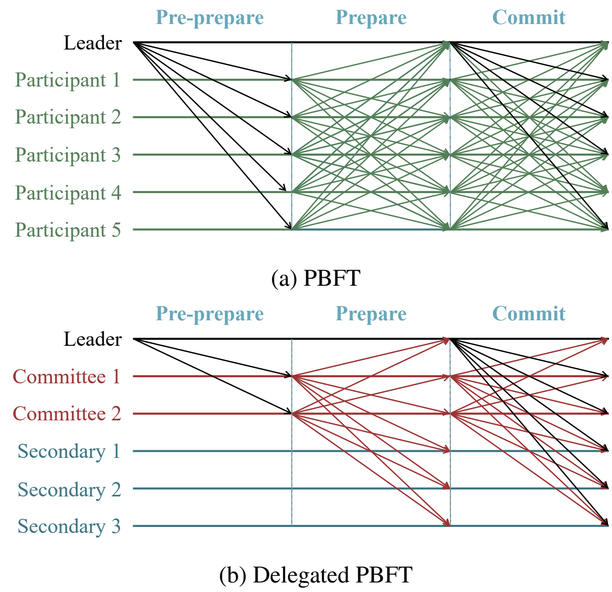


Figure 4: Message flow of PBFT and delegated PBFT.

Double spending is a kind of malicious behavior that attempts to spend the same assets in different transactions. A leader node ℓ could carry out double spending by sending different requests to disjoint committees for the same instance. It will cause forking in the blockchain. This can be mitigated by periodically apply the longest-chain rule. In more detail, the blockchain system will keep the longest subchain and discard other subchains when forks exist.

On the other hand, conspiracy refers to the case where a successful consensus instance approves an invalid request. Once conspiracy is detected, the block containing the invalid request will be directly removed and will not be added to the blockchain.

3.3. Rules for Consensus Nodes

Now we specify the rules of reputation update of consensus nodes:

1. **CN-1.** When a consensus instance for request r succeeds, the reputation of the leader ℓ changes by:

$$R_{CN}(\ell) \leftarrow \min\{\max\{R_{CN}(\ell) + R^{+}_{CN}(\ell) + R^{L,+}_{CN}(\ell), 0\}, 1\}, \quad (2)$$

and the reputation of a committee node $i \in C(r)$ changes by:

$$R_{CN}(i) \leftarrow \min\{\max\{R_{CN}(i)+R^{+}_{CN}(i), 0\}, 1\}, \quad (3)$$

where:

- $R^{+}(i)$ is positively related with the success rate of all consensus instances i has participated, and it is negatively related with the time duration since the last drop in $R_{CN}(i)$ and the current value of $R_{CN}(i)$;

- $R_{CN}^{L,+}(\ell)$ is positively related to the average reputation score of the committee C:

$$R_C(r) = \frac{1}{|C(r)|} \sum_{i \in C(r)} R(i). \tag{4}$$

2. **CN-2.** When a consensus instance for request r fails, the reputation of the leader ℓ changes by:

$$R_{CN}(\ell) \leftarrow \min\{\max\{R_{CN}(\ell) - R_{CN}^{-}(\ell) - R_{CN}^{L,-}(\ell), 0\}, 1\}, \tag{5}$$

and the reputation of a committee node $i \in C(r)$ changes by:

$$R_{CN}(i) \leftarrow \min\{\max\{R_{CN}(i) - R_{CN}^{-}(i), 0\}, 1\}, \tag{6}$$

where:

- $R^{-}(i)$ is positively related with the failure rate of all consensus instances j has participated and the time duration since the last drop in $R_{CN}(i)$, and it is negatively related with the time duration since the last drop in $R_{CN}(i)$ and the current value of $R_{CN}(i)$;
- $R_{CN}^{L,-}(i)$ is negatively related to R_C, the average reputation score of the committee C.

3. **CN-3.** The reputation score $R_{CN}(\ell)$ of the leader ℓ is cleared to 0 if double spending or conspiracy during the consensus process is discovered.

Note that CN-1 and CN-2 will be triggered once the consensus instance has finished, regardless of the result of offline verification. Conspiracy can be discovered during the verification right after the consensus, and double spending can be detected when the longest-chain rule is applied. These rules only change the reputation of the leader ℓ and committee nodes $i \in C(r)$, and reputation scores of non-committee nodes are not changed.

4. Blockchain-Based Peer-to-Peer Energy Trading with Reputation

The architecture of the P2P energy trading system based on blockchain and reputation is shown in Figure 5. The P2P platform will allocate a peer node to each buyer or seller during energy trading. The peer node is mainly used to publish supply or demand orders. It can also become a consensus node to record transactions into the blockchain and approve any change in smart contracts. Peer nodes are usually implemented in smart meters. The platform can stores transaction records into the distributed ledger. The reputation-based trading has 4 stages: order submission, matchmaking, transaction execution, and audit. The trading mechanism can also be implemented as smart contracts to achieve automation. Similarly, any changes to the trading mechanism should be approved by consensus.

In this section, we will go into more details about the reputation-based P2P trading mechanism.

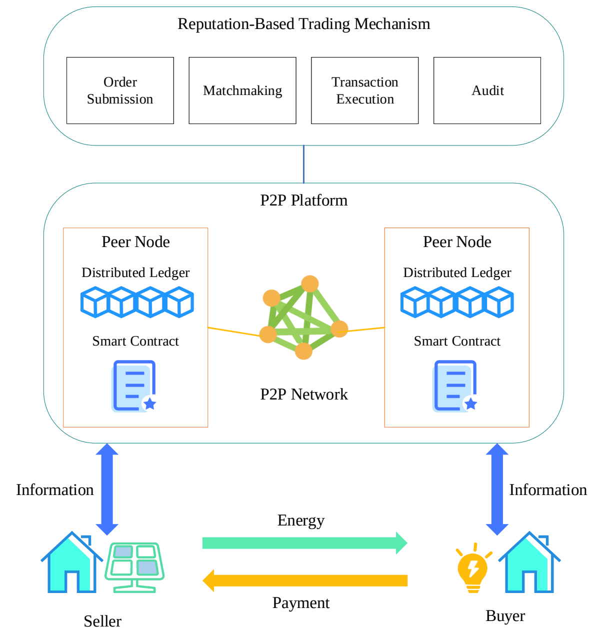


Figure 5: Architecture of P2P energy trading system based on blockchain and reputation.

4.1. Reputation-Based Peer-to-Peer Trading Mechanism

In this paper, we consider the day-ahead energy trading. In other words, the energy delivery plan of a day is determined in the previous day through order submission and matchmaking. The transaction execution takes place on the energy delivery time specified by transactions. The audit will be carried out once the execution finishes. The workflow of the P2P energy trading stages is depicted in Figure 6.

4.1.1. Order submission

In the first stage of energy trading, sellers need to submit supply orders while buyers need to submit demand orders. A supply order includes information about the time of energy supply, the amount of energy supply, and the *minimum* acceptable selling price (called the offering price). A demand order includes information about the time of energy demand, the amount of energy demand, and the *maximum* acceptable buying price (called the bidding price). Due to the consideration of user privacy protection, blockchain uses the account addresses of order submissions to correspond to the identities of prosumers or consumers instead of unique identifiers.

In order to prevent the seller from raising the price maliciously and the buyer from lowering the price maliciously, the system will provide reference price ranges for both parties. Orders whose prices exceed reference ranges will be removed. In addition, orders submitted by participants with reputation scores lower than $R_{\min}$ will also get filtered. Then supply and demand orders will be grouped by the time of supply or demand (collectively referred to as the transaction execution time) since orders cannot get matched if they are

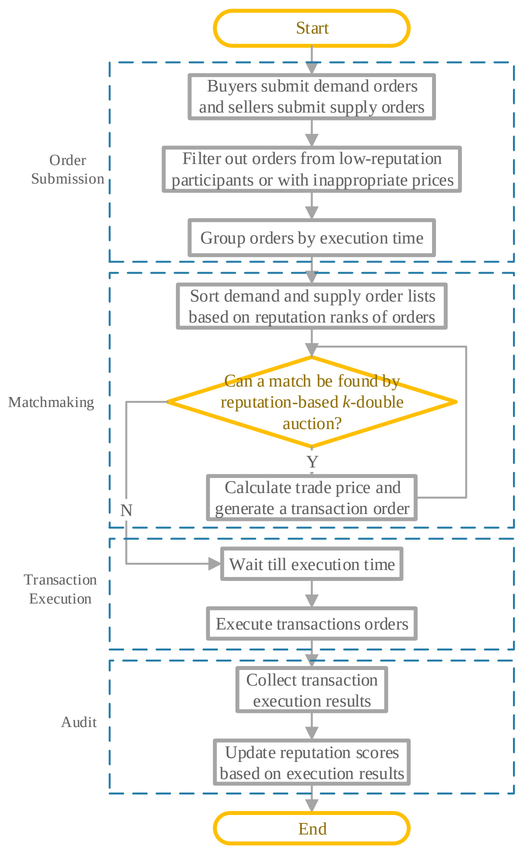


Figure 6: Workflow of reputation-based P2P energy trading.

supposed to take place at different time periods.

4.1.2. Matchmaking

Before applying matchmaking between sellers and buyers, many existing systems will sort supply orders in ascending order of offering price and demand orders in descending order of bidding price [38]. This strategy is to maximize the profits of sellers and minimize the expenses of buyers. In our reputation-based energy trading mechanism, we consider the reputation-based profit and expense.

Similar to the credit defined in [39], reputation scores can also be regarded as an indicator of the contribution of a participant in P2P energy trading. A fairer approach could be to increase the profits of high-reputation sellers and decrease the expenses of high-reputation buyers. To achieve this, we define the reputation-based rank for supply and demand orders similar to the priority value in [22].

In more detail, the buying rank of a demand order from buyer b is defined as:

$$rank_{buy} = \frac{bp}{1 - R(b)}, \tag{7}$$

where bp is the bidding price of the demand order, and $R(b)$ is the comprehensive reputation score of buyer b. Similarly, the selling rank of a supply order from seller s is defined as:

$$rank_{sell} = \frac{op}{R(s)}, \tag{8}$$

where pp is the offering price of the supply order, and $R(s)$ is the comprehensive reputation score of seller s. Once the ranks of orders are calculated, supply orders will be sorted in ascending order of $rank_{sell}$, and demand orders will be sorted in descending order of $rank_{buy}$. As we can see from (7) and (8), when two supply/demand orders have the same offering/bidding price, the one from a higher-reputation seller/buyer has a smaller/larger rank and will be in a higher position.

We then use a reputation-based k-double auction method to decide the trade price. In more detail, the matchmaking between sellers and buyers will start from the top of the supply and demand order lists. A matching is found when it comes across a bidding order from buyer b and an offering order from seller s with $bp \geq op$. Then the trade price is calculated by:

$$tp = k \cdot bp + (1 - k) \cdot op, \tag{9}$$

where k is calculated by:

$$k = \frac{R(s)}{R(b) + R(s)}. \tag{10}$$

Different from the k-double auction method in [36] where k is a constant, the trade price in our reputation-based method is decided by not only the prices of the supply order and the demand order, but also the comprehensive reputation scores of both the buyer b and the seller s. Note that the trade price is closer to the price submitted by the participant with lower reputation. This strategy will in turn increase the profit of the seller or decrease the expense of the buyer with a higher reputation in a transaction.

Finally, a transaction order will be formed, which specifies the buyer's address, the seller's address, the transaction execution time, the amount of energy delivery, and the trade price.

4.1.3. Transaction Execution

Upon the execution time of a transaction, the energy and currency transfer will take effect according to the transaction order. Note that the transaction execution may fail if the seller refuses to transfer the prescribed amount of energy or the buyer refuses to pay the prescribed price.

4.1.4. Audit

The audit stage will review the execution of transactions and then update reputation scores according to the reputation rules for energy buyers and energy sellers. A successful execution of a transaction will enhance the reputation of both parties, while the reputation scores of those who failed to fulfill their transaction contracts will be reduced.

4.2. Rules for Buyers and Sellers

The update in the reputation scores of P2P energy trading participants are as follows:

- **ES-1.** When the supply of a transaction order is successfully executed, the reputation of the seller is changed by:

$$R_{ES}(i) \leftarrow \min\{1, \max\{0, R_{ES}(i) + R^{+}_{ES}(i)\}\}, \quad (11)$$

  where $R^{+}_{ES}(i)$ is positively related to the ratio of total successful supply amount to the number of successful transaction execution and the duration since last reputation drop.

- **ES-2.** When the supply of a transaction order fails, the reputation of the seller is changed by:

$$R_{ES}(i) \leftarrow \min\{1, \max\{0, R_{ES}(i) - R^{-}_{ES}(i)\}\}, \quad (12)$$

  where $R^{-}_{ES}(i)$ is positively related to the ratio of total failed supply amount to the number of failed transaction execution, and is negatively related to the duration since last reputation drop.

- **EB-1.** When the consumption of a transaction order is successfully executed, the reputation of the buyer is changed by:

$$R_{EB}(i) \leftarrow \min\{1, \max\{0, R_{EB}(i) + R^{+}_{EB}(i)\}\}, \quad (13)$$

  where $R^{+}_{EB}(i)$ is positively related to the ratio of total successful energy consumption to the number of successful transaction execution and the time duration since last reputation drop.

- **EB-2.** When the consumption of a transaction order fails, the reputation of the buyer is changed by:

$$R_{ES}(i) \leftarrow \min\{1, \max\{0, R_{ES}(i) - R^{-}_{ES}(i)\}\}, \quad (14)$$

  where $R^{-}_{ES}(i)$ is positively related to the ratio of total failed consumption amount to the number of failed transaction execution, and is negatively related to the duration since last reputatio drop.

These rules can also be implemented as smart contracts to achieve automation and avoid mistakes or tampering during manual calculation.

4.3. Fairness Indicator

Many existing works advocate to bring fairness to energy trading, but few of them has a clear measure of fairness. In this paper, we define seller and buyer fairness indicators to describe a kind of fairness.

Formally, the seller and buyer fairness indicators are defined as follows:

- For sellers, the seller fairness indicator (SFI) is defined as:

$$SFI(s) = \frac{income(s)}{E_{sell}(s) \cdot R(s)}, \quad (15)$$

  where $income(s)$ is the total income of s during a trading period, and $E_{sell}(s)$ is the total amount of energy sold by s;

- For buyers, the buyer fairness indicator (BFI) is defined as:

$$BFI(b) = \frac{cost(b)}{E_{buy}(b) \cdot R(b)}, \quad (16)$$

  where $cost(b)$ is the total cost of b during a trading period, and $E_{buy}(b)$ is the total amount of energy purchased by b.

If we regard the reputation score as a kind of contribution to the P2P energy trading system, then fairness indicators can be seen as the average income and average cost per contribution. Balancing fairness indicators among sellers and buyers can increase the average incomes of high-reputation sellers and reduce the average costs of high-reputation buyers. This strategy achieves an intuitive kind of fairness as it is more friendly to the participants with high cumulative contribution. It also helps to use reputation as incentives due to its favor to participants with high reputation scores.

5. Evaluation

In this section, we evaluate the performance of our comprehensive system by simulation, which consists of a reputation system RBT, a blockchain system, and a P2P energy trading system. We implement the entire system in Go language (GoLand 2020.3.1 x64). The simulation experiments are executed on a computer with Intel(R) Core(TM) i7-6500U CPU at 2.50GHz and 12GB. Each experiment is run 10 times, and each graphs in this section is plotted with the average data collected from these 10 runs.

5.1. RBT Reputation Scores

In order to test the effect of RBT, we need to specify example formulas according to the reputation update rules described in Section 3.3, 4.2. The details of the formulas are described in Appendix A. Figure 7 simulates 4 typical trends of comprehensive reputation scores with 168 transaction instances: Gradually up, gradually down, decline after increase, and rise after decrease.

5.2. Reputation-Based Delegated PBFT

We then evaluate the performance of the blockchain system that implements reputation-based delegated PBFT. We compare it with a blockchain system with the original PBFT algorithm as its consensus mechanism. All the graphs here will use red curves to represent our reputation-based blockchain system and blue curves to represent PBFT-based blockchain system. Link latencies between consensus nodes are randomly drawn from a uniform distribution with an average of 200 ms. Communication messages between nonfaulty nodes are guaranteed to be delivered within 20 s. The time to generate a new block is no longer than 20 s. Transaction records are submitted by the client application in a speed that follows a Poisson process at an average of 2 requests per second [40].

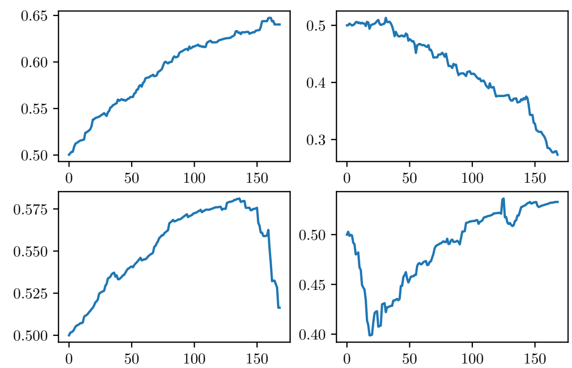
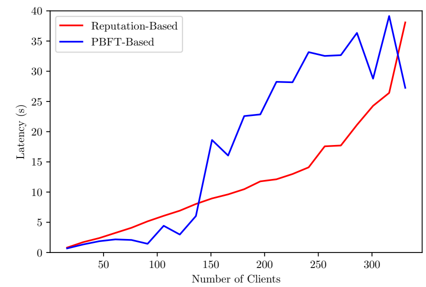
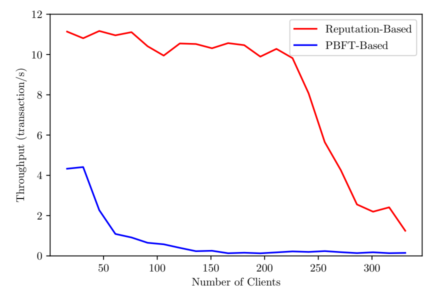


Figure 7: Different trends of reputation. In each graph, the horizontal axis represents transaction instance number, and the vertical axis represents comprehensive reputation score.



(a) Latency vs. Client Number



(b) Throughput vs. Client Number

Figure 8: Performance comparison between delegated reputation-based blockchain with reputation and PBFT-based blockchain as the number of clients increases.

5.2.1. Scalability

Scalability usually has two aspects: client scalability and server scalability [41]. Client scalability reflects the ability to handle the workload caused by the increase in the number of clients, while server scalability reflects the ability to handle the workload caused by the increase in the number of servers.

We first fix 100 servers (consensus nodes), 20 of which could become committee members. As shown by Figure 8a, the red curve is more often below the blue curve, indicating a slight decrease in latecy of reputation-based blockchain on average. Figure 8b shows a great increase in the throughput of reputation-based blockchain. The throughput of PBFT-based blockchain is almost 0 after the client number reaches 150, while the throughput of reputation-based blockchain does not have a dramatic decrease until the client number passes 240. These two graphs indicates the better client scalability of reputation-based blockchain compared to that of PBFT-based blockchain.

Then, we fix 20 clients and 20 committee members. We can see from Figure 9a that the change in the latency of reputation-based blockchain is very small, compared to the sudden increase in the latency of PBFT-based blockchain after the number of consensus nodes passes 215. Figure 9b shows that both curves falls as the number of consensus nodes rises, but the red curve has a slower decreasing speed. Although the size of the committee does not increase, the growth in the total number of consensus nodes slows down the process of offline verification. These two graphs also indicates the improvement in server scalability of reputation-based blockchain compared to that of PBFT-based blockchain.

5.2.2. Fault Tolerance

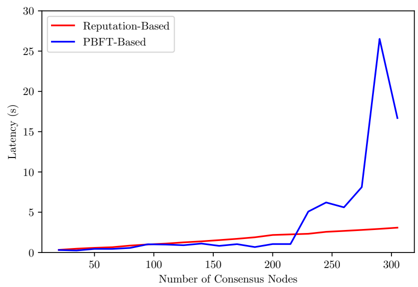
It has been proved that PBFT cannot reach consensus if the proportion of Byzantine nodes, or Byzantine fault rate, is greater than $1/3$ [42]. In contrast, delegated consensus only reach consensus within the committee, and there is still a chance to reach a consensus if the Byzantine fault rate is greater than $1/3$. This point can be confirmed by Figure 10. We can see that the throughput of PBFT-based blockchain falls down to 0, while the throughput of reputation-based blockchain does not converge to 0 until the Byzantine fault rate passes 80%. This indicates an improvement in the fault tolerance capability of reputation-based blockchain compared to that of PBFT-based blockchain.

5.3. Case Study for Reputation-Based Peer-to-Peer Energy Trading

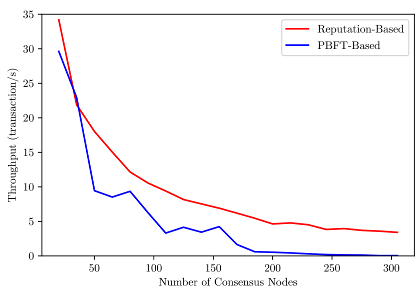
In order to evaluate our reputation-based P2P energy trading system, we run a case study of a certain trading round for the same transaction execution time period. Table 1 and 2 provide detailed information of the supply and demand orders respectively.

The matchmaking will first filter out the orders from participants with reputation lower than $R_{\min} = 0.2$ (U and W), sort the supply order list and the demand order list according to $rank_{sell}$ and $rank_{buy}$ respective, and go through both lists from the top. The matchmaking results are shown in Table 3. We compare our trading strategy to the k-double auction with $k = 0.6445$ without considering reputation in [36], and the corresponding matchmaking results for the same supply and demand orders are shown in Table 4. Note that the seller of Transaction 11 and 12 in Table 4 is U with untrusted low reputation score 0.1680. The consequence of allowing these transactions is that the success of their execution cannot be guaranteed, thus bringing the risk of loss to buyer M and X.

Finally, we compare the fairness indicators of each par-



(a) Latency vs. Server Number



(b) Throughput vs. Server Number

Figure 9: Performance comparison between delegated PBFT-based blockchain with reputation and PBFT-based blockchain as the number of consensus nodes (servers) increases.

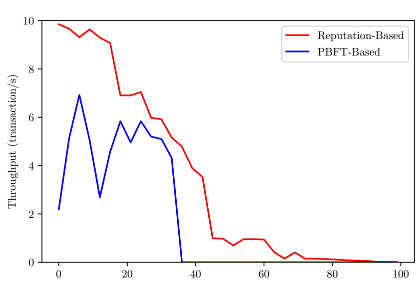


Figure 10: Throughput comparison between delegated consensus-based blockchain and PBFT-based blockchain as the Byzantine fault rate increases.

ticipants based on the trading results of both methods. Table 5 shows that the fairness indicators of our reputation-based k-double auction is more balanced compared to the method without considering reputation. As we mentioned in 4.3, the average revenue for sellers rises and the average cost falls proportionally to reputation, making reputation a good incentive to participants in the P2P energy trading system.

6. Conclusion

Reputation has been proved to be effective in increasing the efficiency of blockchain and the fairness of energy trading in recent works. This paper studies distributed reputation since its implementation has not been fully explored yet in the energy field. With the continuous development of distributed energy system, distributed reputation will become a promising research topic in this area. In the future, we could further extend the application of distributed reputation in other forms of trading in the energy fields, for example, green certificate trading or carbon trading.

Moreover, there are many ways and standards to judge the fairness of the energy trading system. This paper propose the definition of fairness indicator that regard reputation as

Table 1
Supply orders for case study.

Seller	Amount (kW·h)	Offering Price ($/kW·h)	Reputation Score	$rank_{sell}$
A	53	2.24	0.7198	3.1120
D	32	1.82	0.5931	3.0686
E	60	1.63	0.5316	3.0662
F	26	2.34	0.4738	4.9388
H	35	1.62	0.2004	8.0838
J	33	1.69	0.6002	2.8157
K	38	1.82	0.6997	2.6011
Q	40	2.21	0.6046	3.6553
R	59	1.73	0.6815	2.5385
S	35	2.27	0.7414	3.0618
T	31	2.23	0.5875	3.7957
U	32	1.92	0.1680	11.4286
Y	59	2.30	0.6085	3.7798

Table 2
Demand orders for case study.

Buyer	Amount (kW·h)	Bidding Price ($/kW·h)	Reputation Score	$rank_{buy}$
B	31	1.78	0.6361	4.8888
C	59	2.25	0.6781	6.9854
G	28	1.64	0.7911	7.8431
I	27	2.26	0.6426	6.3199
L	51	1.87	0.5646	4.2929
M	60	2.04	0.3653	3.2131
N	28	2.39	0.6783	7.4247
O	25	2.13	0.2000	2.6618
P	40	1.94	0.7390	7.4273
V	33	2.31	0.4699	4.3560
W	28	1.64	0.1178	1.8586
X	27	1.95	0.5111	3.9869
Z	27	2.31	0.6590	6.7702

Table 3
Matchmaking results of reputation-based k-double auction.

Transaction	Buyer	Seller	Amount (kW·h)	Trade Price ($/kW·h)
1	G	H	28	1.62
2	P	R	40	1.83
3	N	R	19	2.06
4	N	K	9	2.11
5	C	K	29	2.04
6	C	J	30	1.95
7	Z	J	3	1.99
8	Z	S	24	2.29
9	I	E	27	1.92
10	B	E	31	1.70
11	V	S	11	2.29
12	V	E	2	1.99
13	V	D	20	2.09
14	L	D	12	1.85
15	L	H	7	1.87

Table 4
Matchmaking results of k-double auction without considering reputation [36].

Transaction	Buyer	Seller	Amount (kW·h)	Trade Price ($/kW·h)
1	N	H	28	2.12
2	V	H	7	2.06
3	V	E	26	2.07
4	Z	E	27	2.07
5	I	E	7	2.04
6	I	J	20	2.06
7	C	R	59	2.07
8	O	D	25	2.02
9	M	D	7	1.96
10	M	K	38	1.96
11	M	U	15	2.00
12	X	U	16	1.94

the contribution to the system. We believe this intuitively makes reputation a good incentive for participants. Our future work will also explore more scientific and legitimate definitions of fairness for energy trading.

A. Formulas for Reputation Update Rules

The formulas for reputation update rules chosen in our simulation in Section 5 are as follows:

1. Reputation increment for consensus nodes of a successful consensus instance in CN-1:

$$R^{+}_{CN}(i) = \begin{cases} 1 - \pi^{ind_{CN}} & R_{CN} \geq R_{\min}, \\ 0 & \text{otherwise,} \end{cases} \tag{17}$$

where

$$ind_{CN} = -\alpha \frac{r^{+}_{CN}(i)\left(1 - 10^{-\beta t^{-}_{CN}(i)}\right)}{\left(100 R_{CN}(i)\right)^2}, \tag{18}$$

$r^{+}_{CN}(i)$ is the overall consensus success rate of i, $t^{-}_{CN}(i)$ is the elapsed time since last drop in $R_{CN}(i)$, and α, β, π are parameters;

2. Reputation reward for the leader of a successful consensus instance in CN-1:

$$R^{\ell,+}_{CN}(\ell) = \gamma R_C(r), \tag{19}$$

where γ is a parameter;

3. Reputation deduction for consensus nodes of a failed consensus instance in CN-2:

$$R^{-}_{CN}(i) = \begin{cases} base^{\rho}_{CN} & R_{CN}(i) \geq R_{min}, \\ 0 & \text{otherwise,} \end{cases} \tag{20}$$

where

$$base_{CN} = \alpha \frac{r^{-}_{CN}(i)\left(1 - 10^{-\beta t^{-}_{CN}(i)}\right)}{\left[100\left(1 - R_{CN}(i)\right)\right]^2},$$

$r^{-}_{CN}(i)$ is the overall consensus failing rate of i, and ρ is a parameter;

4. Reputation penalty for the leader of a failed consensus instance in CN-2:

$$R^{\ell,-}_{CN}(\ell) = \gamma\left(1 - R_C(r)\right). \tag{21}$$

5. Reputation increment for the seller of a successful supply execution of a transaction in ES-1:

$$R^{+}_{ES}(i) = \begin{cases} 1 - \pi^{ind_{ES}} & R_{ES} \geq R_{\min}, \\ 0 & \text{otherwise,} \end{cases} \tag{22}$$

where

$$ind_{ES} = -\alpha \frac{r^{+}_{ES}(i)\left(1 - 10^{-\beta t^{-}_{ES}(i)}\right)}{\left(100 R_{ES}(i)\right)^2}, \tag{23}$$

$r^{+}_{ES}(i)$ is the ratio of total energy of all succeeded supply executions to total energy of all participated transactions of i, $t^{-}_{ES}(i)$ is the elapsed time since last drop in $R_{ES}(i)$;

6. Reputation deduction for the seller of a failed supply execution of a transaction in ES-2:

$$R^{-}_{ES}(i) = \begin{cases} base^{\rho}_{ES} & R_{ES}(i) \geq R_{min}, \\ 0 & \text{otherwise,} \end{cases} \tag{24}$$

where

$$base_{ES} = \alpha \frac{r^{-}_{ES}(i)\left(1 - 10^{-\beta t^{-}_{ES}(i)}\right)}{\left[100\left(1 - R_{ES}(i)\right)\right]^2},$$

$r^{-}_{ES}(i)$ is the ratio of total energy of all failed supply executions to total energy of all participated transactions of i;

7. Reputation increment for the buyer of a successful demand execution of a transaction in EB-1:

$$R^{+}_{EB}(i) = \begin{cases} 1 - \pi^{ind_{EB}} & R_{EB} \geq R_{\min}, \\ 0 & \text{otherwise,} \end{cases} \tag{25}$$

where

$$ind_{EB} = -\alpha \frac{r^{+}_{EB}(i)\left(1 - 10^{-\beta t^{-}_{EB}(i)}\right)}{\left(100 R_{EB}(i)\right)^2}, \tag{26}$$

$r^{+}_{EB}(i)$ is the ratio of total energy of all succeeded demand executions to total energy of all participated transactions of i, $t^{-}_{EB}(i)$ is the elapsed time since last drop in $R_{EB}(i)$;

8. Reputation deduction for the seller of a failed demand execution of a transaction in EB-2:

$$R^{-}_{EB}(i) = \begin{cases} base^{\rho}_{EB} & R_{EB}(i) \geq R_{min}, \\ 0 & \text{otherwise,} \end{cases} \tag{27}$$

where

$$base_{EB} = \alpha \frac{r^{-}_{EB}(i)\left(1 - 10^{-\beta t^{-}_{EB}(i)}\right)}{\left[100\left(1 - R_{EB}(i)\right)\right]^2},$$

Table 5
Comparison of fairness indicators for different trading methods.

Seller	Reputation Score	Reputation-Based	Without Reputation	Buyer	Reputation Score	Reputation-Based	Without Reputation
A	0.7198	-	-	B	0.6361	2.6725	-
D	0.5931	3.3729	3.3841	C	0.6781	2.9419	3.0526
E	0.5316	3.3967	3.8836	G	0.7911	2.0478	-
F	0.4738	-	-	I	0.6426	2.9879	3.1930
H	0.2004	8.3494	10.5087	L	0.5646	3.2848	-
J	0.6002	3.2587	3.4278	M	0.3653	-	5.3947
K	0.6997	2.9373	2.8038	N	0.6783	3.0612	3.1255
Q	0.6046	-	-	O	0.2000	-	10.0990
R	0.6815	2.7950	3.0303	P	0.7390	2.4763	
S	0.7414	3.0917	-	V	0.4699	4.5844	4.3999
T	0.5875	-	-	W	0.1178	-	-
U	0.1680	-	11.7107	X	0.5111	-	3.7944
Y	0.6085	-	-	Z	0.6590	2.9680	3.1385

$r^-_{EB}(i)$ is the ratio of total energy of all failed demand executions to total energy of all participated transactions of i.

In the simulation, we choose $\alpha = 6$, $\beta = 0.02$, $\gamma = 0.05$, $\pi = 5$, $\rho = 0.48$.

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