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RMCT: Distributed electricity transaction based on reputation mechanism and multi-chain technology in blockchain environment

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ABSTRACT

In smart grids, large amounts of private data, such as real-time electricity consumption data, are stored by smart meters. However, they can be turned into malicious nodes due to human attacks, resulting in data leakage and unreliable transactions. Additionally, significant issues in power transaction processes include excessive computational costs and restricted throughput. To enhance the trustworthiness and efficiency of power trading, we innovatively propose a real-time peer-to-peer power trading model (RMCT), integrating reputation mechanism and multi-chain technology in blockchain environment. Firstly, in RMCT, a reputation mechanism is designed based on user behavior management to effectively reduce malicious behaviors and improve transaction compliance in the distributed power trading process. Secondly, a multi-chain model is firstly proposed where the dynamic electricity unit price chain interacts in real-time with the user's real-time electricity consumption chain, enabling efficient electricity billing settlement between the user and the main grid. The validity and performance of RMCT are demonstrated by adequate experimental results and analysis. Additionally, a comprehensive qualitative comparison between RMCT and related work is conducted to fully verify its feasibility and innovation.

1. Introduction

With the rapid development of new power systems and distributed power trading, the reliability of Advanced Metering Infrastructure (AMI) at the endpoints becomes more and more critical. The reliability of AMI directly affects the stability of the distributed power trading market within the Smart Grid, which handles a large amount of power consumption data [1–4]. For users participating in distributed power trading as well as power trading with the main grid, the credibility and reliability of the trading process as well as the efficient synchronization of real-time power consumption billing settlement are challenges that we cannot ignore.

In recent years, cases of smart meter failures have attracted attention. According to a report by the UK Guardian on 5 March 2017 [5], many customers of Scottish Energy have experienced problems with smart meter failures. These malfunctions resulted in electricity bills of up to £33,000 for a single meter in just 24 h, whereas under normal circumstances their daily electricity bill is only £3.80. This increase in abnormal electricity bills not only affects the financial burden of the users, but also adversely affects the electricity trading and scheduling process. In addition, the smart grid system has a large number of users and diverse groups [6,7], and abnormal electricity transaction behavior can also seriously impair the throughput and transmission rate of the data transmission process [8]. In view of this, the system needs to have better real-time data interaction and transmission capabilities to cope with the challenges of large amounts of power supply and demand [9–11].

Researchers have begun to incorporate blockchain technology and reputation mechanisms into smart grids [12]. The aim of this is to limit malicious behaviors and enhance the motivation and market stability of user participation [13,14] in the distributed electricity trading process. However, addressing how to use credit mechanisms to reduce user default in electricity trading processes is a pressing issue that needs resolution [15]. In addition, in power trading and billing settlements with the main grid [16,17], various nodes and organizations in the grid that are deployed to the blockchain for data interaction. However, the traditional single-chain structure may not be able to withstand the massive real-time data and high concurrent transmission from numerous smart meters in a large-scale smart grid system [18,19],

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resulting in blocked data transmission, high latency, and untimely response to power demand [10,19–23], which causes unpredictable economic losses to users.

In this paper, we propose a distributed electricity trading model based on reputation mechanism and multi-chain technology to address the challenges in smart grid system, aiming to provide a credible and efficient market environment for distributed electricity trading. Our contributions can be summarized as follows:

- We design a reward and punishment mechanism based on the prioritization of reputation values to regulate users with malicious defaults and other behaviors during the transaction process. This approach aims to enhance transaction compliance and success rates within the distributed power trading market. For users with excellent trading behavior, we provide more network resources for credible and efficient distributed power trading to enhance the motivation of users in peer-to-peer trading.
- For participants who only conduct electricity transaction billing settlement with the power management center-master, our multi-chain mechanism is able to conduct efficient real-time electricity multi-chain interaction settlement and billing. We compare the block rate and data throughput performance of RMCT-C with that of single-chain power trading approach. Our scheme improves 97.38% and 82.49%, respectively, while ensuring lower transaction communication latency.
- We propose RMCT, includes 2 modules (RMCT-R for distributed power trading and RMCT-C for power trading with the main grid). We verify the effectiveness of the proposed scheme and the reliability of RMCT applied to smart grid scenarios through sufficient experiments.

The rest of this paper is organized as follows: in Section 2, we present the system architecture design and the general framework and details of RMCT. Section 3 describes the design of related experiments and platforms, and provides a comprehensive analysis of the experimental results of RMCT-R and RMCT-C, respectively. Section 4 provides a comprehensive discussion on the security analysis of transaction processing, and the transaction efficiency performance of the electricity billing settlement. In Section 5, we discuss some related work. Finally, Section 6 concludes this paper.

2. System model

In distributed power transaction system model we propose, RMCT is designed for two different power transaction modes: peer-to-peer transactions among users and transactions involving electricity purchases from the main grid. Devices of various users are scored through the design of a reputation mechanism, where higher reputation values lead to resource rewards, while malicious devices face penalties and restrictions. Additionally, the multi-chain interaction design facilitates efficient billing settlement of power transactions between users and the main grid through real-time interaction between the real-time electricity consumption chain and the real-time electricity price chain. In this section, the design and methodology of architecture, reputation mechanism, and multi-chain are detailed.

A. Architectural Design

Our system model consists of four entity ends: (1) smart meter terminal (called SMT) ; (2) collection terminals (called CT) ; (3) station concentrators (called SC) ; (4) billing center master stations (called BC).

The overall framework depicted in Fig. 1 begins with the SMT, which is responsible for collecting electricity consumption data from various households, institutions, and businesses. This data includes real-time electricity usage, cumulative consumption, and user identity information. The SMT engages in bidirectional communication and data exchange with upper-level CT, SC, and the BC.

Table 1
List of notations.

Notation	Description
R_{dev}	The reputation value of the device
T_{abn}	The reputation value threshold for abnormal device
Sta	The device reputation status is labeled Sta.
W_i	The weight of evaluation indicator i of reputation value
S_i	The score of evaluation indicator i
S_{min}	The minimum value of scores for all evaluation indicator
S_{max}	The maximum value of scores for all evaluation indicator
E	Current user power data historical values
A	Current user power data actual values
C	Successful transaction communication frequency
T	Total transaction communication frequency
K	The number of respond to reputation list updates
M	Total number of updated tests
Q	The number of transactions created by a single user
Ω	Transaction compliance operation time
Z	The number of successful electricity transactions
E_t	The real-time power consumption of the user at time t
P_t	The real-time electricity price at time t
B	Total electricity bill settlement price

The CT is responsible for gathering electricity usage data transmitted by SMTs that have been filtered and marked as valid. It subsequently transmits this data to the SC. Each concentrator is deployed within a substation area, where it consolidates metering data collected from the field and transmits it to BC for billing purposes.

The users are allowed to participate in P2P distributed electricity trading markets, and can determine their role as a buyer or seller based on their reputation, also can initiate or respond to electricity trading requests according to their own electricity needs.

For users are not permitted to participate in P2P electricity trading or with no demand for P2P electricity trading, their electricity usage data are transmitted to the power data chain δ. The data are interactively computed with the real-time electricity price chain γ. The settled electricity bills are transmitted to the BC.

B. Reputation Mechanism Design: RMCT-R

The following is our design for reputation mechanism for all smart meters (called RMCT-R). This aims to ensure that the data transmitted upwards at the endpoints is provided by trusted metering devices and not from anomalous devices that have been maliciously compromised, attacked, or have natural corruption. Only if the user's reputation value exceeds the predefined threshold can the user participate in the peer-to-peer power trading market, buying and selling power between users. Otherwise, the user can only engage in power trading with main grid, purchasing power from the BC. The notations used in this section are illustrated in Table 1. Firstly, initialize the reputation value R_{dev}:

$$R_{dev} = \sum_{i=1}^{4} W_i \cdot \frac{S_i - S_{min}}{S_{max} - S_{min}} \cdot 100 \tag{1}$$

we design four evaluation indicators to score the reputation of devices, where $w_1+w_2+w_3+w_4 = 1$.

In this model, we design scores for each evaluation indicator and calculate the smart meter's credibility using a weighted average of these scores. To ensure that the user device reputation value and the evaluation indicator scores are in the same range, we percent-normalized these scores to control the reputation value scores within the range of 0–100. In order to ensure the justice and fairness in the process of calculating the credibility value, and to comprehensively consider the impact of the evaluation indicators on the credibility value. We design the following four evaluation indicators:

1. Electricity data drift is assessed, i.e., the accuracy of the data. Assuming that the data accuracy is weighted as w_1. The historical value is E, the actual value is A, and the error rate is $\frac{|\mathbf{E}-\mathbf{A}|}{\mathbf{E}}$. The score is calculated using the formula:

$$S_1 = w_1 \cdot 100 \cdot \frac{|E - A|}{E} \tag{2}$$

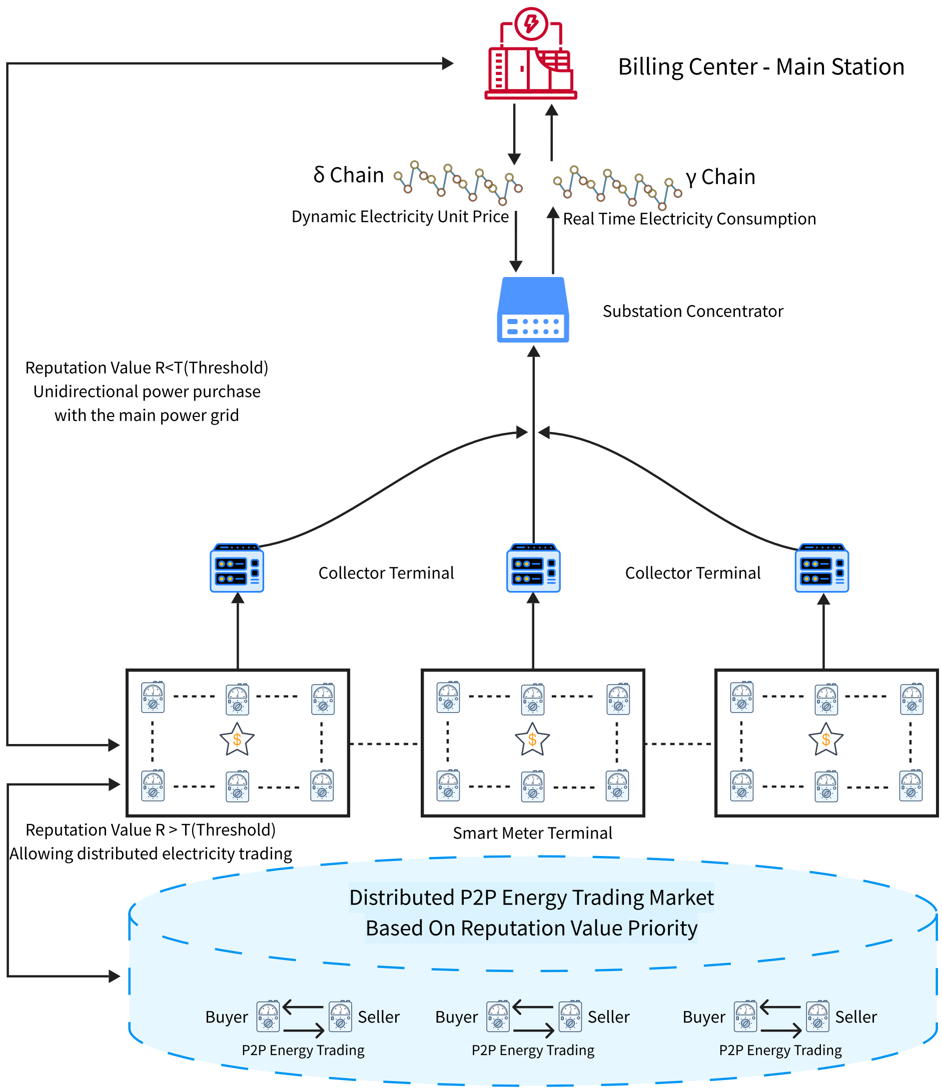

Fig. 1. Overall framework.

2. Communication reliability is assessed as the success rate of the device communication transaction connection. Assuming that the weight of communication reliability is w_2. The number of successful communications is C, the total number of communications is T, and the success rate is $\frac{C}{T}$. The score is calculated using the formula:

$$S_2 = w_2 \cdot 100 \cdot \frac{C}{T} \tag{3}$$

3. Inter-device state response evaluation, i.e., device response rate, which is an index that can reflect whether there is a communication delay and other faults of a device. At each time interval t, reputation lists are updated by devices and immediately broadcast to neighboring devices. Thus, each smart meter in the grid is acted upon as a neighbor device. After issuing these instructions within the time interval, if the updated reputation list is received by neighboring device, communication response delays with adjacent devices are eliminated, and a successful reception acknowledgment is returned. If the list is not received, the response reception is deemed unsuccessful. Thus, the weight of power coordination is w_3, and updates in the credibility list are responded to K times by the smart meter out of M total update tests, with a success response rate of $\frac{K}{M}$. The score calculation formula is:

$$S_3 = w_3 \cdot 100 \cdot \frac{K}{M} \tag{4}$$

4.Additionally, to prevent the existence of malicious attacks on the device, such as DOS or DDOS attacks, which result in the attacked user device maliciously sending frequent transaction requests to many other normal users in the market but are never able to establish a normal transaction, causing a connectivity attack by maliciously occupying a large amount of bandwidth in the electricity trading network, or the default behavior of artificially and intentionally canceling the transaction due to the failure to satisfy the original agreement on the tariff, the default behavior of the user in the process of electricity trading, i.e., the transaction compliance rate also be evaluated. Defined as the weight given to the user's transaction compliance rate is w_4, the total number of transaction connections created by a single user is Q, where Z represents the number of times an electricity transaction is successfully completed without the operation being willfully or maliciously canceled by the user within a specified time Ω. The transaction compliance rate is $\frac{Z}{Q}$. The score is calculated using the formula:

$$S_4 = w_4 \cdot 100 \cdot \frac{Z}{Q} \tag{5}$$

Algorithm 1 A Credit Mechanism Model for Power Trading

1:**Input :**
2:Current user power data historical and actual values: E,A; Successful transaction communication frequency and total communication frequency: C,T;The number of times smart meters respond to reputation list updates and the total number of updated tests: K,M;The total number of transaction connections created by a single user and their compliance with electricity trading within a specified time Ω: Q, Z; Pre set reputation threshold: T_{abn};The quantity of all devices:n;The total reputation value of all devices $R_{All}=\{R_{dev_1}, \dots, R_{dev_n}\}$;The device reputation status: Sta
3:**Procedures:**
4: Initialize reputation value $R_{dev} = 0$
5:**foreach** $(R_{dev} : S_1 : S_2 : S_3 : S_4)$
6: Eq. (1)
7: $T_{abn} = \frac{R_{All}}{n}$
8: **if** $R_{dev} > T_{abn}$ then
9: Sta = 1
10: **else** Sta = 0
11:**end if**
12:**end foreach**
13:**until** $R_{dev} > T_{abn}$
14:The device is allowed to conduct distributed power trading

The pseudo-code of the designed RMCT-R model is depicted in Algorithm 1. Each evaluation index ranges from 0 to 100, with 100 indicating the best state or highest score, and 0 indicating the worst state or lowest score. After the calculation of the four evaluation indexes, the reputation value R_{dev} of the user device is derived. A threshold T_{abn} is set for device with abnormal reputation values. The device reputation status is labeled Sta, its value is defined as 0 and 1. If $R_{dev} \leq T_{abn}$ in this round of calculation, a penalty mechanism is applied, preventing the device from participating in peer-to-peer electricity trading. Sta is set to 0. Conversely, if $R_{dev} > T_{abn}$, a reward mechanism is implemented to incentivize participation in the electricity trading market. Sta is set to 1. A reputation prioritization strategy is devised, allocating more resources such as network bandwidth to devices with higher reputation values, enabling quicker responses to electricity trading requests. Experimental results demonstrate improved transaction compliance rates and increased motivation for users to participate in the distributed electricity trading market in a standardized manner. Devices with persistently abnormal reputation scores are identified as problematic and sent for maintenance. Devices can improve their reputation scores through consistent normal behavior after experiencing temporary abnormalities (e.g., delays, offline periods followed by normal operation).

C. Multi-chain Design for Electricity Settlement Transactions with Main Grid: RMCT-C

For users who cannot enter the P2P electricity trading market due to low reputation and non-compliance, the method of transmitting their electricity data from the SC end to BC is proposed for real-time bill settlement through a multi-chain design (called RMCT-C). This is aimed at facilitating real-time interactive transaction and settlement of electricity bills between electricity purchaser and the BC under dynamic electricity price scenarios, with the goal of enhancing the efficiency of the settlement process.

For electricity billing settlement in the electric grid scenario, some electricity billing management centers, managed by third-party organizations, utilize a method where researchers aim to protect users' private electricity data. A large amount of encrypted electricity data is uploaded to the BC through the SC, where it is decrypted uniformly and concurrently. Mathematical operations are then performed on the decrypted data using the unit price of electricity consumption to determine the final total price of the electricity bill, which is subsequently sent to the users.

The aforementioned billing method increases the time delay of the electricity scheduling process in the electricity grid to a certain extent. Therefore, by leveraging the distributed transaction characteristics of blockchain, user electricity data collected by the SC is uploaded and transmitted to the BC. This approach ensures the security of data transmission and avoids unnecessary communication overhead caused by data encryption and decryption operations, the efficiency of data transmission is improved.

In integrating blockchain with electricity billing, a large amount of data is first transmitted to a designed single-chain blockchain, and real-time interactive calculations with the electricity unit price are performed. A consortium blockchain design is utilized, with node entities established including SC and BC. Defined as real-time electricity consumption data of a single user as $E_1, E_2, E_3, \dots, E_t$ (where E_t denotes the real-time electricity consumption at time t), and real-time electricity prices as $P_1, P_2, P_3, \dots, P_t$ (where P_t represents the real-time electricity unit price at time t), the total electricity billing settlement price is expressed as:

$$B = (E_1, E_2, E_3, \dots, E_i) \cdot P_i + (E_{i+1}, E_{i+2}, E_{i+3}, \dots, E_j) \cdot P_j + \dots + (E_{j+1}, E_{j+2}, E_{j+3}, \dots, E_k) \cdot P_k \tag{6}$$

Based on the above Eq. (6) and Fig. 2, it is assumed that the real-time electricity prices at moments i, j, and k during the time period t are P_i, P_j and P_k respectively. Using the single-chain electricity billing method, a large amount of real-time electricity consumption data $E_1, E_2, E_3, \dots, E_i$ are aggregated before billing, and then interacted with the current real-time electricity price. In this process, power dispatch delays can occur.

Therefore, the single-chain method for electricity billing does not effectively handle real-time electricity data and dynamic pricing. In addition to single-chain data uploads, transitions such as $\mathbf{P_i} -> \mathbf{P_j}$ and $\mathbf{P_j} -> \mathbf{P_k}$ must be determined in the billing process. Real-time electricity data should be divided into multiple parts corresponding to the dynamic prices and their calculations. This undoubtedly increases the communication overhead of electricity billing, potentially affecting the timeliness of dispatching to users.

Next, a multi-chain design using a consortium blockchain is proposed by us. It is divided into two organizations: the first organization's node being the SC, and the second organization's node being BC. Each chain has its own function. The chain at BC is responsible for delivering real-time electricity consumption data, while the chain from the center provides the real-time unit price of electricity consumption.

Assume the real-time electricity consumption data of a single customer is $\boldsymbol{E}'_1, \boldsymbol{E}'_2, \boldsymbol{E}'_3, \dots, \boldsymbol{E}'_t$ (where $\boldsymbol{E}'_t$ denotes the real-time electricity consumption at time t), and the real-time electricity prices are $\boldsymbol{P}'_1, \boldsymbol{P}'_2, \boldsymbol{P}'_3, \dots, \boldsymbol{P}'_t$ (where $\boldsymbol{P}'_t$ represents the real-time electricity price corresponding to time t). The total electricity cost in the real-time interaction process across multi-chain is represented as:

$$B' = E'_1 \cdot P'_1 + E'_2 \cdot P'_2 + E'_3 \cdot P'_3 + , \dots , + E'_i \cdot P'_i + E'_{i+1} \cdot P'_j + E'_{i+2} \cdot P'_j + E'_{i+3} \cdot P'_j + , \dots , + E'_j \cdot P'_j + , \dots , + E'_{j+1} \cdot P'_k + E'_{j+2} \cdot P'_k + E'_{j+3} \cdot P'_k + , \dots , + E'_k \cdot P'_k \tag{7}$$

From the above Eq. (7) and Fig. 3, it can be seen that during the time period T_1 to T_7, the real-time electricity prices at moments i, j and k are P'_i, P'_j and P'_k, respectively. When the real-time electricity consumption data E'_1 in the designed multi-chain is transmitted to the power data chain γ, it is immediately interacted with the real-time price chain δ for data calculations with the real-time electricity price P'_i transmitted by chain δ. The corresponding settlement results are promptly sent to BC. This allows the multi-chain electricity billing method to interactively process electricity data with dynamic unit prices in real time.

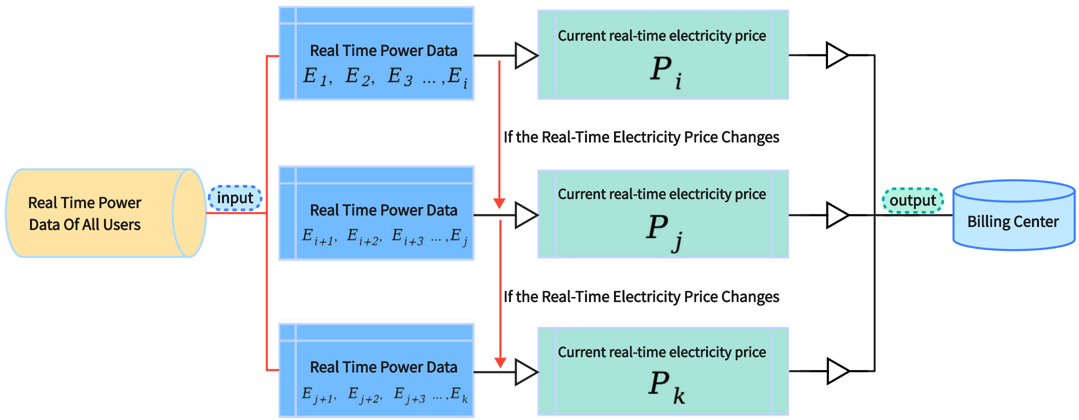

Fig. 2. Electricity transaction interaction use single-chain power trading with main grid.

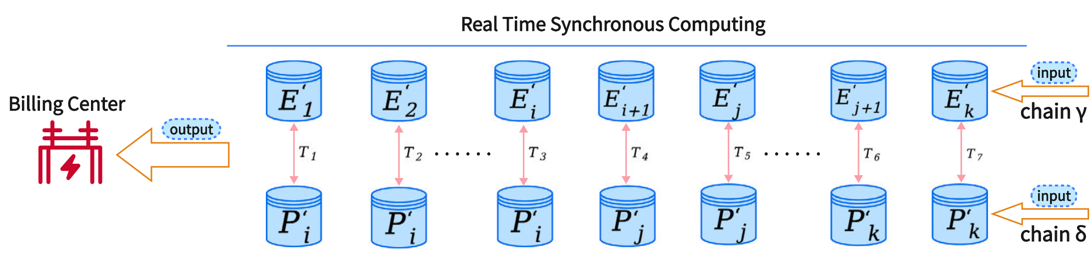

Fig. 3. Real-time interactive transactions with the main grid under multi-chain design.

In addition, since each uplinked electricity data point is matched one-to-one with the dynamic electricity unit price at the current moment, changes in the electricity price do not need to be determined. Thus, each transaction is settled efficiently.

The performance of the designed single-chain and multi-chain is tested, and the resulting logs show that the data throughput and outgoing block delivery rate on the blockchain are greatly improved with a certain block size and low latency.

3. Experiments

RMCT-R and RMCT-C are the two most important modules in our experimental design. Next, the platform and design of the experiments are introduced, the experimental results presented, and the analysis of the reliability and effectiveness of the experiments provided.

A. Platform and Design of Experiment

In our study, to better simulate the process of users' distributed electricity transactions in a smart grid and to verify the effectiveness and credibility of the proposed method, VMWare virtualization software was used to create 15 Kali Linux virtual machines as smart meter devices. One of the Kali Linux VMs was configured as a centralized meter-reading terminal (the grid station) in the multi-chain experiments. Additionally, 1 Windows 2016 Server VM was used as a server and electricity management center to establish a smart grid scenario with 15 user nodes and 1 grid master. The network adapter of each VM was configured in bridge mode, and the network connection of each VM was set under the same network segment to enable communication between any two devices. Furthermore, the external network interface of each device was configured so that devices within its grid could access the Internet.

The electricity data of the user's smart device nodes 1–15 is sourced from the daily real-time electricity consumption data of residents in an Australian community [24]. From this dataset, the real-time electricity consumption data of 15 residents out of 300 was selected, and the dataset content was organized and optimized. Considering the two modes where users can conduct distributed P2P electricity transactions or normal transactions with the grid master, and the grid station node can serve as a centralized storage unit, electricity consumption data from 0:30 AM to 24:00 PM was chosen for the dataset. Each Kali Linux virtual machine is equipped with a simple distributed P2P electricity trading system developed by us, enabling legitimate users to choose their roles as purchasers or sellers according to their needs.

The system can update the user's reputation value in real-time based on the designed reputation mechanism, and provide information such as the current market reputation threshold, the user's current reputation ranking, the current market electricity transaction demand, and the remaining electricity situation. During the system's initialization phase, to better trigger distributed P2P electricity transactions between users, the daily electricity consumption data of each user was optimized from the dataset, and each user's initial rated electricity balance E_r was set to 30. As shown in Eq. (8). The remaining electricity data for the day was calculated. If a user's electricity consumption E_p exceeds E_r for the day, the role automatically switches to a buyer (users using less than E_r can choose between being a power buyer and a power seller), and they need to exchange electricity with other users who have surplus electricity in the distributed P2P electricity market or purchase electricity from the main power grid of BC.

$$E_p - E_r \begin{cases} < 0 \quad \Rightarrow \quad \text{Buyer} \\ \qquad Role \\ \geq 0 \quad \Rightarrow \quad \text{Buyer or Seller} \\ \qquad Role \end{cases} \tag{8}$$

Fig. 4 illustrates the user device information background of electricity user 0001 during peer-to-peer electricity trading on the easy-implement distributed electricity trading platform developed by us. It includes transaction history information, the current reputation value of user 0001 in the distributed electricity trading, the reputation threshold within the electricity trading market, the ranking of the reputation value, the device's IP address, the remaining electricity amount, the

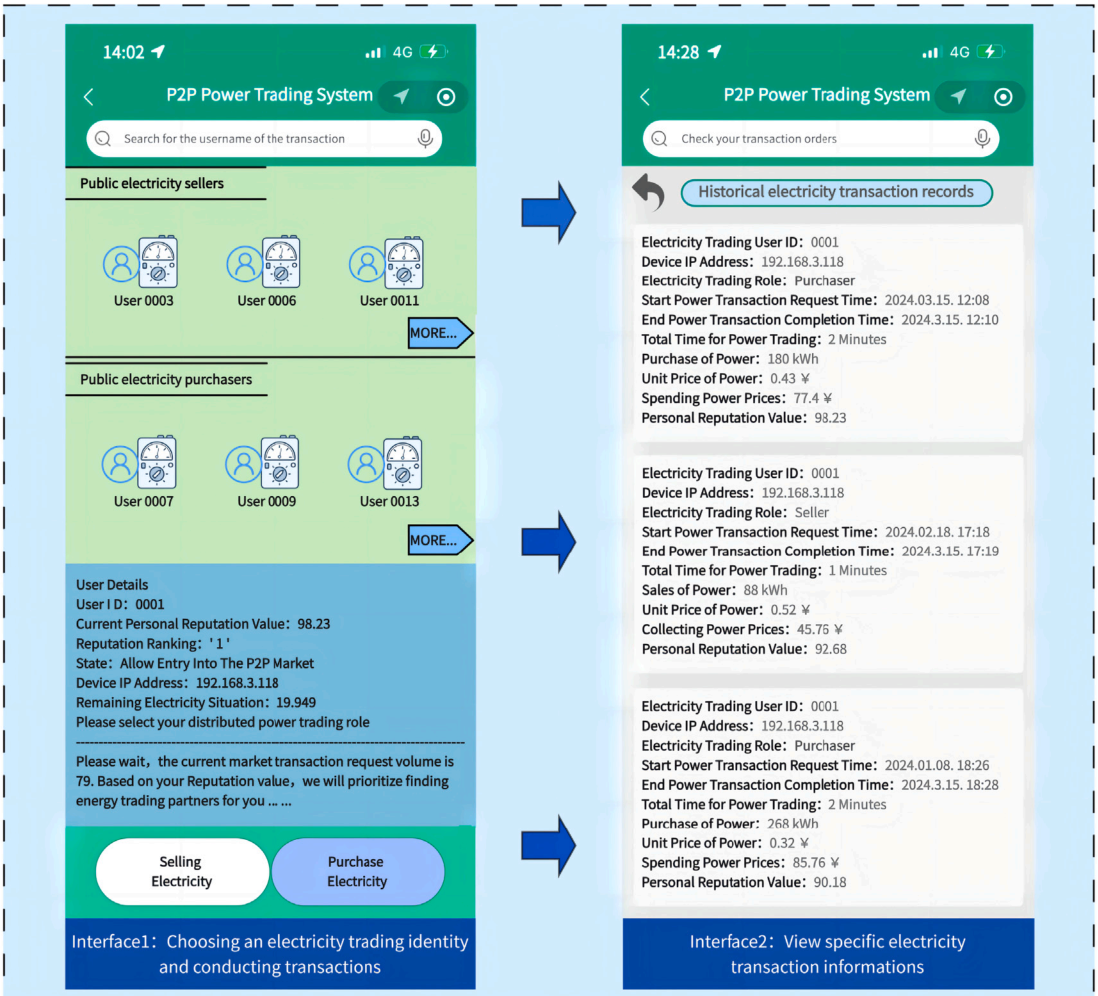

Fig. 4. Easy-implement distributed electricity trading platform developed for scenarios.

trading role, market transaction request volume, and historical transaction records to be viewed. These background data provide intuitive insights into the user's device information, enabling users to stay informed about their device status and market transaction situations, ensuring that the subsequent electricity trading process can be carried out smoothly.

For users intending to purchase electricity from the main grid of BC, or who can only do so due to their reputation value being lower than a set threshold, the efficiency of our proposed blockchain-based multi-chain electricity billing settlement method needs to be verified. To address this, a Kali Linux virtual machine is being designed as a centralized meter reading terminal-grid station. This station is responsible for reading the smart meter electricity data from the subdistributed smart meters and transmitting this data to the Windows 2016 Server virtual machine configured to act as BC. Between SC and BC, two federated blockchains have been established using the Fabric Hyperledger architecture [25]. Chain γ is designated for the transmission of user electricity data in real-time by SC, while chain δ is used for the transmission of dynamic electricity unit prices in real-time by SC. In this process, the nodes in the alliance chain consist of SC and BC. Real-time dynamic unit prices and electricity consumption data are transmitted by each node within the corresponding time period, ensuring time consistency and achieving real-time data interaction between the two chains. This setup efficiently completes the billing settlement process of the user's electricity consumption.

For Hyperledger, the modular architecture forms the core of our multi-chain design to enable multi-chain real-time interaction. Its self-authentication and access control mechanisms allow access to the electricity grid only by our authorized nodes. These advantages provide significant support in the process of designing the multi-chain architecture and achieving multi-chain real-time interaction.

The main grid's electricity price is determined by the real-time dynamic electricity price U_{tj}. The price U'_{tj} in the distributed P2P electricity trading market is adjusted by users based on the current advantageous main electricity grid price. It is assumed that surplus electricity E_{tk}, corresponding to U_{tk}, is sold by electricity sellers at a price lower than the current main electricity grid price U_{tj}. Both electricity buyers and sellers can achieve maximum market efficiency α_{tj} in the distributed P2P electricity trading market. As shown in Eq. (9). This forms the basis for significantly reducing user transaction defaults and device failures in the electricity trading market through a reputation value prioritization reward and punishment mechanism designed to enhance user motivation to participate in the distributed P2P electricity trading market.

$$\alpha_{tj} = (U_{tj} - U'_{tj}) \cdot E_{tk}, \text{ where } U_{tk} \leq U'_{tj} \leq U_{tj} \tag{9}$$

Distinguishing from the electricity trading model, the ways for users to trade electricity are classified into two major types: ①entering the distributed P2P electricity trading market for electricity trading; and ②trading electricity with the main grid of the electricity management

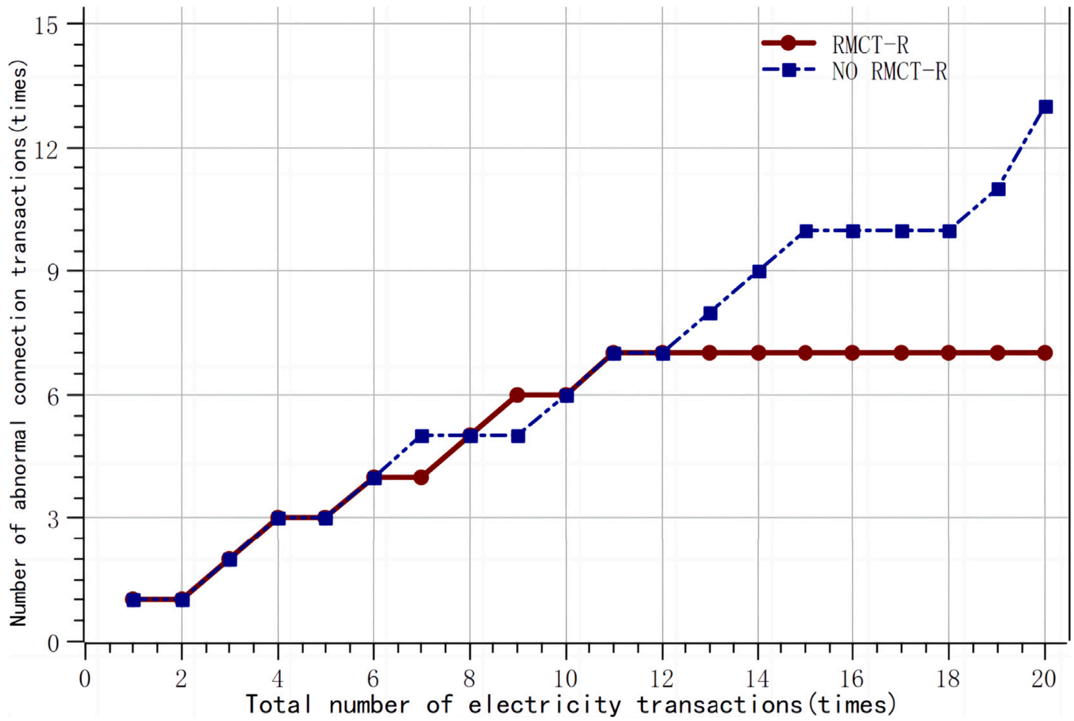

Fig. 5. Number of transaction connections established with the attacker by normal users with or without RMCT-R in 20 electricity transactions.

center. Next, the performance experimental results of the schemes designed for these two electricity trading paths are analyzed.

B. Experimental Analysis and Results

a. The performance of the transaction model for type ①

(1) Comparing the performance with and without the use of our proposed RMCT-R, and device 0015 was attacked by TCP FLOOD to establish 20 communications with device 0001: In this experiment, it is necessary to verify that the reputation-based mechanism in this scenario can credibly manage user behavior in the process of electricity transactions, and provide a strong guarantee for the credibility and fairness of the distributed electricity trading market environment. During the system initialization phase, the reputation values of the corresponding smart meters of 15 smart grid users have been calculated, and their reputation values all meet the threshold criteria, allowing them to successfully enter the distributed P2P electricity trading market for electricity transactions. The Kali Linux virtual machine with user ID 0015 is selected as a smart device capable of TCP FLOOD attack, and a large number of electricity trading connection requests frequently are sent by it to other Kali Linux VMs acting as smart devices in the electricity trading market network.

At this time, the VM corresponding to the 0001 smart device with a higher reputation value in the market receives a trading connection request from 0015 and is immediately responded to with a response packet by the attacker 0015, which is then awaited for its reply to establish a trading connection. However, since the attacker 0015 sends a large number of forged IPs in the transaction connection request packet, the response packet sent by the target device 0001 is ignored, and the attacker 0015 continues sending transaction connection requests within the trading market. Consequently, the attacked smart meter 0001 is left waiting for a long time for the TCP electricity transaction connection to be established and is unable to connect with other normal user devices.

As depicted in Fig. 5, in these 20 electricity transaction communications without the RMCT-R mechanism, the normal device 0001 was subjected to 13 instances of establishing electricity transaction communication with the attacker device 0015. Conversely, when the RMCT-R mechanism was adopted, among the 20 communication requests to establish electricity transactions with other market users, the communication with the attacker device 0015 occurred 7 times around the 12th communication, after which no further communication was observed.

(2) The network bandwidth consumption performance of normal user device 0001 with or without credit management operation through the RMCT-R after being attacked by attacker device 0015's TCP FLOOD attack during electricity transaction communication is then tested: In Fig. 6, it can be observed that within 5 s of the establishment of electricity transaction request communication between Device 0001 and Attacker 0015, the network bandwidth occupancy measured by the Kali Linux virtual machine corresponding to Device 0001 without using the RMCT-R mechanism shows a continuous upward trend, reaching nearly 100% network bandwidth occupancy. This is due to the fact that, for a short period after Device 0001 suffered the FLOOD attack, it did not receive the connection response message sent by attacker 0015, causing it to wait for a long time to establish the connection and preventing it from establishing electricity transaction connections with other normal market users, thereby occupying a large amount of network resources of the device.

After the RMCT-R mechanism is added, the abnormal transaction behavior of the user is evaluated, and the reputation value of the corresponding device is calculated, effectively curbing the attacker's cyber-attack behavior and promptly blocking abnormal transaction connection requests. This allows the normal user's device to quickly recover its network bandwidth and other resources within a short period, ensuring that the device can continue to establish transaction connections with other normal user devices. For example, after the RMCT-R mechanism is adopted, the network bandwidth utilization of the flooded device 0001 reaches nearly 80% in the second, then quickly converges, and returns to normal levels by the fifth second when electricity transaction communication is not established.

(3) A reward and punishment mechanism based on reputation value priority has been established to effectively manage user behavior in the distributed P2P electricity trading market and incentivize compliant participation: Users with high reputation values, whether buyers or sellers, are granted more network bandwidth resources to swiftly connect with other participants upon entry into the electricity trading market.

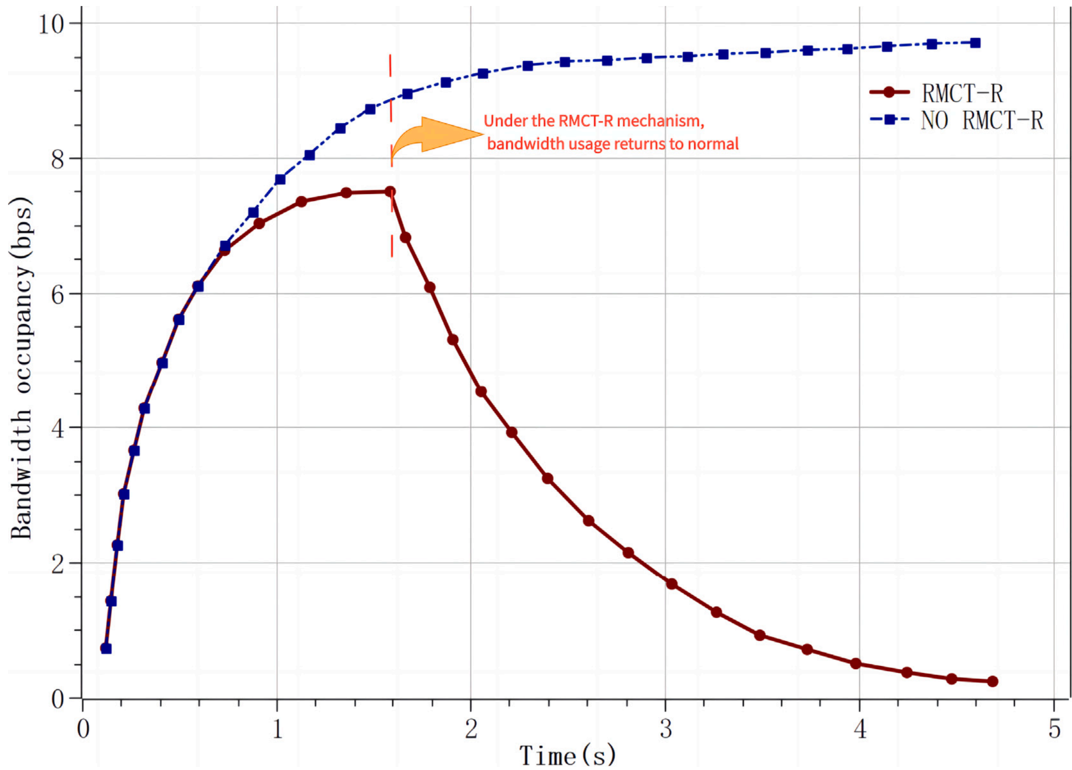

Fig. 6. Bandwidth consumption of user devices with and without joining RMCT-R after a TCP FLOOD attack.

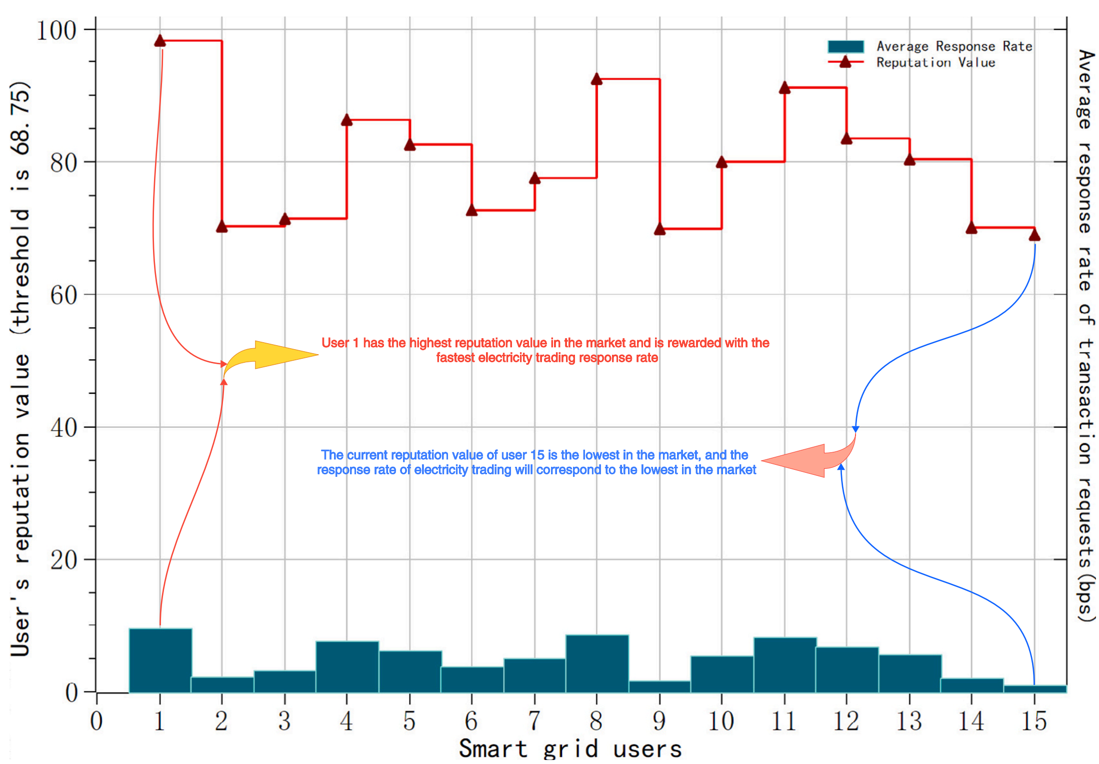

Fig. 7. Average response rate and the size of the corresponding reputation value of each user's electricity transaction request connection under RMCT-R.

Devices with reputation values below a set threshold is prohibited from joining the distributed P2P electricity trading market due to potential behaviors such as frequent transaction defaults or device failures.

Fig. 7 illustrates the reputation records of 15 user devices, all running Kali Linux VMs, in the electricity trading market. The efficacy of our reputation prioritization reward mechanism is demonstrated by the chart. The average response rate of these devices to electricity trading connection requests is tested under their current reputation values. A clear correlation is shown: higher device reputation values correspond to higher average response rates for electricity trading connection requests.

For instance, user device 0001 currently holds the highest reputation value at 98.23, achieving a response rate of nearly 10 bps, the highest in the market. This allows corresponding counterparts to be efficiently found by users, whether buying or selling electricity. This efficiency is the reward granted to users by our reputation-based prioritization mechanism.

The penalty mechanism mentioned above is designed to curb situations where contracts may be maliciously defaulted on by users after the transaction is connected, due to their own interests being affected by main grid tariff adjustments, or their devices being impacted by malicious attacks and other factors leading to failures and defaults. Such defaults are penalized by calculating corresponding evaluation indexes to deduct their reputation value. When the reputation value falls below a specified threshold, participation in the distributed peer-to-peer electricity trading market is prohibited for the device.

(4) Next, the number of successful connections of 15 user devices in the distributed P2P electricity trading market out of 680 transaction connection requests are recorded: For convenience in statistics, the number of successful connections due to transaction compliance is recorded every 40 transactions. Two devices, device 0002 and device 0009, are attackers using TCP FLOOD, continuously sending out transaction connection requests without responding. The compliance and success rates of users within the electricity trading market with and without the penalty mechanism corresponding to RMCT-R is compared.

From the experimental results in Fig. 8, it can be seen that under this penalty mechanism, attackers are prevented from joining the trading market due to frequent defaults, resulting in their reputation value falling below the threshold. This has led to a significant increase in the rate of transaction compliance within the electricity market, with a total of 604 successful transaction connections out of 680 rounds of transaction request connections recorded. The market's transaction compliance rate reaches 88.8%. The defaults occurred primarily in the first 200 transactions due to the presence of attackers and occasional device failures.

In the case where RMCT-R is not used, the presence of attackers, out of the total of 680 transaction request connections recorded, only 252 transaction connections were successful. The market transaction compliance rate was only 37%, with a large number of default transactions occurring. Effective curbing of the attacking behavior of malicious devices is crucial to reducing default behavior, and this issue is effectively addressed by our proposed method.

(5) The electricity transaction liquidity and cumulative changes in electricity transaction liquidity each quarter are compared under the conditions of TCP FLOOD attacks by malicious devices, with and without the use of our RMCT-R reputation mechanism method: since malicious behavior can lead to transaction defaults and impact the success rate of electricity transactions and user activity, a representative dataset from the Australian Grid Distributed Electricity Trading Market between 2010 and 2011 is utilized. This dataset comprises more than 15,332 real data points of Australian electricity transactions from 0:30 a.m. to 24:00 p.m. For trading markets that do not employ the RMCT-R mechanism, a TCP FLOOD attack may be triggered by users during the electricity transaction request connection process, where transaction connections are frequently requested by malicious devices but fail to respond, significantly reducing the transaction success rate within the electricity trading market.

Fig. 9(a) clearly shows that the electricity transaction volume of the distributed electricity trading market with our RMCT-R mechanism is significantly larger than that without the RMCT-R mechanism in the same quarter. From the experimental results in Fig. 9(b), it is evident that the growth of the electricity transaction volume in the electricity trading market is greatly enhanced by the RMCT-R mechanism. This also verifies that the attack behavior of malicious devices is effectively inhibited by the RMCT-R mechanism. With the reduction of malicious devices in the market, electricity transactions between users can be carried out normally, thereby improving the success rate of the transactions.

The protection of the distributed electricity trading market by RMCT-R stimulates market activity significantly, improving both market trustworthiness and activity levels. This encourages active participation by users in the distributed electricity trading market. Active user participation in the market positively impacts the reliability of electricity transactions within the grid and enhances overall market activity.

(6) A total of 11 smart meters, devices 0001–0011, were prepopulated into three major categories of states: normal devices, faulty devices, and devices attacked by TCP FLOOD, and their reputation value changes were monitored over 14 days in the RMCT-R reputation mechanism environment. In this experiment, devices 0001–0006 are normal devices that engage in normal electricity purchase and sale transactions. Device 0007 is a hardware faulty device that lacks the ability to perform P2P transactions. Devices 0008–0011 are TCP FLOOD-attacked devices, continuously sending electricity transaction requests within the Distributed Energy Marketplace but not responding to transactions. These devices make a electricity transaction with each other once a day during these 14 days, and for the convenience of monitoring the change of reputation value, we set their initial reputation value to a higher reputation value that is more similar to each other, and the reputation threshold inside the distributed electricity trading market is set to a constant 62.26, and the devices are not able to enter the distributed electricity trading market to make a P2P electricity transaction when the reputation value of the device is less than . At the same time, devices attacked by the TCP FLOOD attack is restored to normal device.

Over these 14 days, one electricity transaction was conducted daily by each device. To facilitate monitoring of reputation value changes, their initial reputation values were set to a higher level. The reputation threshold within the Distributed Energy Marketplace was set constant at T_{abn} equal to 62.26. Devices whose reputation values fell below T_{abn} were unable to participate in peer-to-peer electricity trading within the marketplace. As shown in Fig. 10. Additionally, devices affected by TCP FLOOD attacks were restored to normal operation.

b. The performance of the transaction model for type ②

Users unable to enter the distributed P2P electricity trading market due to their reputation value not reaching the threshold use the multi-chain electricity data transaction billing settlement method RMCT-C. This method enables them to conduct electricity transactions with the main grid managed by the electricity management center. Assuming all 15 users conduct electricity transactions with the main grid, device 0008, a Kali Linux virtual machine, serves as a centralized meter reading terminal. This terminal collects real-time electricity consumption data from the 15 users of the Australian electricity grid through the chains γ and δ that we designed, facilitating real-time delivery of user's electricity data and dynamic unit price of electricity transmission.

They are connected to the virtual machine corresponding to device 0008, which serves as a centralized meter reading terminal. Real-time electricity consumption data from the 15 users of the Australian electricity grid is collected by this terminal and transmitted to the Windows 2016 Server virtual machine for real-time billing settlement of electricity data transactions. During the data transmission process, real-time electricity consumption data from users 1–15, collected by the centralized meter reading terminal 0008 from 0:30 to 24:00 every day for one year, is transmitted to the electricity billing center-main grid via chain γ. The metropolitan real-time dynamic electricity unit price for the corresponding time period is transmitted to chain δ by the main grid device. Real-time interactive billing settlement occur across these two chains, with electricity billing amounts fed back to the main grid and the user smart meters in real-time.

In these two chains, organization nodes are designated. The station concentrator and main station of the electricity billing center correspond to the organization and master nodes on chain γ, respectively,

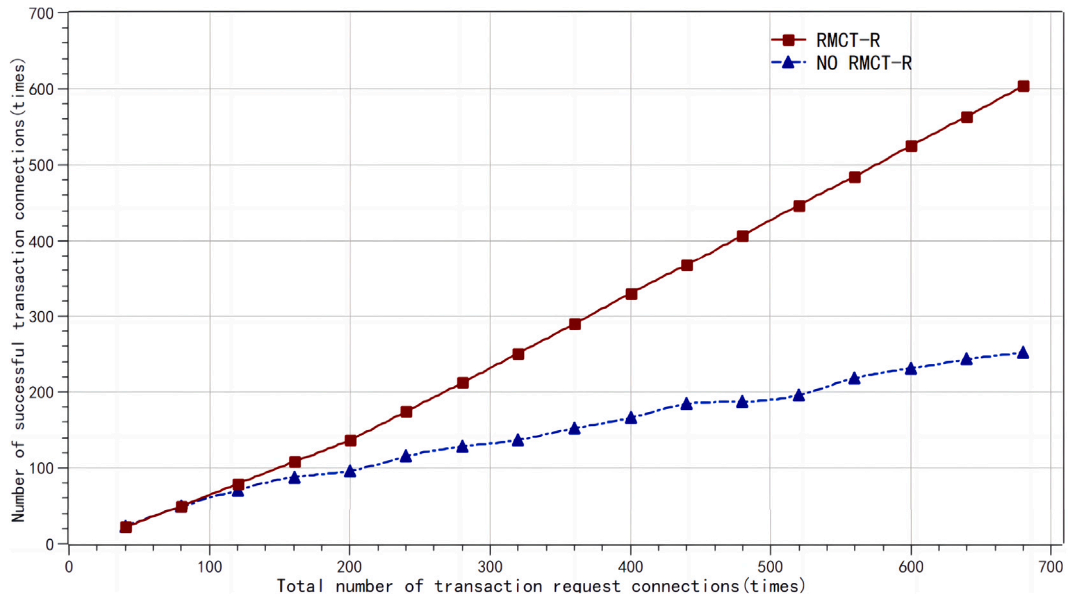

Fig. 8. Number of successful transaction connections for each user within a total of 680 transaction requests with and without RMCT-R penalty mechanism.

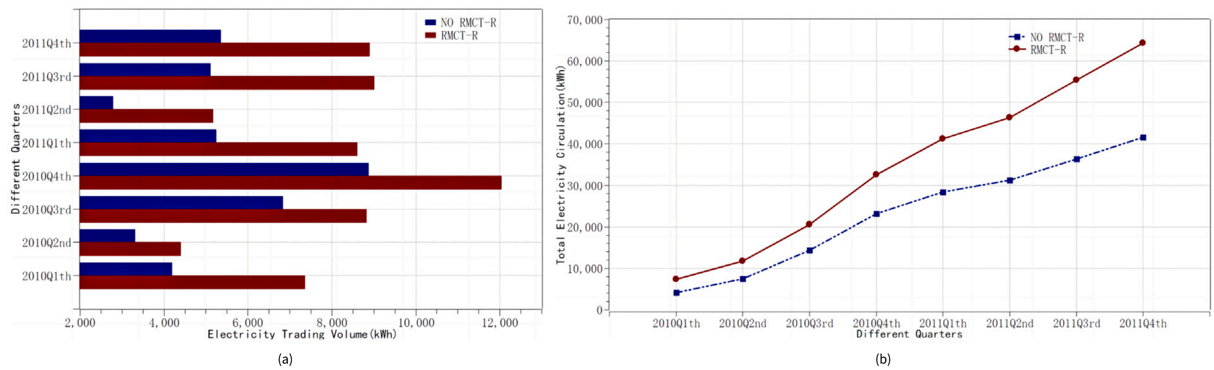

Fig. 9. (a) Quarterly electricity transaction liquidity in distributed electricity markets with and without RMCT-R under TCP FLOOD attack (b) Cumulative change in electricity transaction liquidity under TCP FLOOD attack for distributed electricity trading markets with and without RMCT-R.

through which real-time electricity consumption data of grid users is transmitted via the book node on the chain. Similarly, the station concentrator and main station of the electricity billing center also correspond to the organization and master nodes on chain δ. The distinction lies in real-time dynamic tariffs being transmitted through the book node on chain δ. Data interaction between the two chains facilitates real-time dynamic tariff transmission to the main grid and user smart meters through multi-chain real-time interactive billing settlement. The synchronized data interaction of the two chains achieves the goal of real-time dynamic response for electricity billing, enabling real-time and efficient electricity scheduling from the main grid to users.

On-chain performance tests of RMCT-C billing settlement and single-chain billing settlement were conducted using Caliper. The performance of RMCT-C and single-chain billing settlement for on-chain data communication was evaluated, including transmission rate, latency, and throughput under block sizes of 10, 50, 100, 150 and 200. The experimental results in Fig. 11 demonstrated that our method could reduce the average latency of each transaction execution in environments with faster-updating real-time electricity prices, in Fig. 12(a) and (b), block generation rate is improved by 97.38% and data throughput by 82.49%, significantly enhance the block generation rate and transaction throughput of the transaction process, and improve the timeliness and reliability of power scheduling in power transactions between users and the main power grid.

4. Discussion

A. Security Analysis of Transaction Processing

To ensure the security and trustworthiness of power transactions, RMCT-R is implemented by calculating four reputation evaluation indicators — power data drift, communication transaction success rate, device response rate, and transaction compliance rate — to derive the dynamic reputation value R_{dev} for each user device. This reputation value is updated within a specified time interval Ω based on the latest evaluation results. Each user device compares its current reputation value R_{dev} with a preset abnormal reputation threshold T_{abn}. Devices exceeding T_{abn} are marked with a status flag Sta of 1; otherwise, they

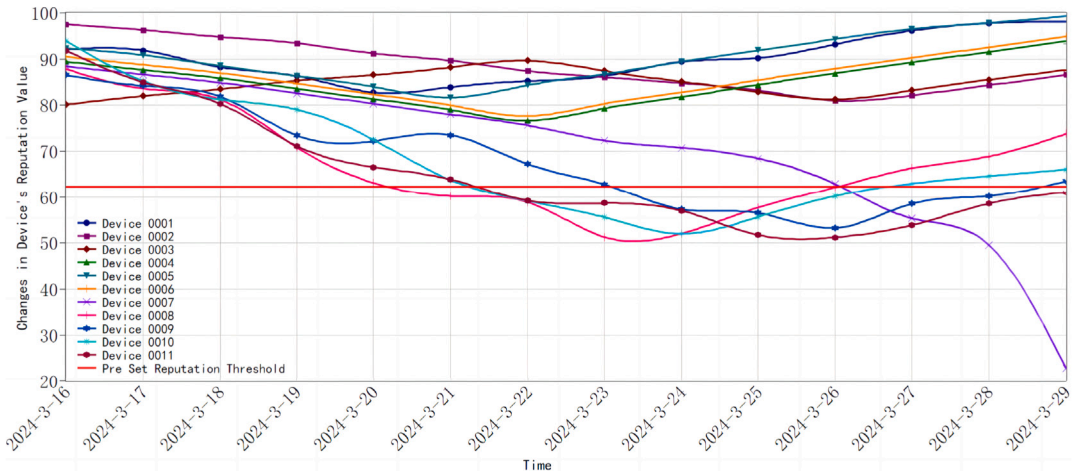

Fig. 10. Reputation value changes for normal devices, faulty devices, and devices attacked by TCP FLOOD in RMCT-R.

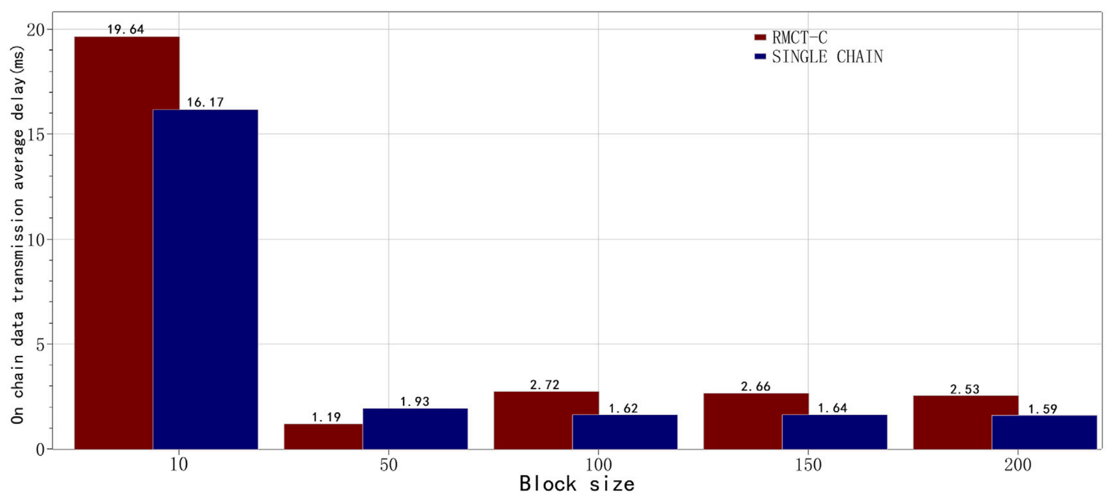

Fig. 11. Average latency of RMCT-C transactions with different block sizes versus single-chain trading approach for electricity data interaction.

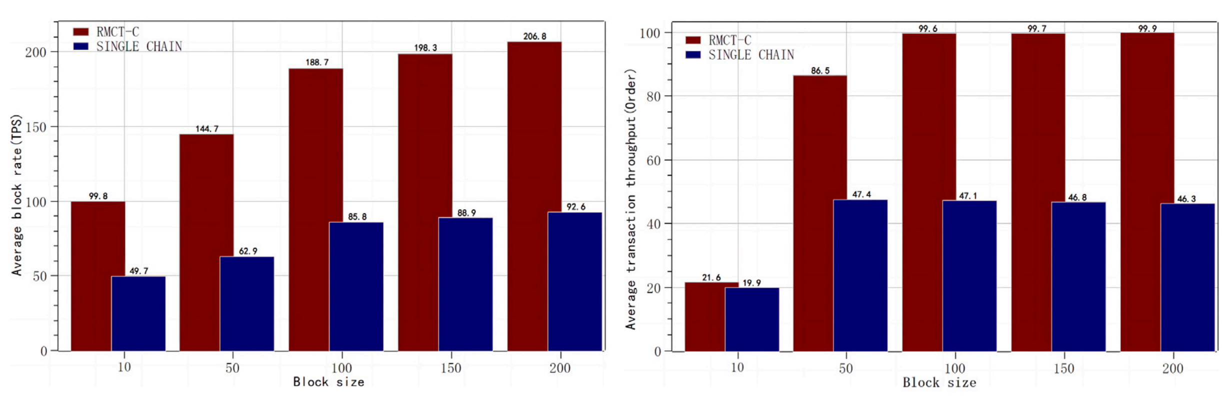

Fig. 12. (a) On-chain block-out rates for RMCT-C transactions with different block sizes versus single-chain trading approach for electricity data interaction (b) Transaction throughput of RMCT-C transactions with different block sizes versus single-chain trading approach for electricity data interaction.

are penalized with Sta set to 0, identifying them as abnormal. To safeguard the internal security and trustworthiness of the distributed power trading market, abnormal devices (Sta = 0) are restricted to transactions with the main grid BC and are only allowed to re-enter peer-to-peer trading once their reputation value recovers above T_{abn}.

Security analysis of extensive experimental results in the TCP FLOOD attack environment demonstrated that the RMCT-R mechanism significantly reduced the connection ratio with abnormal devices from 70% to 40%, effectively mitigating power transaction connections between normal and abnormal devices. Furthermore, the proposed method rapidly decreased abnormal device flood attacks' consumption of network bandwidth and converged it to normal levels. Additionally, the reputation-based priority reward mechanism enabled higher-reputation devices to access more network communication resources during distributed power transactions, accelerating transaction connections and enhancing user participation. In an abnormal device flood attack environment, the compliance rate of power transaction connections increased from 37% to 88.8%, significantly boosting trust and security in distributed power transactions.

B. Transaction Efficiency Performance of Electricity Billing settlement

To demonstrate the effectiveness of our designed multi-chain mechanism, we compare the average latency of real-time power data interaction and billing settlement between our proposed RMCT-C transaction settlement and a single-chain transaction settlement environment, under varying block sizes and interacting with the main power grid.

The average latency performance of transaction execution for real-time power data interaction and billing settlement with the main power grid was compared in two scenarios: (1) With block sizes set to 10, 100, 150, and 200 using peak-off-peak electricity price data (i.e., time-of-use pricing with long intervals of dynamic price changes), the average latency of each transaction in the RMCT-C multi-chain mechanism was compared with that in the single-chain environment; (2) With a block size set to 50 using real-time dynamic electricity price data with short intervals of changes, the average latency of each transaction between RMCT-C and the single-chain environment was compared.

As shown in Fig. 11, the experimental results revealed that: (i) In scenario (1), due to the use of peak-off-peak electricity price data with minor real-time variations and fluctuations, the RMCT-C significantly improved the block generation rate and transaction throughput compared to single-chain transaction settlement, increased by 97.38% and 82.49% respectively, as illustrated in Fig. 12(a) and (b), while ensuring low latency with only millisecond-level differences compared to single-chain settlement, thereby guaranteeing the real-time nature of the billing settlement process; (ii) In scenario (2), where real-time dynamic electricity price data with short intervals of changes were used, the real-time update cycle of electricity prices was short and highly flexible, necessitating higher real-time requirements for the billing settlement process. Compared to single-chain transaction settlement, our average latency has been reduced by 38%, the RMCT-C for billing settlement could quickly respond to rapid updates in real-time electricity prices.

5. Related work

A. P2P Electricity Trading

In recent years, researchers have proposed a series of relevant frameworks and schemes for data communication processes such as peer-to-peer power trading and electricity consumption cost settlement in smart grids. Wayes et al. [26] used an analytical framework for peer-to-peer power trading to study the trading problem in a new type of power system and demonstrated that the scheme can effectively reduce the excess energy storage from producers during peak hours, but did not take into account the impact of malicious or anomalous trading requests on the grid. Wang et al. [27] proposed an improved feedforward long short-term memory (FF-LSTM) modeling method to improve power energy management and safety. Guan et al. [28] proposed a distributed power market trading mechanism based on Stackelberg game, which enhanced the enthusiasm of power buyers and sellers to participate in distributed power trading. Wang et al. [29] proposed a new ANA-LSTM model to obtain the optimal expression, which effectively optimized the design, manufacturing and operation management of the battery system. Wayes et al. [30] another study pointed out a technical approach to enhance the reliability of the power system by solving the peer-to-peer trading challenges at the physical layer, but these works did not investigate the trust between users. Esteban et al. [31] argued that the P2P power trading plays an important role in the low-carbon energy transition and has a higher flexibility than the traditional centralized power trading system. Robbie et al. [32] proposed a privacy-preserving peer-to-peer electricity trading market billing settlement system to securely calculate the monthly electricity billing charges and transaction data of grid users, but did not consider the real-time nature of the electricity billing and transaction process, and did not manage the electricity trading behavior of users, as well as did not take into account the throughput of the data and the communication delay.

However, in P2P power transactions, relying on a third party to store and calculate power transaction data is difficult to ensure transaction transparency and security, resulting in a generally low level of trust among users, and thus the introduction of blockchain technology to solve the above problems is necessary.

B. Distributed Electricity Trading System Based on Reputation Mechanism

In the process of electricity trading and billing settlement, malicious and unusual violations may cause damage to trading market users, affecting consumer experience and market stability. Therefore, researchers have begun to explore the combined application of reputation mechanism (RM) and blockchain.

In blockchain-enabled peer-to-peer distributed power transactions, reputation mechanisms are combined to achieve inter-user credit management. Zhang et al. [33] proposed a verification strategy based on reputation mechanisms and blockchain to securely and efficiently reduce invalid or abnormal transaction forwarding, but did not provide a specific computation methodology, and was unable to limit the propagation of malicious transactions. Khamila et al. [34] support a reputation prioritization mechanism in a blockchain environment to incentivize contract-abiding behavior, but do not constrain the behavior of the power buyer. Zhou et al. [35] propose a solution combining RM and blockchain, and devise a reliable method to penalize defaults, Zhang et al. [36] designed a reputation-based mining incentive scheme to enhance users' enthusiasm for participating in V2V transactions during electricity trading, but their works do not consider incentives and fairness of the user's continued participation in the transaction after a default, or the effect of introducing blockchain on the power trading performance. Bao et al. [37] fused reputation mechanism and blockchain to improve the consensus mechanism in the transaction process and address the security threats in the power grid.

To the best of our knowledge, no researcher has yet used the reputation mechanism to restrict abnormal user privileges in the current trading scenario. Utilizing reputation mechanism to manage credit among users is to provide guarantee for the reliability of power transactions and is also our design goal.

C. Blockchain-based Multi-chain Interaction Design for Electricity

Blockchain has rich applications within the field of smart grid. Gao et al. [38] proposed a peer-to-peer power trading platform based on privacy protection and blockchain, which effectively protects user privacy, authenticity, and data integrity, but does not guarantee the ability of transaction settlement and communication. Ping et al. [39] proposed an optimization method for power transmission based on privacy protection and blockchain that resist the damage of dishonest nodes to the interests of power trading participants and ensure the

Work	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8
Wayes et al. [25]	✗	*	✓	✗	✓	✗	✗	✗
Guan et al. [26]	*	✓	✓	✗	✓	✗	✗	✗
Robbie et al. [29]	✗	✗	✗	✗	✗	✗	✗	✓
Zhang et al. [30]	✓	✓	✗	✗	✗	✗	✗	✓
Khamila et al. [31]	✓	✗	✗	✗	✓	✗	✗	✓
Zhou et al. [32]	✓	✓	✗	✗	✗	✗	✗	✗
Yang et al. [39]	✓	✗	*	✓	✓	✓	✗	✓
Ours	✓	✓	✓	✓	✓	✓	✓	✓

H_1: Reputation Incentive Mechanism. **H_2:** Abnormal transaction monitoring. **H_3:** User transaction behavior management. **H_4:** Multi-chain real-time billing and settlement. **H_5:** Optimizing communication latency. **H_6:** Optimizing Throughput. **H_7:** Optimize block rate. **H_8:** Suppress attacks from malicious nodes.

Note: ✓ is **"Yes"** (related to this content), ✗ is **"No"** (not related to this content). * is **"Unknown"** (can not be identified).

Fig. 13. Qualitative comparison of related work.

convergence of the trading process. Yang et al. [40] proposed a double-chain carbon emission trading method based on blockchain to ensure the privacy of data transactions. Wei et al. [41] proposed a cross-chain trading model of power carbon rights in microgrids based on quantum blockchain technology, and verified that the scheme can safely and efficiently carry out the trading of power carbon rights. Yang et al. [42] proposed a dual-chain blockchain through the reorganization of multi-chain and peer-to-peer power trading model.

Currently, no solution has been proposed to enable real-time multi-chain interaction of participants' data during electricity trading and billing settlement by designing multi-chain. However, throughput, block out rate and latency are the most important performance metrics in blockchain-enabled electricity trading market. Therefore, RMCT is proposed to make the power trading process more reliable and efficient.

Based on the above work, there are still some refinements that can be made. We provide a detailed comparison in Fig. 13.

6. Conclusion

In existing research on distributed power transaction systems, the use of reputation mechanisms to restrict abnormal user permissions has not been employed by researchers, and a solution for achieving real-time multi-chain interaction of participant data during power transactions and billing settlement through the design of multi-chains has not been proposed. Therefore, in this study, we propose a electricity trading model (RMCT) for grid users with different methods of electricity trading (P2P trading or trading with the main grid) based on user reputation and blockchain technology. The goal is to provide a credible and efficient distributed electricity trading market environment for smart grid.

We developed a easy-implement blockchain-enabled distributed electricity trading simulation system. A reward and punishment mechanism was designed based on the priority of reputation value to restrain users with malicious and aggressive behaviors, such as frequent transaction defaults. This mechanism significantly improved the compliance rate and success rate of electricity trading within the market. Additionally, incentives were provided to normal users with excellent trading behavior. This allowed these users to access more network resources to conduct efficient and credible distributed electricity transactions, thereby safeguarding the reliability and activity of the trading market. In addition, for participants who only conduct electricity transaction billing settlement with BC, our multi-chain mechanism enables credible and efficient real-time multi-chain interaction for electricity billing settlement, this improves the reliability of electricity scheduling. In the future work, we will conduct a study of sharding and dynamic resource allocation, to optimize the performance of the on-chain data transfer process between CT and SMT.

CRediT authorship contribution statement

Shenglong Lv: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Xuan Zhang:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Jishu Wang:** Methodology, Investigation, Formal analysis, Data curation. **Weidong Xiong:** Visualization, Validation, Data curation. **Li Yang:** Resources, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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