

# SmartStore: A blockchain and clustering based intelligent edge storage system with fairness and resilience

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## Abstract

With the development of edge computing, edge storage solutions are attracting widespread attention. When facing the requirements of lower latency and faster access speed from end devices, edge storage solutions are considered to be an alternative to the cloud. However, edges are usually owned by small organizations which have limited operations and maintenance capabilities. This makes these edge devices can be easily disabled by external attacks or internal hardware failures. Besides, the heterogeneity of the edge devices will also make it difficult to price the edge resources uniformly. To tackle these problems, we propose SmartStore: an auction mechanism based on blockchain to allocate edge resources. Considering centralized solutions have access bottlenecks and trust issues, we built SmartStore on the smart contract. With Bayesian game theory, SmartStore can analyze how data owners (DO) and edges price the resources can maximize their benefits. From an economic perspective, both DO and edges can make full use of edge heterogeneous resources with SmartStore. Besides, a two-stage submission strategy is proposed to complete the sealed auction. Furthermore, considering the

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reliability of edge storage, we propose a cluster-based block distribution algorithm for SmartStore's intelligent edge recommendation process. SmartStore ensures the reliability of edge storage while maximizing the benefits and resource utilization of both parties. Finally, we conduct specific experiments on the proposed auction smart contract through "Ethereum" and the experimental results of implementation show the effectiveness and efficiency of our SmartStore.

#### KEYWORDS

blockchain, edge storage, game theory, IoT devices, sealed auction

## 1 | INTRODUCTION

With the continuous development of the Internet of Things (IoT), the amount of data generated by varied kinds of sensors are increasing dramatically. According to Cisco's estimates, the amount of data generated by IoT, such as humans and machines, will be close to 850 ZB by 2021.<sup>1</sup> Traditional cloud storage cannot meet the data storage requirements of low latency, high access, and fast backup. Edge computing<sup>2</sup> has emerged as a new computing paradigm for data computing and storage. With edge computing solutions, computing power and data storage can be transferred from clouds to edges. Edge devices can be close to terminal devices geographically<sup>3</sup> to provide lower-latency computing and data access services.

Edge storage solutions, with the development of edge computing, have attracted widespread attention. Researchers have proved that portable or mobile devices, such as cameras or handheld tablets, with SD cards or other storage devices, can work as edge storage and send locally processed information to the cloud.\* Due to the limitation of network bandwidth and storage capability, it is impossible to back up all the data of the smart cameras deployed at home or surveillance cameras in the community to the cloud. In the field of smart transportation (e.g., floating car sensors, videos, GPS information), Qiao et al.<sup>4</sup> use edge servers to store data, and adjust the distribution of data according to the state of the edge server through reinforcement learning-based intelligent scheduling, providing a new storage solution for intelligent transportation systems (ITS).

However, while edge storage brings convenience for data storage and access, it also brings some new problems. Storing data at the edge (e.g., SD cards, edge servers deployed by the third party) could be a security risk when facing attacks like network disconnection, power failure or equipment disruption. Without a well-established backup mechanism, data may be at risk of loss when abnormal cases happen to the edge. Some researchers recommend using erasure code<sup>5</sup> to perform redundant data backups on multiple edges to ensure reliable storage of data.<sup>3,6</sup> However, they did not take into account the heterogeneity of edge devices and the requirements of storage reliability. Edges with different storage resources, such as bandwidth, access speed, and different storage spaces, can provide users with different quality of service. There has been limited work on distributed data storage on edges and fog resources,<sup>7-10</sup> and most of

those previous works are based on centralized resource allocation schemes, these schemes hindered the optimization of system performance and scalability. Besides, instead of improving the data storage reliability, most of these works focus on saving bandwidth or enhancing the speed of response. It is particularly important to provide a flexible and extensible backup scheme for edge storage data. It should fully utilize the edge heterogeneous resources to maximize the profit of multiple parties and the reliability of storage.

However, designing such a mechanism will face some challenges:

- (1) *How to maximize revenue?* In edge storage, how to correctly and reasonably price storage resources so and maximize the revenue is an important issue. The edges tend to price storage space as high as possible to obtain greater revenue. But, overpriced storage space may not be accepted by the data owners (DO). Therefore, how to make reasonable pricing in the system to maximize the revenue of the edges and achieve the purpose of encouraging consumers to use their storage space is a fundamental problem.
- (2) *Who does the resource allocation?* When consumers request storage service, edges need to report their price and some attributes to a third-party platform, and a group of edges can be allocated to consumers through a reasonable algorithm. Choosing which platform to run the allocation algorithm is a tough problem. The client ends may not willing to provide their computing resources. If running on a third-party platform, it may have a single-point bottleneck problem. And the credibility issues such as conspiracy or unreasonably allocate storage requirements.
- (3) *How the data are distributed?* The storage system needs to ensure the reliability of data storage. Simply considering the price factor may result in redundant data clustering in a geographic area. When some abnormal conditions occur (e.g., regional power outages or network disconnections, malicious persons damaging the storage SD cards of camera equipment), data aggregation in the same areas may lead to data loss. How to secure the reliability of storage based on realizing the benefit of both parties is also a key challenge.

To address these challenges, we designed a blockchain-based resource auction mechanism in the distributed edge storage scenario. The proposed auction mechanism considers not only price but also nonprice attributes such as bandwidths and locations when determining edges. Using the smart contract of the blockchain as a trusted third-party platform can build a more reasonable and credible match between DO and Edges. Besides, we use an auction game theory based on Bayesian Nash equilibrium to analyze how to maximize the profit of two parties. Then, we implement the auction mechanism on the platform of Ethereum and verify the feasibility of auction games through simulation experiments. Our mechanism not only provides the price-based auction mechanism that considered both edge resources and reliability but also includes a blockchain to further enhance the system reliability. To the best of our knowledge, this is the first work that meets all the above requirements. Compared with some existing studies, the advantages of our work are shown in Table 1.

In summary, the main contributions of this paper are as follows:

- We propose to use Bayesian Nash equilibrium, a game theory concept that has been widely applied in the field of economy, to analyze how edges and clients price the storage resources to maximize their revenue. By comprehensively weigh the benefits of buyers (DO) and sellers (Edges), SmartStore can achieve reasonable pricing.

TABLE 1 Comparison of related studies

Studies	Decentralized	Fairness	Reliable	Scalable	Traceable	Price	Attribute
vStore <sup>9</sup>	High	Low	Low	Middle	–	–	–
He et al. <sup>11</sup>	Middle	Low	High	Middle	–	–	–
Linaje et al. <sup>12</sup>	Low	High	Middle	High	–	Involved	–
Xia et al. <sup>3</sup>	High	Low	Middle	Middle	–	Involved	Involved
Qiao et al. <sup>4</sup>	High	Low	Middle	Middle	–	–	Involved
Our method	High	High	High	High	Yes	Involved	Involved

Note: “–” means that it is not involved or discussed in the paper. Decentralized, Fairness, Reliable, and Scalable are features of the edge storage system. Traceable indicates whether the resource allocation can be traced. Price and Attribute refer to whether price and resource attributes are considered in resource allocation.

- We propose to apply smart contract as a trusted third-party platform to guarantee the credibility of multiple parties and implement a sealed auction mechanism that considers multiple attributes through a two-stage submission mechanism.
- We propose a cluster-based block distribution algorithm. It is not only a discrete blocks distribution algorithm but also a storage solution recommendation mechanism with multi-attribute priority and storage reliability for users.
- Our sealed auction implementation on the Ethereum platform verifies the feasibility and experimental evaluation shows the efficiency and flexibility of our SmartStore.

## 1.1 | Orgnization

We organized the rest of the paper as follows. Section 2 summarizes the related work. In Section 3, we briefly describe the system model. Section 4 analyzes the auction mechanism and the detail of our auction mechanism. Section 5 introduces our cluster-based selection algorithm. Section 6 describes our specific application implementation and the performance. We conclude this article in Section 7.

## 2 | RELATED WORK

There are limited works on distributed data storage on edge and fog resources, as reviewed and classified in Moyasiadis et al.<sup>13</sup> We describe the decentralized storage solution from the perspectives of fog/edge computing.<sup>7,9,11,3,14</sup> FogStore<sup>7</sup> proposes a distributed key-value store on fog resources with replication and differential consistency. vStore<sup>9</sup> supports context-aware placement of data on fog and cloud resources, with mobile devices generating and consuming these data. It uses a rules engine to place and locate data based on its context metadata but ignores reliability as edge devices do not store data. He et al.<sup>11</sup> propose a data security storage model to improve the security of the storage in fog computing. Xia et al.<sup>3</sup> make the first attempt to formulate this Edge Data Distribution (EDD) problem as a constrained optimization problem from the app vendor's perspective to realize APP high-speed data access.

Aimed to achieve fair resource allocation, we use an auction mechanism to realize resource allocation and auction. This is a popular way to provide fair resource allocation between buyers and

sellers in the case of competition.<sup>15</sup> In the study,<sup>16</sup> the authors proposed a truthful auction mechanism in mobile cloud computing to achieve resource allocation between mobile devices and cloudlets. Kiani et al.<sup>17</sup> introduced a hierarchical mobile edge computing which contains different types of cloudlets and proposed a resource allocation mechanism with a two-time scale. Sun et al.<sup>18</sup> considered the industrial Internet of things scenario in which the edge node is a resource-rich data center and extended the above truthful auction mechanism. Bahreini et al.<sup>19</sup> solved the resource auction problem at the edge/cloud levels. However, it cannot meet the property of truthfulness. Peng et al.<sup>20</sup> proposed the multiattribute-based auction toward resource allocation in vehicular fog computing. However, the above works either only consider the price factor of storage nodes when determining the winners or ignoring some factors like location, bandwidth, or consumer choice. In particular, none of the above methods are suitable for solving storage reliability problems in storage scenarios. Besides, some of these works cannot assure trustfulness, which is a problem solved by using blockchain technology in our research.

Besides, to maximize the profits of buyers and sellers, we use game theory<sup>21</sup> to analyze pricing strategies from an economic perspective. Li et al.<sup>22</sup> applied the incomplete information game theory and proposed a multiwinners grid resource allocation model, which maximized social welfare and improved resource utilization. Pillai et al.<sup>23</sup> proposed a resource allocation mechanism for machines on the cloud. Guo et al.<sup>24</sup> modeled the bandwidth sharing problem as a Nash bargaining game, and proposed the allocation principles by defining a tunable base bandwidth for each virtual machine. In the research,<sup>25</sup> a game-theoretic framework is proposed for resource allocation but the framework only considered a market model consisting of one infrastructure provider and multiple mobile virtual network operators. Li et al.<sup>26</sup> introduced Bayesian Nash Equilibrium to realize multi-to-multi resource allocation based on resource attributes, which gave us a lot of inspiration. Some other studies<sup>27,28</sup> have proposed some resource allocation schemes based on game theory about energy constraints. However, all the above studies have only studied the attributes of resource allocation and cannot meet the requirements of simultaneously achieving storage reliability in our edge storage scenarios.

In this paper, we utilize a blockchain-based smart contract as a third party to realize the auction mechanism. Blockchain is considered to be a suitable platform for implementing incentive-driven distributed storage systems. In recent years, a line of work has been dedicated to the study of distributed storage systems for wireless networking applications based on public blockchains. Also, blockchain technology has also been introduced to solve problems such as data access control<sup>29</sup> and log recording.<sup>30</sup> In this article, blockchain can also be used to record data distribution related logs for resource allocation records. In the paper,<sup>31</sup> a trading platform for device-to-device (D2D) computation offloading is proposed using a dedicated cryptocurrency network. Therein, resource offloading is executed between neighbor D2D nodes through a blockchain-based auction, and the block mining tasks are offloaded to the cloudlets. In Henning's research,<sup>32</sup> a Proof-of-Work-based public blockchain is adopted as the backbone of a P2P file storage market, where the privacy of different parties in a transaction is enhanced by the techniques such as ring signatures and one-time payment addresses. When identity verification is required for market access granting, for example, in the scenarios of autonomous network slice brokering<sup>33</sup> and P2P electricity trading,<sup>34</sup> the public blockchains can be adapted into consortium blockchains by introducing membership authorizing servers with little modification to the consensus protocols and smart contract design.

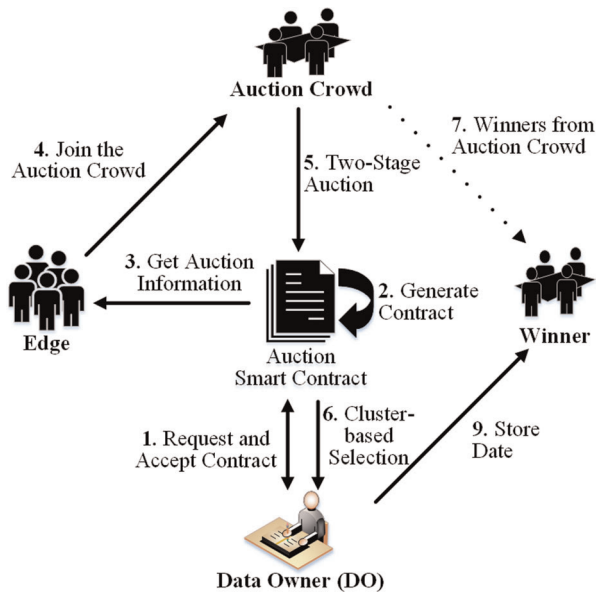


FIGURE 1 System overview of auction model based on smart contracts [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

### 3 | SYSTEM MODEL

Figure 1 depicts the architecture of SmartStore mainly with five parts, the *DO*, Edge, Auction Crowd, Auction Smart Contract, and Winner. the *DO* consists of diverse equipment (e.g., smart-phones, tablet or personal PCs) with different storage requirements. Small and medium-sized data centers underutilized in enterprises/schools/hospitals and central telecommunication offices can serve as edges to provide storage service and get paid. Also, in the field of video surveillance, an SD card in a monitoring device can be used as an edge to provide storage space for other monitoring devices. When the *DO* releases a series of requirements, the eligible edges can join Auction Crowd for auction competition. They report their resources and prices to the smart contract for target resource indicators based on the details of the requirements released by the *DO*. The smart contract selects edge's resources and prices according to the requirements reported by *DO* and the edges are then selected in a second-round based on the *DO* bias. *DO* clusters the locations of edges that have passed the auction and then selects the appropriate edges in each cluster as the final winners.

Each *DO* may have a certain type of storage task and different requirements for different resources. For example, users with lower latency requirements may be willing to pay a higher price to choose faster edges. Assuming that each *DO* has the overall price for the target resources. Correspondingly, the resources of each edge contain different attributes, such as storage resource bandwidth, interrupted increment, and interrupted service online time. The prices of different resources are varied.

When a *DO* submits its request in a publicly accessible blockchain, it will trigger the generation of a smart contract for resource auction. The bidders meeting the requirements participate in the auction. Please note that the blockchain is responsible for verifying the availability of service. The edge will be punished if they cannot deliver the promised service. Various service auditing or data auditing methods can ensure that the service provided by edge



works correctly. After each edge makes a reasonable price, a group of edges whose prices meet the requirements is initially screened out by the smart contract. The price of the edges and the price submitted by DO constitute a Bayesian game. The rationality of the auction and the solution to maximize the benefit is given in the paper.

After the DO obtains edges whose prices and resources satisfy the requirements suggested by the smart contract, edges are clustered using a geography-based clustering algorithm, and the number of clusters is equal to the number of blocks. Edges in each cluster are closest to the cluster centroid, which ensures that each edge selected is relatively independent with others selected from other clusters. In each cluster, an edge is selected according to a certain attribute and price requirement as the final winners, which ensures that the data are as dispersed as possible, and price or attribute requirements meet the requirements of DO. We outline the edge selection process into the following steps:

- (1) *Initial*. The client initiates the smart contract by submitting storage requirements. The submitted content includes a list of requirements for each resource  $R = (R_1, \dots, R_t)$ , where  $t$  is the number of resources. The highest cost  $P_{total}$  required for storage is used to pay the edges that successfully bids. Besides, the smart contract also needs to include the two-stage submission time interval requirements,  $T_1$  and  $T_2$ . Each edge needs to submit commitment  $c$  within the time of  $T_1$  and the prices  $P$ , the secret random number  $s$  within the time of  $T_2$ .
- (2) *Bidding*. Each edge and clients respectively price each resource  $P$  according to the pricing standard in Bayesian Nash equilibrium theory. Through the secret random number  $s$  generated by each node, combined with the pricing  $P$ , a commitment  $c$  is generated. Commitment  $c$  needs to be submitted within time  $T_1$ . All commitments submitted within the specified time are registered in the blockchain distributed ledger to ensure that the commitment cannot be modified.
- (3) *Revealing*. Bidders and client submit the price  $P$  and secret random numbers  $s$  within the  $T_2$  time interval as required, and the smart contract checks and calculates the commitment value  $c'$ . The newly calculated commitment value  $c'$  is compared with the value  $c$  submitted by each node in the first stage to determine the validity of the submitted price. The valid price is stored in the smart blockchain.
- (4) *Reselecting*. The client obtains the list of winning edges from the auction mechanism, including location information and related attributes. Based on the attributes and location information of the edges, clustering-based methods are used to select the final winning edges, taking into account the requirements of clients and the storage reliability.

In the Initial phase, Edges and DO give reasonable prices for resources. Section 4.1 analyzes the price strategy, which guarantees that both DO and Edges can get the maximum benefit, through Bayesian game theory and gives a detailed description of the “bidding” and “revealing” process in Section 4.2. After the smart contract selects the edges, we use the clustering-based algorithm introduced in Section 5 to select the final edges that take into account DOs’ requirements and storage reliability.

## 4 | SMART CONTRACT-BASED AUCTION MECHANISM

In this section, we introduce the key technologies involved in the smart contract-based auction mechanism.

## 4.1 | Game theory based price strategy

In this section, we analyze the issue of resource prices from the economic perspective. Specifically, we target at determine a price that can maximize the interests of both parties. That is, how to set the price of the resource seller (marginal price) to make the price more acceptable to the resource demander (DO). We use Bayesian games to analyze this problem.

In our scenario, there are two main parties involved in the auction: resource sellers (Edges) and resource buyers (Clients of DO). For edges, they hope to sell as high as possible and selling their own resources as much as possible. The client hopes to buy the resources he/she needs at the lowest possible price. For both parties, it is hoped to obtain the highest expected benefits from the transaction according to their different resources. Besides, we assume that both parties to the auction have an accepted price that is not known to other participants. Moreover, all parties have a distribution function to measure resource prices. When the auction starts, all parties will price the resources they need or they own and each party submits a sealed price set of resources to the smart contract to form a static game.

We assumpt that  $m$  edges provide storage resources for  $n$  clients (DO).  $P_{max}$  and  $P_{min}$  are the highest and lowest unit prices of resources in the market,  $P_{max} = \{p_{max_1}, \dots, p_{max_i}, \dots, p_{max_k}\}$ ,  $P_{min} = \{p_{min_1}, \dots, p_{min_i}, \dots, p_{min_k}\}$ ,  $0 < j \leq k$ ,  $k$  is the type of resource. Besides, we assume that each node knows its own linear valuation function of resources. Then, We model the auction price problem as a game  $\Gamma$  of incomplete infomation and the auction game is defined as follows:

**Definition 1.** *Game  $\Gamma$ :* It is a  $(m \oplus n)$ -players game represented as a triple  $(\mathcal{P}, \Sigma, \Pi)$ .

- $\mathcal{P}$  means the set of  $m$  edges (sellers) and  $n$  clients (buyers), including the resources set that they own or require,  $\mathcal{P} = \mathcal{C} \cup \mathcal{E}$ ,  $\mathcal{C}$  and  $\mathcal{E}$  are defined as follows:
  - $\mathcal{C} = \{c_1, c_2, \dots, c_n\}$  ( $n > 1, n \in \mathbb{N}^+$ ) is the set of clients (buyers).  $R_i^C$  is the resources needed by client  $i$ ,  $R_i^C = \{r_{i1}^c, \dots, r_{it}^c, \dots, r_{ik}^c\}$ .
  - $\mathcal{E} = \{e_1, e_2, \dots, e_m\}$  ( $m > 1, m \in \mathbb{N}^+$ ) is the set of  $m$  edges (sellers) and  $R_j^E = \{r_{j1}^E, \dots, r_{jt}^E, \dots, r_{jk}^E\}$  represents the resource set that edge  $e_j$  provides to the system.
- $\Sigma = \Sigma_1 \cap \Sigma_2$  is the auction price strategy of all participates. We denote  $\Sigma_1$  as the expected price strategy of clients and  $\Sigma_2$  as the auction price strategy of edges.
  - In  $\Sigma_1$ , the client  $i$ 's valuations for the  $k$  kinds of resources,  $PV_i^C = \{pv_{i1}^c, \dots, pv_{it}^c, \dots, pv_{ik}^c\}$ .  $pv_{it}^c$  is independent and identically distributed on  $[p_{min}, p_{max_i}]$ . For each resource in  $R_i^C$ , the price set that the client can accept is  $P_i^C = \{p_{i1}^c, \dots, p_{it}^c, \dots, p_{ik}^c\}$ .
  - in  $\Sigma_2$ , the edge  $j$ 's valuations for the  $k$  kinds of resources,  $PV_j^E = \{pv_{j1}^E, \dots, pv_{jt}^E, \dots, pv_{jk}^E\}$ .  $pv_{jt}^E$  is independent and identically distributed on  $[p_{min}, p_{max_i}]$ . For each resource in  $R_j^E$ , the price that the edge  $j$ 's bid price set is  $P_j^E = \{p_{j1}^E, \dots, p_{jt}^E, \dots, p_{jk}^E\}$ .



- $\Pi = \Pi^1 \cap \Pi^2$  is the set of payoff functions of two parties. where  $\Pi: \Sigma \rightarrow \text{Profit}$  is the payoff function under a certain strategy.

The quantity set of the resources when edges  $j$  and client  $i$  reach a deal is  $Q = \{q_1, \dots, q_t, \dots, q_k\}$ ,  $0 < t \leq k$ . From the Definition 1, we get the total bid price of edge  $j$  for the resource set  $R_j^E$  is  $\sum_{t=1}^k q_t p_{jt}^E$  and the highest acceptable price for client  $i$  is  $\sum_{t=1}^k q_t p_{it}^C$ . Besides, the client  $i$  evaluates the  $t$ th resource as  $pv_{it}^C$ , and the price submitted to the smart contract is  $p_{it}^C$ , obviously, the client only benefits when  $p_{it}^C < pv_{it}^C$  is satisfied; Similarly, the edge  $j$  evaluates the  $t$ th resource as  $pv_{jt}^E$  and the auction price is  $p_{jt}^E$ ,  $p_{jt}^E > pv_{jt}^E$ . All participants only know their own valuations, do not know the valuations of others, but everyone knows the valuation is uniformly distributed on  $[p_{min}, p_{max}]$ .

**Definition 2.** *Price strategy:* Assume the pricing strategies of both parties are linear functions of their own valuations. That is, using linear pricing strategies:

$$p_{it}^C = a_{it}^C + b_{it}^C pv_{it}^C, \quad b_{it}^C > 0 \quad (1)$$

$$p_{jt}^E = a_{jt}^E + b_{jt}^E pv_{jt}^E, \quad b_{jt}^E > 0 \quad (2)$$

In Equations (1) The acceptable price strategy for any client  $i$  is a functions  $\{p_{i1}^C, \dots, p_{it}^C, \dots, p_{ik}^C\}$  that specify the ask price of the client under each possible valuation. Similarly, the bidding strategy for any edge  $j$  is a collection of functions  $\{p_{j1}^E, \dots, p_{jt}^E, \dots, p_{jk}^E\}$  that specify the bid price under different valuation scenarios.

**Definition 3.** *Profits:* If the client  $i$  and the edge  $j$  reach a deal, the total price will be:

$$D_{ij} = \frac{P_i^C + P_j^E}{2} Q = \sum_{t=1}^k \frac{p_{it}^C + p_{jt}^E}{2} q_t, \quad (3)$$

and the profits for the client  $i$  and the edge  $j$  are respectively:

$$\Pi^1(P_i^C): \sum_{t=1}^k \left[ pv_{it}^C - \frac{p_{it}^C + p_{jt}^E}{2} \right] q_t, \quad (4)$$

$$\Pi^2(P_j^E): \sum_{t=1}^k \left[ \frac{p_{it}^C + p_{jt}^E}{2} - pv_{jt}^E \right] q_t. \quad (5)$$

Besides, we denote  $\Pi^1(P_{-i}^C)$  as the profits of all client participates without the client  $i$ 's profit,  $\Pi^2(P_{-j}^E)$  as the profits of all edge participates without the edge  $j$ 's profit. Therefore,  $\Pi(P_i^C, P_{-i}^C)$  or  $\Pi(P_j^E, P_{-j}^E)$  is the profits of all participates.

**Definition 4. Nash equilibrium:** A price strategy profile  $\Sigma = \Sigma_1^* \cap \Sigma_2^* = \{P_1^{C*}, \dots, P_n^{C*}, P_1^{E*}, \dots, P_m^{E*}\}$  is the Nash equilibrium of game  $\Gamma$  if no clients or edges can further increase its profits by unilaterally changing its strategy at equilibrium. Mathematically,

$$\Pi(P_i^{C*}, P_{-i}^{C*}) \geq \Pi(P_i^C, P_{-i}^{C*}), 1 \leq i \leq n, \quad (6)$$

$$\Pi(P_j^{E*}, P_{-j}^{E*}) \geq \Pi(P_j^E, P_{-j}^{E*}), 1 \leq j \leq m. \quad (7)$$

If the game state reaches the Nash equilibrium, for the acceptable price of any client  $i$  and the bidding price of any edge  $j$ , no other higher prices can achieve higher benefits. This is a game of incomplete information. Through Harsanyi transformation,<sup>35</sup> the game under the condition of incomplete information can be converted into a complete but imperfect information game. We introduce a virtual participant “Nature,” which gives the corresponding of the valuations  $pv_{it}^C$  and  $pv_{jt}^E$ .

**Theorem 1.** *If the game state reach the Bayesian Nash equilibrium, the each acceptable resource price  $P_i^C$  of any client  $i$  and the each bidding resource price  $P_j^E$  of any edge  $j$  should satisfy the following conditions:*

$$(a) \max_{P_i^C} \left\{ pv_{it}^C - \frac{P_i^C + Exp^E}{2} \right\} * Prob^C, \quad (b) \max_{P_j^E} \left\{ \frac{P_j^E + Exp^C}{2} - pv_{jt}^E \right\} * Prob^E, \\ s. t. \max \Pi(P_i^C) \quad \text{and} \quad \max \Pi(P_j^E) \quad (8)$$

where  $pv_{it}^C$  and  $pv_{jt}^E$  within the interval  $[p_{min_i}, p_{max_i}]$ .  $Prob^C = p\{p_{it}^C \geq p_{jt}^E(v_{jt}^E)\}$ ,  $Exp^E = E[p_{jt}^E(pv_{jt}^E) | p_{it}^C \geq p_{jt}^E(pv_{jt}^E)]$ ,  $Prob^E = p\{p_{it}^C(pv_{it}^C) \geq p_{jt}^E\}$ , and  $Exp^C = E[p_{it}^C(pv_{it}^C) | p_{it}^C(pv_{it}^C) \geq p_{jt}^E]$ .

In Equation (8), the first item in the curly braces is the actual transaction price of the  $t$ th resource when the  $i$ th client and the  $j$ th edge reach a deal;  $Exp^E$  is the expected value of the  $j$ th edge's bid price when the transaction is successful; And  $Prob^E$  is the probability that a transaction will succeed when the  $j$ th edge is bidding  $p_{jt}^E$ .

In Equation (8), the second item in the curly braces is the actual transaction price of the  $t$ th resource when the  $i$ th client and the  $j$ th edge reach a deal;  $Exp^C$  is the expected value of the  $i$ th client ask price when reaching a deal; And  $Prob^C$  is the probability that a transaction will succeed when the  $i$ th client is asking  $p_{it}^C$ .

We reference the similar proof work in the literature<sup>26</sup> to resolve the problem of how to price the storage resources to achieve Nash equilibrium.

*Proof.* Considering that  $pv_{it}^C$  and  $pv_{jt}^E$  in the above assumptions are uniformly distributed on  $[p_{min_i}, p_{max_i}]$ , the probabilities and mathematical expectations for Equations (8) and (8) can be calculated as follows:

$$\begin{aligned}
Prob^E &= p\left\{p_{it}^C(pv_{it}^C) \geq p_{jt}^E\right\} = p\left\{(a_{it}^C + b_{it}^C pv_{it}^C) \geq p_{jt}^E\right\} = p\left\{pv_{it}^C \geq \frac{p_{jt}^E - a_{it}^C}{b_{it}^C}\right\} \\
&= \frac{p_{max_t} - \frac{p_{jt}^E - a_{it}^C}{b_{it}^C}}{p_{max_t} - p_{min_t}} = \frac{p_{max_t} b_{it}^C + a_{it}^C - p_{jt}^E}{b_{it}^C (p_{max_t} - p_{min_t})}
\end{aligned} \tag{9}$$

Similarly,

$$Prob^C = p\left\{p_{it}^C \geq p_{jt}^E(pv_{jt}^E)\right\} = \frac{p_{it}^C - p_{min_t} b_{jt}^E - a_{jt}^E}{b_{jt}^E (p_{max_t} - p_{min_t})} \tag{10}$$

Besides,

$$\begin{aligned}
Exp^C &= E\left[p_{it}^C(pv_{it}^C) \mid p_{it}^C(pv_{it}^C) \geq p_{jt}^E\right] = E\left[(a_{it}^C + b_{it}^C pv_{it}^C) \mid \left(pv_{it}^C \geq \frac{p_{jt}^E - a_{it}^C}{b_{it}^C}\right)\right] \\
&= \frac{E\left[a_{it}^C + b_{it}^C pv_{it}^C, pv_{it}^C \geq \frac{p_{jt}^E - a_{it}^C}{b_{it}^C}\right]}{p\left\{pv_{it}^C \geq \frac{p_{jt}^E - a_{it}^C}{b_{it}^C}\right\}} = \frac{p_{jt}^E + a_{it}^C + b_{it}^C p_{max_t}}{2}
\end{aligned} \tag{11}$$

Similarly,

$$Exp^E = E\left[p_{jt}^E(pv_{jt}^E) \mid p_{jt}^E(pv_{jt}^E) \geq p_{it}^C\right] = \frac{p_{it}^C + a_{jt}^E + b_{jt}^E p_{min_t}}{2} \tag{12}$$

Then, we can get the following translations:

$$Max_{p_{jt}^E}: \max_{p_{jt}^E} \left\{ \frac{p_{jt}^E + \frac{p_{jt}^E + a_{it}^C + b_{it}^C p_{max_t}}{2}}{2} - pv_{jt}^E \right\} \frac{p_{max_t} b_{it}^C + a_{it}^C - p_{jt}^E}{b_{it}^C (p_{max_t} - p_{min_t})} \tag{13}$$

$$Max_{p_{it}^C}: \max_{p_{it}^C} \left\{ pv_{it}^C - \frac{p_{it}^C + \frac{p_{it}^C + a_{jt}^E + b_{jt}^E p_{min_t}}{2}}{2} \right\} \frac{p_{it}^C - p_{min_t} b_{jt}^E - a_{jt}^E}{b_{jt}^E (p_{max_t} - p_{min_t})} \tag{14}$$

Considering that the general way to find the optimal solution is to make the first-order partial derivative of equation equal to 0, and then verifying that the second-order partial derivative of the equation is less than 0, the optimal solution of the equation can be obtained. Therefore, we first let the first-order partial derivative of Equations (13) and (14) equal to 0, respectively:

$$\frac{\partial(Max_{p_{jt}^E})}{\partial(p_{it}^C)} = 0 \rightarrow p_{jt}^E = \frac{1}{3}(a_{it}^C + b_{it}^C p_{max_t}) + \frac{2}{3}pv_{jt}^E \tag{15}$$

$$\frac{\partial(\text{Max}_{it}^C)}{\partial(p_{jt}^E)} = 0 \rightarrow p_{it}^C = \frac{1}{3}(a_{jt}^E + b_{jt}^E p_{min_t}) + \frac{2}{3}pv_{it}^C \quad (16)$$

Besides,  $\frac{\partial^2(\text{Max}_{jt}^E)}{\partial(p_{it}^C)^2} < 0$  and  $\frac{\partial^2(\text{Max}_{it}^C)}{\partial(p_{jt}^E)^2} < 0$ , so Equations (15) and (16) are the optimal solutions. Comparing with Equations (1) and (2), we can get  $p_{jt}^E$  and  $p_{it}^C$  as follows:

$$p_{jt}^E = \frac{1}{12}p_{min_t} + \frac{1}{4}p_{max_t} + \frac{2}{3}pv_{jt}^E, \quad p_{it}^C = \frac{1}{4}p_{min_t} + \frac{1}{12}p_{max_t} + \frac{2}{3}pv_{it}^C \quad (17)$$

□

It can be seen that when clients and edges set prices of resources according to Equation (17). Then, the game state can gain equilibrium. The pricing strategies for all participants are functions of their respective valuations, the highest and lowest market prices.

## 4.2 | Two-stage submission auction

Since the transaction is transparent in the public blockchain, how to realize a sealed auction using a smart contract is a challenge. To ensure normal payment to the auction winner, DO should transfer the highest price they can accept and some requirements (the number of blocks, bandwidth, throughput, etc.) to the smart contract during the bidding stage. Besides, the price stored in the blockchain may also be read by other bidders. This will cause bidders to change their bids accordingly instead of bidding truthfully, which will result in loss of profits for the seller and loss of fairness in the auction. For example, suppose that for a user with storage requirements, the maximum acceptable file storage value is \$2, once the bidder knows that the minimum required price is \$2, the bid is reduced to \$1.99 to win the auction, and for the bidder who bid first will bid \$1.99, and the bidder who bid later can bid \$1.98 to win the bid. Therefore, it is necessary and challenging to realize a sealed auction through blockchain.

To achieve a sealed auction and solve the fairness problem, we propose a two-stage submission mechanism to realize the “bidding-revealing” process, as shown in Figure 2. The proposal requires that the commitment be submitted first in the stage of “bidding,” and all bidders will uniformly reveal the price corresponding to the commitment after all commitments are submitted. Edge’s conditions (bandwidth, throughput, etc.) submitted by each bidder do not need to be sealed, and these conditions can be detected by the system. If a bidder reports false-positive information, it will be punished. Submit the commitment first to protect the quotation and prevent bidders from modifying their quotations by reading the prices of other bidders. We use the Keccak-256 hash function<sup>36</sup> to realize the conversion from price to promise.

In the first stage of the bidding process, to ensure the fairness of the auction of each node, both the edges and the clients need to submit a commitment  $c$ . Commitment  $c$  at the second submit stage can reveal the auction price of storage services and the acceptable price of the client. We assume that the resource price is  $P = (p_1, \dots, p_i, \dots, p_n)$ , and  $p_i$  represents the price of different types of resources, such as bandwidth, throughput, and so on. Each node first needs to submit its own commitment  $c$  to the smart contract based on its auction price. Commitment  $c$  is

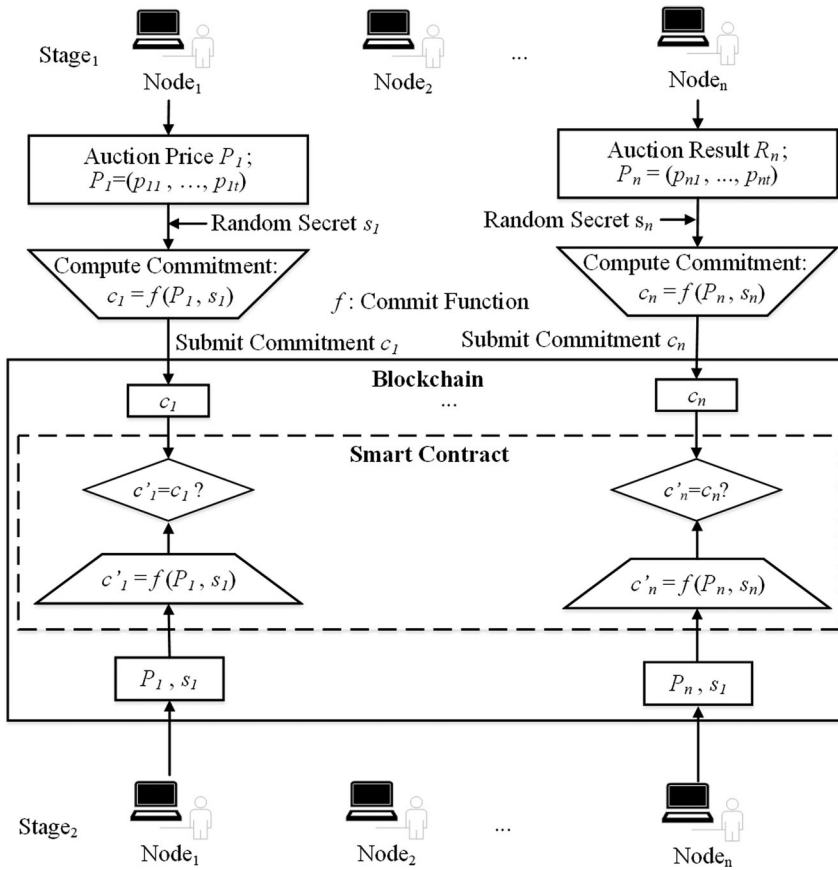


FIGURE 2 The two-stage submission mechanism

generated by each node according to the price  $P$  and a secret random number  $s$ , by calculating the commitment  $c = \text{Commit}(P, s)$ . Each node has a random number  $s$ , so the commitments submitted by each node are not the same. If a collision is promised during the submission stage, then the submitted node will regenerate the secret random number  $s$  and recalculate  $c$  for submission. Using commitment, each node submits promises within a certain period to ensure that the price will not change. The node that does not submit a promise is deemed to have given up the current round of auction.

Once the bidding time is over or all nodes have submitted their commitment. The commitment  $c$  is registered in the blockchain, and the nontamperable property of the blockchain ensures that the commitment cannot be modified. Next, the bidder sends the auction price  $P$  and secret random number  $s$  to the smart contract in the revealing stage. After all nodes submit the price and secret random number or the submit time is over, the smart contract calculates  $c$  according to the secret random number  $s$  and the action price  $P$  through the *Commit* function. We denote the commitment calculate by smart contract is  $c'$ ,  $c' = \text{Commit}(P, s)$ . If  $c'$  is equal to  $c$ , it means that the bidder has complied with the bidding rules and submitted the quotation at the time of promise honestly, then the bid price will be registered in the blockchain.  $c' \neq c$  means the bidder modifies the price during the price submission stage, and the bid is invalid.

## 5 | CLUSTER-BASED SELECTION ALGORITHM

In some studies of computing resource allocation, most of the goals pursued are maximization of benefits. However, in storage scenarios, the reliability of file storage is an indicator that cannot be ignored. In the edge computing scenario, data are distributed to edge servers after splitting into blocks. The scattered and redundant storage of blocks can ensure that the data can always be recovered after one or more blocks are lost. However, when we seek to maximize revenue through the auction, we ignore the issue of data storage reliability. Therefore, we propose to use a cluster-based selection algorithm to further filter edges, achieving the two goals of maximizing revenue and high file reliability.

### 5.1 | Analysis of block distribution problems

The files stored are fragmented to many blocks to be stored in different edges. Some edges may be owned by the same organization or communities that have the same public power supply settings, access gateway equipment, and the same external threats. Suppose that the blocks of a file are gathering in a concentrated area, and the above-mentioned accidents, such as power outages, network disconnections, and attackers' vandalism have occurred in this geographic area. This will directly cause the blocks in this geographic area to be offline at the same time, and the data will be lost. Besides, although it is likely to be true that not all the aggregated edges belong to the same organization, geographical clustering can also cause these edges to face the same threat. For example, the memory cards on video surveillance equipment gathered in a certain geographic area may store the data of this node or other nodes in the edge storage system. When some nodes in this geographic area are maliciously damaged, it may cause data loss. Therefore, by distributing blocks in different geographic locations of the storage system (specified ranges according to system requirements or data transmission delay), ensuring that all blocks of a unified file are nongathering and dispersed as much as possible can achieve higher file storage reliability.

We randomly generate data and use the form of Figure 3 to further illustrate the problem we described above. The locations of all points in Figure 3 represents locations of edges in storage services in different campuses, hospitals, and other organizations within a geographic range. From the above figure, we can intuitively observe that the edges in the two circles are very clustered. If too many data blocks of the same file are concentrated in the circled position, and internal or external threats occur at this position, the file will face a greater risk of loss.

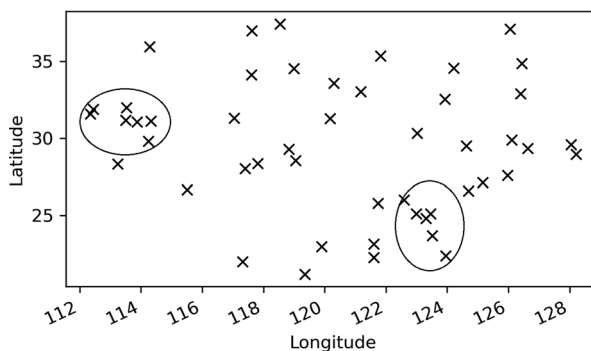


FIGURE 3 Example of location distribution

## 5.2 | Cluster-based block distribution mechanism

In response to the problems described above, this paper proposes a storage configuration recommendation that uses a cluster-based block distribution mechanism to achieve multi-objective selection.

Supposed that  $m$  Edges win the auction and the Client can obtain the price information and location information of the winners ( $e_1, e_2, \dots, e_m$ ). Then, the client performs central clustering according to the location information of the edges. The number of clusters is the same according to the number of blocks. For example, if there are  $k$  blocks, the number of clusters is  $k$ . After clustering, all edges fall into  $k$  relatively independent spaces. The edges transmitted from the  $k$  spaces constitute a combination to achieve as much price or resource demand as possible based on considering reliability.

Since the total number of edges and the blocks are known, we choose to use KMeans central clustering algorithm for the clustering process. The KMeans algorithm is the most commonly used clustering algorithm. In our paper, the known set to be clustered is  $E = \{e_1, e_2, \dots, e_m\}$ , the number of subspaces that need to be clustered is  $k$ , therefore, the problem of clustering is to find  $k$  locations  $L = \{l_i\}_{i=1}^k$  to minimize the following cost function:

$$\text{cost}(E, L) := \sum_{e \in E} \min_{l_i \in L} \|e - l_i\|^2.$$

Equivalently, the KMeans clustering problem can be considered as the problem of finding the partition  $P = \{p_1, p_2, \dots, p_k\}$  of  $E$  into  $k$  clusters that minimizes the following cost function:

$$\text{cost}(P) := \sum_{i=1}^k \min_{l_i \in \mathbb{R}^{2d}} \sum_{p \in P} \|p - l_i\|^2.$$

KMeans clustering is used to find  $k$  clusters, and the set of all positions is equally divided into  $k$  clusters. The  $k$  relatively independent clusters ensure that the sum of the distances between each position point and the centroid is the smallest. The client can select edges according to the attributes required by itself. For example, if bandwidth is required first, then each cluster can be sorted according to the bandwidth, so as to select the best edges in each cluster. However, if the resources in some clusters are consistent or there are multiple consistent optimal, how to give an edge selection is a problem. If some edges have been selected in some clusters, how to continue selecting from the remaining clusters.

We make supplementary modifications to KMeans algorithm. After the clustering and sorting by the attributes of one or more items in each clusters, some edges in clusters can be selected, while there are multiple edges in some other clusters. At this point, we select edges based on the principle of storage reliability. Supposed that the selected edges are  $E = \{e_1, e_2, \dots, e_t\}$  located in the cluster  $P = \{p_1, p_2, \dots, p_t\}$ , the centroid set is  $CP = \{cp_1, \dots, cp_t\}$ , the unselected cluster  $\hat{P} = \{p_{t+1}, p_{t+2}, \dots, p_k\}$ , and the centroid set of unselected cluster is  $\hat{C}P = \{cp_{t+1}, \dots, cp_k\}$ . We continue to iterate the following process to select the optimal edges in each of the remaining clusters.



$$\forall p \in \hat{P}: \max_{l_j \in P} \left( \min_{cp_i \in CP} |cp_i - l_j| \right).$$

By maximizing  $cost(\hat{P})$ , we find the edges farthest from the selected set in the remaining clusters one by one. Of course, this is not necessarily the optimal choice, because the above selection method is related to the order of the remaining clusters. If we want to find the optimal combination, we can constantly change the iterative sequence of the remaining clusters. Considering that the iterative selection process is located on the DO's side, the complexity cost is too high. Therefore, we only realize the selection by randomly selecting the remaining clusters. In the following experiments, we will show through a large number of experiments that the effect of the above-mentioned maximization of  $cost(\hat{P})$  selection is far greater than the method of random selection in each cluster.

The specific selection process is shown in Figure 4, the winners ( $e_1, e_2, \dots, e_m$ ) from smart contract are clustered into  $k$  clusters ( $cluster_1, \dots, cluster_k$ ). We assume that edges  $e_{12}$  and  $e_{2j}$  have been selected according to a certain attribute in cluster  $Cluster_1$  and  $Cluster_2$ , and the centroids of  $Cluster_1$  and  $Cluster_2$  are  $cp_1$  and  $cp_2$ . Then, we can find the farthest edge  $e_{3?}$  from  $cp_1$  and  $cp_2$  in  $Cluster_3$  and find the farthest edge  $e_{4?}$  from  $cp_1, cp_2$ , and  $cp_3$  in cluster  $Cluster_4$ . Continuously iterating the above process, we finally choose the edges ( $e_{12}, e_{2i}, e_{3?}, e_{4?}, \dots, e_{k?c}$ ) that takes into account storage reliability. We give our pseudo-code implementation in Algorithm 1.

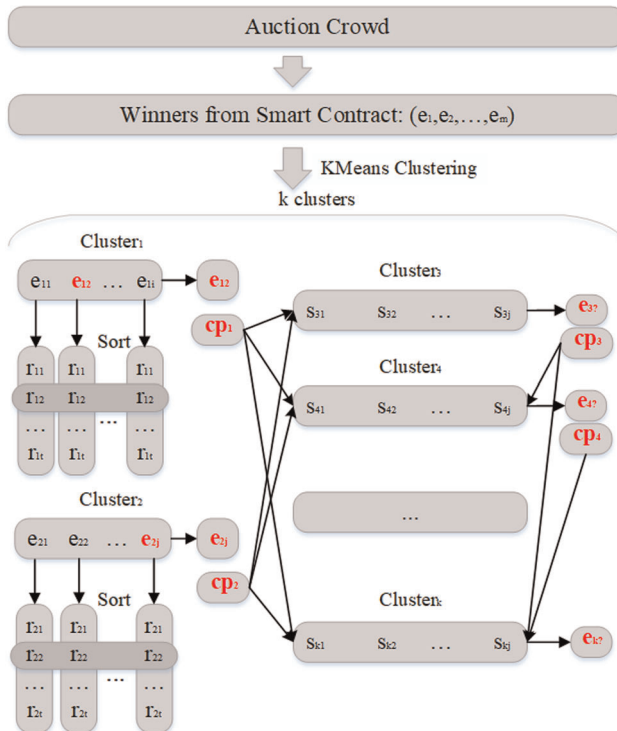


FIGURE 4 Clustering-based selection mechanism [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

**Algorithm 1.** Joint Attribute and Reliability Selection Algorithm**Input:**

Blocks number  $k$ ;  
 Resource number  $t$ ;  
 $m$  edges:  $E_m = \{e_1, \dots, e_m\}$ ;  
 Location set of  $E_m$ :  $\{L_1, L_2, \dots, L_m\}$ ,  $L_i = \{\text{latitude}_i, \text{longitude}_i\}$ ,  $1 \leq i \leq m$ ;  
 Preferred resource of edges:  $a$ ;

**Output:**

Set of selected edges: *selectedSet*;  
 1: Random select  $k$  items from  $S_m$  as starting centroid  $C_k = \{c_1, \dots, c_k\}$ ;  
 2:  $C_k$  corresponds to  $k$  clusters:  $Cluster_k = \{cluster_1, \dots, cluster_k\}$ ;  
 3: **while** The cluster state has changed and the maximum iterations number has not been reached **do**  
 4:   **for** each item  $e_i$  in  $E_m = \{e_1, \dots, e_m\}$  **do**  
 5:     Distance[] *DisArr*;  
 6:     Distance[][][] *DisArrs*;  
 7:     **for** each item  $c_j$  in  $C_k$  **do**  
 8:       Distance  $d_j = Dis(e_i, c_j) = Dis(L_i, L_j)$ ;  
 9:       *DisArr*  $\leftarrow d_j$ ;  
 10:       *DisArrs*[ $i$ ][ $j$ ]  $\leftarrow d_j$ ;  
 11:     **end for**  
 12:     Shortest distance  $d_s = \text{minDis}(\text{DisArr})$ ;  
 13:     Corresponding cluster  $cluster_{d_s}$ ;  
 14:      $cluster_{d_s} \leftarrow e_i$ ;  
 15:   **end for**  
 16:   **for** each  $cluster_i$  in  $Cluster_k$  **do**  
 17:     Update centroid:  $c_i \leftarrow \text{getCentroid}(cluster_i)$ ;  
 18:   **end for**  
 19: **end while**  
 20: Selected edges: *selectedSet* =  $\emptyset$ ;  
 21: The Clusters of selected edges set  $P$ ;  
 22: The Clusters of remaining to be select:  $\hat{P}$ ;  
 23: # Select some preferred edges according to the attribute.  
 24: **for** each  $cluster_i$  in  $Cluster_k$  **do**  
 25:    $P, \hat{P}, \text{selectedSet} = \text{getOptimal}(cluster_i, a)$ ;  
 26: **end for**  
 27: # Select edges from remaining clusters  $\hat{P}$ .  
 28: each  $cluster_j$  in  $\hat{P}$   
 29:   Distance[] *DisArrTemp* =  $\emptyset$ ;  
 30:   # Compute the distance between each edge and *selectedSet* and get the shortest one.  
 31:   **for** each  $e_k$  in  $cluster_j$  **do**  
 32:     *DisArrTemp*  $\leftarrow \text{minDis}(\text{DisArrs}, \text{selectedSet})$ ;  
 33:   **end for**  
 34:   *selectedSet*  $\leftarrow \text{maxDis}(\text{DisArrTemp})$ ;  
 35: **end for**  
 36: Return *selectedSet*

## 6 | PROTOTYPE IMPLEMENTATION AND EVALUATION

There are mainly two parts in the implementation and evaluation process: one is the smart contract implementation and measurements on the consumption of interfaces; The other is the analysis and experiment of the cluster-based data distribution algorithm.

### 6.1 | Auction smart contract implementation and analysis

#### 6.1.1 | Auction smart contract implementation

We implement an auction model based on smart contracts in Ethereum. Figure 5 shows the state transition process in the smart contract. Three roles are mainly involved in the model: Client (C), Service Node (SN), and Service Provider (P). We define the states in the smart contract: “Init,” “Active,” “Bidding,” “Reveal,” and “Complete.” The interfaces used for the transition between states in the figure belong to the content of the smart contract, “{Role}; {Interface Name}.” The judgment box is used for selection when the contract conflicts. In Ethereum, a specific role can access a specific breach to realize the interaction between the role and the contract.

In Ethereum, instead of running automatically, smart contracts can only be triggered and executed through interfaces. The transition of a smart contract from one state to another needs to be triggered by calling an interface function. Also, the implementation of interface functions in smart contracts requires a certain fee to be paid to Ethereum. For example, to switch from the “Bidding” state to the “Reveal” state, *SN* is required to submit the specific information of the quotation, which is to trigger the state transition through the interface function “*SN*: submitResourceDetail.” After the state transition is completed, the smart contract needs to pay a certain amount of Ether to Ethereum.

#### 6.1.2 | Consumption of each interface in auction smart contracts

We use Online Ethereum Studio<sup>#</sup> to develop Ethereum smart contracts. Online Ethereum Studio supports automatic deployment of simulated contracts with multiuser establishment,

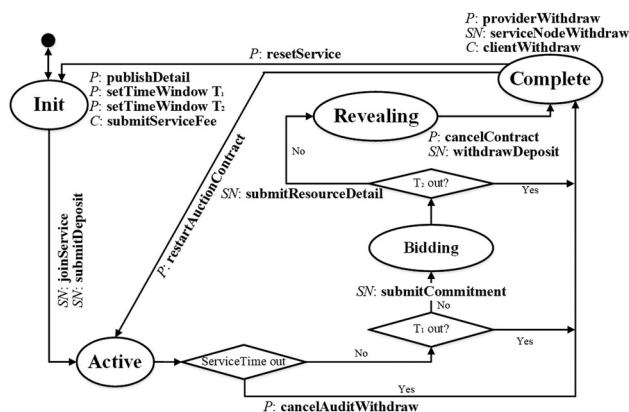


FIGURE 5 Auction task smart contract implementation

and users can interact with contracts through the Web client. Users can also test the usage of the interface in the contract, that is, the transaction fee and the cost of the Ethereum cryptocurrency “Ether.” To simulate actual application scenarios, we test all interfaces of the auction model by deploying contracts on the Ethereum blockchain test network “Rinkeby.” Rinkeby is a global blockchain test network for developers to debug smart contracts. It can simulate the secret currency “Ether” in the real Ethereum blockchain, which is convenient for us to debug the interface. We generate multiple accounts on “Rinkeby” to simulate different roles, and use the “Ether” retrieved from each simulated account to execute the interface and prepay different types of fees. The service information submitted by the client triggers the service party to establish a smart contract and deploy the contract to the blockchain. The service node chooses to join Crowd for bidding through the task details. Run all interfaces through different situations to realize functional testing and data collection of all interfaces.

Based on the economic game model of edges and clients, reasonable quotations for different resources are determined. The edges submit all quotations at once within a certain period through a two-stage submission strategy. The economic game model ensures that each edge makes quotations from the perspective of the greatest benefit; the two-stage submission strategy ensures fairness and rationality in the auction process and prevents the edge from arbitrarily changing prices or tampering with quotations through late submission. Therefore, we mainly study and analyze some performance information from the deployment and application of smart contracts. The complexity of the interface in the smart contract determines the performance of the operation, and the complexity of the interface determines the cost of state transition. In the Ethereum network, miners need to consume power to execute the procedures defined in the interface for verification and state conversion. Therefore, the more complex the interface, the higher the cost to pay. The “Gas” defined in Ethereum is used to measure execution costs. Transaction cost is the product of the consumption of “Gas” and the price per unit of “Gas.” Therefore, the “Gas” consumption in the test network is similar to the consumption in the main network. Therefore, we recorded all the “Gas” consumption of each interface from the transaction records of the experiment to reflect the performance of our interface.

Figure 6 shows the amount of “Gas” in the main interface of the contract. The results show that the supplier’s interface consumes more gas. Since the supplier needs to issue a smart contract and set some details in the contract, some of the interfaces run by the supplier also include the processing of the submitted data, so the “Gas” consumption is larger. Besides, the consumption of “Gas” mainly depends on the definition and implementation of the interface. More optimized and reasonable interface design can further reduce the consumption of “Gas.”

## 6.2 | Cluster-based block distribution algorithm analysis

### 6.2.1 | Algorithm complexity analysis

The complexity of the cluster-based data distribution algorithm mainly consists of two parts, one is the clustering process, and the other is the process of selecting nodes from each cluster. Below we analyze the two processes and the overall complexity.

In the clustering process, the algorithm we choose is the KMeans clustering algorithm. The time complexity of KMeans is  $O(l * n * k * m)$ , and the space complexity is  $O(n * m)$ . Among them,  $m$  is the number of element fields,  $n$  is the amount of data,  $l$  is the number of iterations,

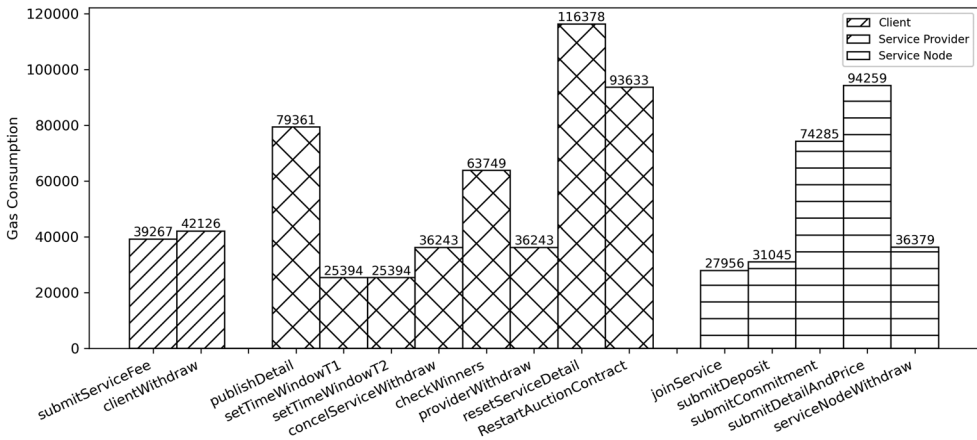


FIGURE 6 The Gas consumption of each interface in auction task smart contract

and  $k$  is the number of clusters. At the same time, generally,  $l$ ,  $k$ ,  $m$  can be regarded as constants, so the time and space complexity can be simplified as  $O(n)$ , that is, the synthesis of the complexity of the KMeans algorithm is linear.

In the second process, the edges are selected from each cluster, mainly by performing a loop in each cluster. After clustering, the number of clusters is fixed, so it is equivalent to traversing all the data once. Therefore, the time complexity of the second process is also  $O(n)$ , which is also linear.

## 6.2.2 | Algorithm comparison analysis

In this section, we mainly compare the method of the random selection directly, random selection in each cluster after each clustering, and our cluster-based selection. We take the longitude and latitude as (120, 30) as the center and randomly generate 50 positions within a certain range. We set the block number as 7 and the cluster number is also 7. For random selection, the number of clusters can be regarded as only 1. Then, we respectively calculate the sum of the distances of the two positions and the minimum distance in each group as the measurement standard. The greater the distance sum and the greater the minimum distance, the better the file dispersion. The results are shown in Table 2. For each item, we tested 20 rounds and calculated the average value. It can be seen from the table that our clustering-based algorithm takes the distance between the selected edge and the unselected cluster as the selection condition when selecting, and the selected result is better than the other two methods.

The distribution of the randomly generated data set is shown in Figure 3. The distribution of red points is the distribution of selected edges when using different methods and the

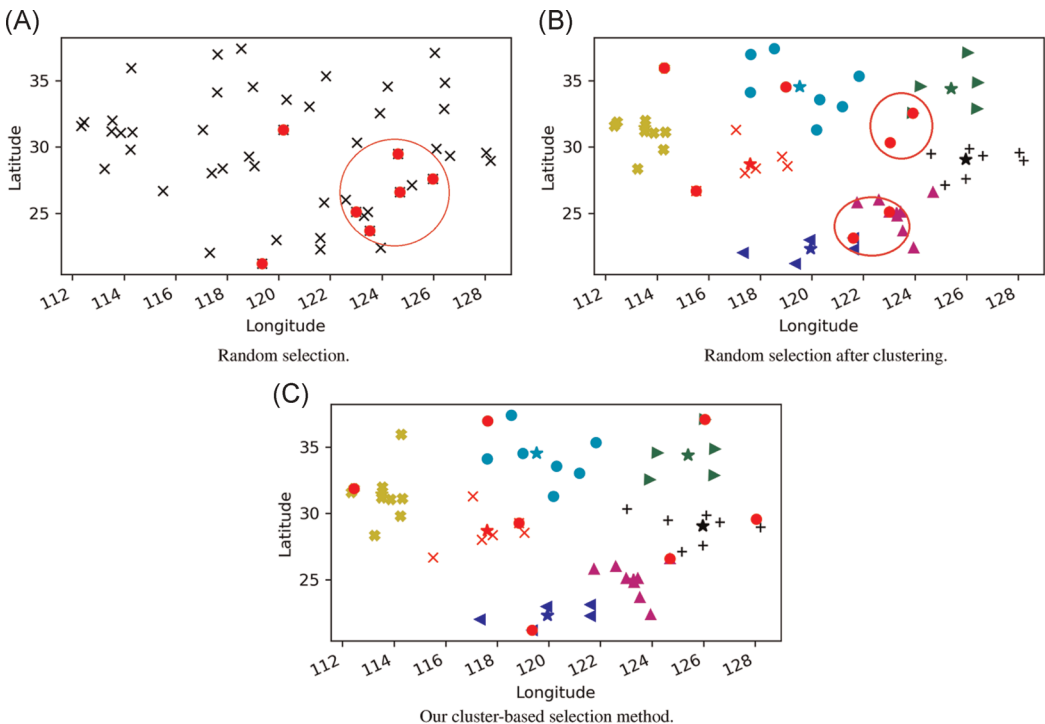
TABLE 2 Results of reliability measures

Algorithm	Cluster number	Average distance	Shortest distance
Direct random selection	1	7.7985	1.0309
Random selection in each cluster	7	8.6452	3.2717
Our cluster based method	7	10.0075	4.4857

five-pointed stars with different colors represent the centroid of each cluster in Figure 7. From Figure 7, we can see the characteristics of edges distribution very intuitively. In Figure 7A, the selected edges are clustered in a certain geographic area. As we marked with a red circle in the figure, the attack on this area is likely to cause these edges to be dropped at the same time. For the random selection after clustering, edges selected in each cluster may result in the selected edges being located at the junction of two adjacent clusters, making an unwise choice, as shown in Figure 7B where we use the red circles marking it out. In terms of location, two edges may be dropped by the same abnormal event, which reduces the reliability of file storage. In contrast, the edges selected using our cluster-based method in Figure 7C can be well distributed in the region. The results in Figure 7 and the results in Table 2 can be mutually confirmed.

### 6.2.3 | Reliability analysis

We assume that the different clusters have the same probabilities of being attacked due to external forces, denoted as  $p$ . We represent a file as  $F$  and the file  $F$  are consisted of  $n$  blocks, where  $m$  blocks in  $n$  blocks are redundant blocks,  $n > m > 0$ . In extreme cases, if all or  $n$  blocks are gathered in the same cluster. The probability of data loss is  $p$ . If all blocks are distributed in different clusters, the blocks number of being damaged are  $n * p$ . If more than  $m$  blocks are lost, the file  $F$  is lost and cannot be recovered. For a better explanation, we assume that a data composed of four original data blocks and three redundant blocks, data will be lost only when more than three blocks are lost. Besides, to simulate the distribution area of edges, we



**FIGURE 7** The distribution of selected edges using different methods. (A) Random selection, (B) random selection after clustering, and (C) Our cluster-based selection method [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

randomly generate a series of edge locations and describe their locations as shown in Figure 7B,C. These generated position points represent the winning points in the auction process. The locations with different colors are clustered by KMeans. We can calculate the loss probability of the file  $F$  by the following formula:

$$P_{lost} = C_n^{m+1} p^{m+1} (1-p)^{n-m-1} + C_n^{m+2} p^{m+2} (1-p)^{n-m-2} + \dots + C_n^n p^n (1-p)^{n-n}$$

$$= \sum_{i=m+1}^n C_n^i p^i (1-p)^{n-i} (m, n, i \in \mathbb{N}^+, 0 \leq p \leq 1).$$

The result is shown in Table 3. Obviously,  $\sum_{i=m+1}^n C_n^i p^i (1-p)^{n-i}$  keeps decreasing with the increase of redundant data blocks and is much smaller than  $p$ . The probability of data loss is much smaller than that if the blocks are stored in a gathering distribution. Therefore, The decentralized distribution of blocks greatly improves the reliability of edge storage. Besides, we show in Figure 8 the file loss probability under different conditions when the

TABLE 3 Probability of file loss under different aggregation situations

$n - m$	$n$	$m$	Gathered	Dispersed	$n - m$	$n$	$m$	Gathered	Dispersed
3	4	1	0.1	0.0523	6	8	2	0.1	0.03809
3	5	2	0.1	0.00856	6	8	3	0.1	0.00833
4	5	1	0.1	0.08146	6	10	4	0.1	0.001635
4	6	2	0.1	0.01585	6	11	5	0.1	0.0002957
4	7	3	0.1	0.002728	7	8	1	0.1	0.186895
5	6	1	0.1	0.025692	7	8	2	0.1	0.07019
5	7	2	0.1	0.00502	7	10	3	0.1	0.012795
5	8	3	0.1	0.00089	7	11	4	0.1	0.00275
5	9	4	0.1	0.00089	7	12	5	0.1	0.0005412
6	7	1	0.1	0.14969	7	13	6	0.1	$9.9285 \times 10^{-5}$

Note: We set probabilities of each cluster being attacked,  $p = 0.1$ ,  $n$  is the total blocks number,  $m$  is redundant blocks number and  $n - m$  is the original blocks number.

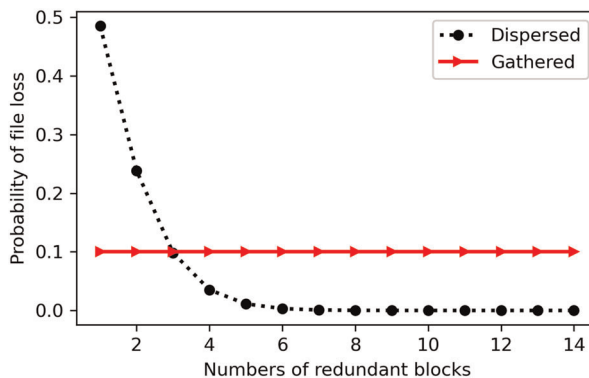
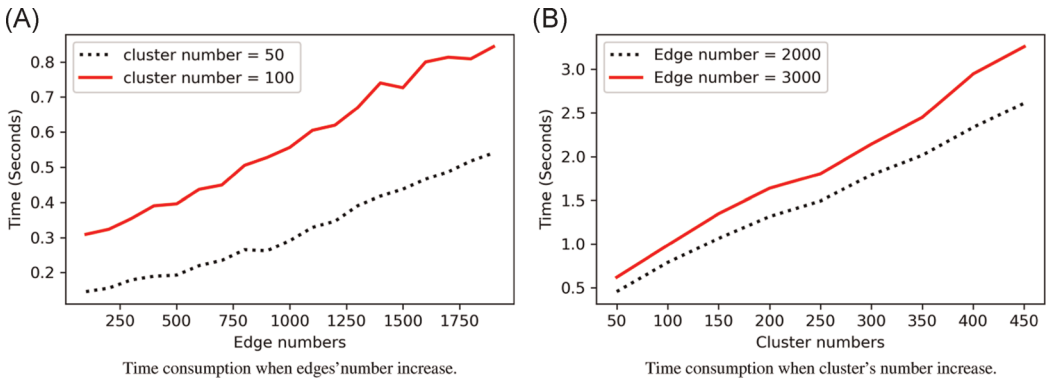


FIGURE 8 Probability of file loss in different redundant data blocks [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]





**FIGURE 9** Time consumption in different situations. (A) Time consumption when edges' number increase and (B) time consumption when cluster's number increase [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

number of original blocks is 15. We can intuitively observe that when the redundant data block is 1, the probability of file loss in dispersed storage is greater than the probability of gathered storage. This is because the file is stored in 16 locations, and any loss of two blocks can cause the loss of the file. With the increase of redundant data blocks, the probability of file loss under decentralized storage continues to decrease until it is far less than that of gathered storage. This phenomenon is confirmed by the two situations (6,1) and (7,1) in Table 3. Choosing an appropriate redundancy ratio can greatly improve the reliability of file storage.

#### 6.2.4 | Time consumption

To test the time consumption of the cluster-based selection algorithm, we conduct experiments on the Windows PC with 64-bit intel-core i5-8250U CPU at 1.8 GHz and 8 GB memory. Besides, we test each result 15 times and average the experimental results.

As shown in Figure 9, we test the time consumption in different situations. First, we take the number of edges from 50 to 2000 and set the number of clusters to 50 and 100, respectively. We test time consumption to run each cluster-based clustering algorithm. We can get that as the number of edges increases, the time consumption also increases linearly as the results shown in Figure 9A. Besides, setting the number of edges to 2000 and 3000, respectively, we continued to test the time consumption of running the algorithm in the range of the number of clusters from 50 to 450. Similarly, for the same number of edges, the time consumption also increases as the number of clusters increases, and the results are shown in Figure 9B.

Besides, in an actual system, the size of the data and the number of clusters can be specifically selected for the performance of the terminal device. In the case of too much data on the edges, some edges can also be selected in advance through some specific attributes required. For example, prefer to select the edge with fast access speed or large storage space.

## 7 | CONCLUSIONS

Through model construction and solution, mechanism design, implementation, and evaluation, we provide an edge storage solution named SmartStore. The SmartStore uses smart contracts to replace the traditional centralized data distribution platform. Besides, we propose using the game theory to conduct price analysis from an economic perspective and using a two-stage submission strategy to ensure the fairness of the SmartStore. After all edges and clients make reasonable prices, the edges that pass the auction are reselected using improved clustering-based clustering methods to determine the final selected edges. SmartStore provides users with recommendations for storage solutions that take into account maximum revenue and storage reliability. Furthermore, some content can be further studied in the future. For example, the interfaces of the smart contract can be further improved to increase the operating speed and reduce “Gas” consumption. In this paper, the main idea is to provide solutions for edge storage that take into account the prices of heterogeneous resources and storage reliability and leave users with more independent customization options.

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## ENDNOTES

\*<https://www.micron.com/solutions/video-surveillance>

#<https://studio.ethereum.org/>

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