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Blockchain-Based Incentive Mechanism in Internet of Things: Survey and Vision

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***Abstract*—The rapid proliferation of the Internet of Things (IoT) has resulted in an exponential surge in data generation, necessitating robust and secure platforms for data transactions. Blockchain technology, characterized by its immutability and decentralized architecture, emerges as a promising solution offering enhanced transparency and security. This survey provides an in-depth exploration of blockchain-based incentive mechanisms for IoT applications, systematically categorized into Shapley value, Stackelberg game, and auction model. Each category is examined through its theoretical underpinnings, analytical methodologies, and specific advantages within IoT. By discussing the unique challenges and opportunities at the convergence of blockchain and IoT, this paper seeks to furnish a comprehensive guide for future endeavors in blockchain-enabled IoT ecosystems.**

***Index Terms*—Internet of Things, Incentive Mechanism, Blockchain, Game Theory**

I. Introduction

With the widespread use of Internet of Things (IoT) sensors and advancements in information technology, IoT has been rapidly developed in various aspects of our lives. IoT systems now play an increasingly significant role in diverse industries, such as smart homes [1], smart cities [2], energy systems [3], [4], transportation systems [5], and healthcare systems [6], [7]. The IoT continues to proliferate, generating enormous volume of data by IoT devices, which is now a new factor of production and driving a new wave of technological innovation [8]. Therefore, effective utilization of the data generated by and provided for IoT systems is both important and pressing.

Despite the enormous potential of IoT, devices operating as independent entities often generate data involving privacy concerns [9], [10]. Consequently, there is a growing need for a secure platform to facilitate data transactions [11]. Blockchain technology presents a promising solution to these challenges due to its inherent characteristics such as transparency, reliability, privacy protection, and traceability [12], [13]. Blockchain mechanisms can be part of a security framework to protect many IoT-oriented applications, ensuring integrity and privacy even when datasets are released to the public. For example, Han et al. [14] highlighted common security issues in current

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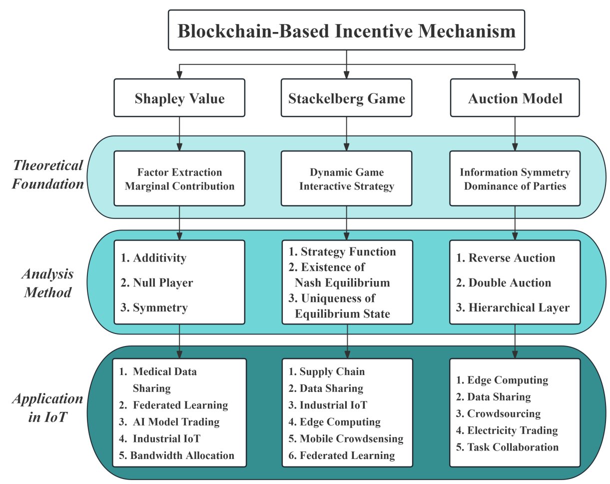

Fig. 1. Overview of Blockchain-Based Incentive Mechanism

IoT architecture and the advantages of integrating blockchain with IoT. Andoni et al. [15] investigated blockchain applications in IoT transaction scenarios, including decentralized markets, electric vehicle charging, and electronic mobility.

However, IoT devices often lack the computational power or incentive to engage in data transactions [16], [17]. In this context, implementing incentive mechanisms is crucial to stimulate initial participation, fostering a virtuous cycle of increased engagement and data exchange. While existing literature reviews cover blockchain-based incentive mechanisms and blockchain applications in IoT [18]–[21], there is a notable gap in comprehensive surveys that systematically detail blockchain-based incentive mechanisms for IoT applications.

Therefore, to address this gap, this survey categorizes existing blockchain-based incentive mechanisms based on their design logic, explores their workflows, and examines their applications and future prospects in IoT scenarios. It aims to provide an in-depth investigation to help newcomers obtain a general understanding of this complex and emerging research field. The survey divides the blockchain-based incentive mechanisms for IoT into three categories: Shapley value-based,

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Stackelberg game-based, and auction-based, analyzing their theoretical foundations, analysis method, and application in IoT as illustrated in the framework shown in Fig 1.

II. Related Work

In recent years, significant research has been conducted on incentive mechanisms in both blockchain and IoT contexts. As IoT technology has rapidly advanced, many scholars have envisioned IoT devices profiting through data exchange. To address this, Li et al. [7] identified two critical challenges in the IoT trading market: "efficiency" and "safety." They emphasized privacy-preserving auction mechanisms for IoT-based transactional markets, systematically explaining these mechanisms and addressing the privacy-efficiency trade-off.

The inherent characteristics of blockchain, such as decentralization, transparency, immutability, and distributed ledger technology, make it a powerful tool for addressing IoT challenges. Dai et al. [22] investigated the integration of blockchain with IoT, examining the architecture and how blockchain can provide opportunities to address IoT challenges. Similarly, Uddin et al. [23] analyzed the latest advancements in IoT blockchain applications in contexts such as e-health, smart cities, and intelligent transportation, and proposed barriers, research gaps, and potential solutions.

In the context of these platforms, the importance of incentive mechanisms becomes evident. Song et al. [24] highlighted the necessity of reasonable monetization rules and incentive systems for the sustainability of blockchain-based data-sharing systems. Therefore, more research towards incentive mechanisms has been conducted and reviewed. Huang et al. [25] provided a comprehensive overview of blockchain incentive mechanisms, focusing on the issuance and allocation of tokens and analyzing the development of the token economy. Han et al. [14] categorized blockchain incentive mechanisms based on blockchain versions, incentive forms, and goals, discussing the advantages and disadvantages of current mechanisms.

Further research has been conducted on the application of incentive mechanisms in different specific domains. For example, Xu et al. [18] provided a survey of blockchain-based crowd-sensing incentive mechanisms, classifying them by incentive goal and reward form. Yu et al. [19] summarized the consensus and incentive mechanisms of blockchain networks derived from P2P systems, discussing issues related to blockchain storage and application scenarios. Ihle et al. [20] reviewed incentive mechanisms in peer-to-peer networks, categorizing them based on monetary, reputation, and service rewards and evaluating each mechanism's data management, attack resistance, and contribution model.

Integrating blockchain and IoT generates new opportunities and challenges for incentive mechanisms. Panarello et al. [8] conducted a systematic survey on the integration of blockchain and IoT, focusing on device manipulation and data management while analyzing current research trends and categorizing literature based on application domains. Maddikunta et al. [21] provided a systematic review of incentive techniques, offering a background on IoT data networks and describing several key incentive technologies, including blockchain, game theory, and artificial intelligence. They explored the potential of incentives in critical IoT applications, covering possible scenarios from smart healthcare to smart industries.

Despite the broad view provided by existing literature on incentive mechanisms in blockchain and IoT independently, there is a lack of systematic reviews focusing specifically on blockchain-based incentive mechanisms for IoT applications. This survey aims to fill this gap by offering a comprehensive overview and analysis of existing solutions, discussing the challenges and opportunities in this rapidly developing field. By doing so, it aims to help newcomers understand the complexities and potential of blockchain-based incentive mechanisms in IoT, thereby contributing to the advancement of research and practical applications in this area.

III. Shapley Value-Based Incentive Mechanism

A. Theoretical Foundation

The Shapley value (SV), rooted in cooperative game theory, provides a fair method for distributing total gains among participants based on their marginal contributions [26]. This ensures that rewards are proportionate to each participant's input, particularly in scenarios where contributions are unequal but cooperation is essential for achieving payoffs [27].

In IoT applications, multiple devices often collaborate to provide data or solve complete tasks. However, a simple equal distribution of rewards may diminish individual motivation, leading to lower quality and efficiency. The Shapley value addresses this by quantifying each participant's contribution, ensuring fair distribution based on actual input and effort.

The Shapley value calculation takes into account all possible combinations of participants and their marginal contributions to each possible subset of participants, allowing for a comprehensive evaluation of each participant's role [28]. Implementing SV in a blockchain-based IoT scenario enables smart contracts to autonomously calculate and distribute rewards, incentivizing devices to share more resources for higher returns.

Moreover, the Shapley value is particularly suitable for environments where the value generated by the collaboration is not simply additive. In many IoT applications, the combination of data from multiple sources can create more value than the sum of individual contributions. For example, in a smart city application, data from various sensors can be combined to provide comprehensive insights that are far more valuable than isolated data points. The Shapley value captures these synergies, ensuring that participants who contribute to these valuable combinations are adequately rewarded.

Using the SV as an incentive mechanism in IoT can lead to more efficient and high-quality outcomes by promoting active participation and fair reward based on contributions.

B. Analysis Methods

The SV is typically calculated by considering all possible coalitions of participants and averaging each participant's marginal contribution weighted across all these feasible coalitions. SV is usually expressed as a function of several factors:

$$\text{SV}(i) = \frac{1}{N(S)} \sum_{S \subseteq P} \left(f(S \cap P) - f(P) \right)$$

where S is any feasible coalitions; P is a particular participant. f is a function that measures the value of a coalition. Depending on the scenario, different metrics are used, such as the F1-score and loss function;N is the normalization factor.

The Shapley value need to satisfy properties such as Additivity, Null Player, and Symmetry, which ensure its unique advantages in fair reward distribution:

- Additivity: $\text{SV}(A \cup B) = \text{SV}(A) + \text{SV}(B)$
- Null Player: $\text{SV}(A \cup \{i\}) = \text{SV}(A)$ if i is a null player
- Symmetry: $\text{SV}(A \cup B) = \text{SV}(B \cup A)$

However, calculating the Shapley value is often both time-consuming and computationally intensive [29], with a complexity of $O(N!)$, where N is the number of participants. Therefore, practical applications often require optimizations.

C. Application Scenarios in IoT

Medical Data Sharing: Blockchain's immutability and transparency have been widely applied to improve the efficiency and security of medical data sharing. Zhu et al. [6] developed a blockchain-based cooperation model for medical data sharing. They defined and derived SVs for data owners, the unit model, and the cooperation model separately. The normalized SVs were used to calculate income distribution among data owners, miners, and third parties. This system demonstrates the effectiveness of the SV-based incentive mechanism in promoting data sharing in medical scenarios.

Federated Learning (FL): Liu et al. [30] proposed a peer-to-peer payment system for FL, where the Shapley value is used to calculate each client's fair contribution to the global model. This method uses the Shapley Proof consensus protocol to ensure accurate calculations and encourages FL clients to provide high-quality data. However, this method does not address potential free-riding issues. Yang et al. [31] extended this by introducing a joint optimization mechanism that combines contract theory and Shapley value. This mechanism includes penalties and rewards assignments to further ensure high-quality contributions, providing a more robust incentive structure for clients with varying resources and data sizes.

AI Model Trading: Nguyen et al. [32] introduced a blockchain-based AI model trading marketplace, where vast amounts of data are crucial. They evaluated the proportionate relationship between local data and the quality of the trained model and estimated the value of sellers' data in training the model using a distributed SV approach. This incentivized IoT devices to share data, ensuring fair compensation based on each data set's contribution to model training quality.

Industrial IoT (IIoT): In IIoT, the security and accuracy of data transmission are crucial. To address the single point of failure in traditional centralized systems, Sohail et al. [33] proposed a Shapley value-based incentive distribution framework for secure data sharing using blockchain technology. The profit distribution is based on each data provider's contribution to the coalition, with data value determined by its uniqueness and quality. The framework fairly distributes incentives based on the data provider's contribution to the overall F1-score.

Bandwidth Allocation: Efficient resource utilization in dynamic IoT environments necessitates effective bandwidth allocation. Kim et al. [29] extended the concept of the SV to bandwidth allocation. This algorithm operates through a two-step process involving cooperative games both between Access Points (APs) and within APs. In the inter-APs game, the base station dynamically allocates available bandwidth among APs using an advanced SV method. This advanced SV incentive mechanism can not only ensure balanced performance but also enhance overall system resource utilization compared to existing schemes, demonstrating its efficiency in managing multimedia services in IoT environments.

IV. Stackelberg Game-Based Incentive Mechanism

A. Theoretical Foundation

The Stackelberg game is a classic two-stage dynamic game with complete information, describing sequential interactions between strategic players. In this model, the leader first chooses a strategy with full knowledge of the follower's decision criterion, and then the follower makes decisions based on the leader's strategy. This model is crucial in systems where rational participants optimize returns, inspiring the development of efficient and secure trading environments [34].

Combining blockchain with IoT opens new opportunities for applying the Stackelberg game in distributed settings. Scholars modeled incentive mechanisms based on this game to establish optimal strategies for devices with varying capabilities. The leader-follower dynamic provides a structured interaction framework, essential for fair and efficient resource allocation.

Furthermore, the Stackelberg game can adapt to multi-leader and multi-follower scenarios, capturing the complexities of IoT environments [35]. This adaptation allows for realistic modeling of interactions among devices with distinct objectives and constraints. With blockchain technology, interactions in these models can be transparently recorded and verified, ensuring the trustworthiness of rules and outcomes.

In conclusion, the Stackelberg game provides a robust framework for designing incentive mechanisms in IoT applications. By addressing traditional limitations of traditional models and leveraging blockchain, researchers can develop systems that enhance cooperation, optimize resource allocation, and ensure fair interactions among IoT devices.

B. Analysis Methods

When modeling the Stackelberg game, both parties' strategy and equilibrium are key aspects that need to be considered:

1) Strategy Function: The strategy function, usually expressed as $p_A(S)$, describes a rational player's action A towards the current situation S of the game. It is essential to analyze the actions that both parties will take in a given situation, which can usually be described as an optimization calculation to maximize utility under certain constraints. This involves designing the utility function, typically focusing on benefits minus costs, while considering other factors that influence decisions, such as time and distance.

2) Existence of Equilibrium: Stackelberg Equilibrium (SE) is defined as the following: Let $\mathbf{T}^*$ be a solution for P1 and $\mathbf{S}^*$ be a solution for P2. Then, $(\mathbf{S}^*, \mathbf{T}^*)$ denotes an SE for the game if for any $(\mathbf{S}, \mathbf{T})$, the following conditions are fulfilled:

$$U_{P1}(\mathbf{S}^*, \mathbf{T}^*) \geq U_{P1}(\mathbf{S}, \mathbf{T})$$
$$U_{P2}(\mathbf{S}^*, \mathbf{T}^*) \geq U_{P2}(\mathbf{S}, \mathbf{T})$$

If the equilibrium is reached. both the two rational parties will not move after then. Then the strategy can be further analyzed. Therefore, when establishing incentive mechanisms using the Stackelberg game, proving the existence of equilibrium is crucial. This is often done by designing effective algorithms or using mathematical tools to demonstrate the presence of Nash equilibrium. For example, Markov decision processes are used to observe the state changes over time, maintaining optimal decisions and establishing Nash equilibrium to ensure the interests of all parties in the supply chain [36].

3) Uniqueness of Equilibrium: Proving the uniqueness of Nash equilibrium often involves technical methods and efficient algorithm design. If the utility function is strictly concave, the NE problem can be transformed into a concave utility-maximizing problem and solved using first and second derivatives, yielding the unique solution [37]. Additionally, methods like Lagrange and Karush–Kuhn–Tucker conditions are commonly employed to solve Stackelberg equilibrium [38].

C. Application Scenarios in IoT

Supply Chain Management: In supply chain management, Stackelberg game effectively coordinates the decisions of various parties. The transparency provided by blockchain allows participants to make more accurate decisions, enhancing coordination efficiency [39]. Research has shown that blockchain possesses the necessary attributes to establish Nash equilibrium, applicable in coordinating complex supply chains to ensure security, trust, and profit. Game theory models have developed novel incentive methods that encourage participants in the supply chain to establish a more effective balance, reducing uncertainty across the entire supply chain by maximizing individual benefits. Blockchain's transparency helps organize information related to making effective decisions on the blockchain, relevant in complex supply chain networks like aircraft and automobile manufacturing and assembly networks.

Data Sharing in IIoT: In IIoT, the Stackelberg game model can set price strategies for data storage and transmission, incentivizing data owners to share data [40]. The data trading in IIoT is modeled as a multiple-leader and multiple-follower Stackelberg game. In the first stage, edge devices act as leaders and set data service task prices. In the second stage, data owners, as followers, decide the amount of data to store and transmit. Simulation results show that total revenue for edge devices increases by 59%, and utility for data owners increases by 52% compared to traditional schemes.

Edge Computing: IoT devices generate vast amounts of data, but a lack of trust among IoT entities and mistrust of data-sharing platforms can hinder data sharing. Blockchain's decentralization and transparency can effectively mitigate these challenges, facilitating data storage, acquisition, and exchange among IoT devices and platforms [38]. However, the mining process in blockchain demands significant computing power, which lightweight IoT devices frequently lack. Consequently, establishing a blockchain platform requires incentivizing IoT devices to procure computational resources from edge servers [17]. To encourage IoT devices to buy more computing resources, a Stackelberg game model-based incentive mechanism can be employed. In the first stage, edge servers or the blockchain platform, acting as the computing power providers, set rewards to motivate miners' participation in the mining process. The pricing strategy is determined by the services offered to miners. In the second stage, miners assess the optimal quantity of computational power to purchase based on the previously established price and rewards.

Mobile Crowdsensing: In mobile crowdsensing, the Stackelberg game-based incentive mechanism can effectively encourage a larger amount of end users to participate. Hu et al. [41] modeled a three-stage Stackelberg game, captured interactions between task initiators, participants, and base stations, and achieved automated task allocation and reward distribution. In the first stage, monthly-pay participants sign up for long-term engagement and receive monthly payments. In the second stage, task initiators select monthly-pay participants according to the requirements of the sensing tasks and determine rewards to hire additional instant-pay participants to complete the tasks. In the third stage, instant-pay participants decide the size of the sensory data they provide based on their utility. By structuring the game in this way, the model optimizes participation while balancing costs and benefits for each stakeholder. Furthermore, the hierarchical nature of the game ensures adaptability to varying task complexities and participant availability. Blockchain enables smart contracts to support the automation of sensing task allocation, task execution, and reward distribution, facilitating secure and efficient trading of massive IoT data from mobile end users.

Federated Learning in IoT: Federated Learning (FL) is a popular collaborative learning framework that significantly improves model performance without collecting raw data. To invite data owners to participate in FL, researchers have designed various incentive mechanisms. However, due to information asymmetry, uncertainties about data owners' reputation, computing power, and data volume present high costs and low efficiency in existing solutions. Chen et al. [42] proposed a multi-factor incentive mechanism for federated learning based on the Stackelberg game, combined with a reputation mechanism to enhance participation enthusiasm and data quality. In the first stage, the task publisher announces the task, and data owners determine the optimal training strategy, considering the model accuracy contributed by the data owner, under the condition that they know the reward received from the task publisher. In the second stage, all data owners try to determine a training strategy greater than the model accuracy in the first stage, thus receiving more rewards from the task publisher, forming a non-cooperative game.

V. Auction-Based Incentive Mechanism

A. Theoretical Formulation

An auction is a process of buying and selling goods or services, involving the offering of items for bid, waiting for the highest bid, and selling the item to the highest bidder under the supervision of an auctioneer. Due to its fairness, auction theory has become one of the most successful and active branches in the field of economics [43]. Incentives can increase participation and competition in auctions, leading to higher revenues for sellers and higher perceived value for buyers. Therefore, they are often used as incentive schemes to maximize objectives such as revenue, profit, or social welfare.

With the growing demand for data and transactions in IoT, more scholars are shifting their focus to this area. However, without an effective incentive strategy for participants, balancing interests between multiple parties is difficult. As a result, most IoT users are reluctant to share data or forward messages. Moreover, massive sensing data (such as locations) are vulnerable to personal privacy leakage, which hinders IoT users from joining the data-sharing market [44].

Traditional centralized auctions typically require a trusted third party to control the market, record transactions, and manage the entire auction process [45]. This model faces high costs due to commissions and significant potential risks from single-point attacks, where auctioneers may be malicious. To address these issues, many scholars have introduced blockchain technology, which offers decentralization, security, and trust advantages for resource transactions, such as energy, data, and computational resources. Specifically, smart contracts in blockchain can act as autonomous agents to enforce predefined rules (such as auction mechanisms) without any censorship or third-party interference. However, most blockchain platforms' smart contracts cannot support overly complex logic in predefined rules because each step consumes significant resources. Therefore, relatively simple auction-based incentive mechanisms have become a research focus and have demonstrated great potential in various experiments.

B. Analysis Method

Designing an auction mechanism based on blockchain can save the commissions of hiring a trusted third party. Instead, smart contracts can manage, execute, complete, and record transactions through predefined rules [46]. Incentives can be used in auctions to attract more bidders, increase competition, and enhance revenue. When simulating IoT application scenarios on blockchain using auctions, constructing an incentive mechanism typically needs to consider information symmetry and the dominance of auctioneers and bidders.

Commonly used auction approaches for blockchain-based incentive mechanisms include the following three models:

Double Auction: Double auction is a multi-item auction widely applied to deal with optimal allocation problems, featuring a many-to-many structure where sellers and buyers respectively submit their asks and bids [47].

Reverse Auction: Reverse auction is a buyer-side auction where the traditional relationship between buyers and sellers is reversed. Sellers compete to obtain business from the buyer, and prices usually decrease as sellers underbid each other, thus benefiting buyers by saving costs [48].

Hierarchical Auction: Hierarchical auction utilizes a hierarchical idea to solve complicated allocation issues. Hierarchical auctions address complex allocation issues by dividing them into multiple layers, each treated as a separate allocation problem where various auction methods can be applied [49].

Moreover, incentive mechanisms in IoT scenarios entail trade-offs requiring careful consideration by auctioneers and bidders. Auctioneers must consider various factors such as the type and value of IoT data services, the heterogeneity of participants, the form and rules of the auction, the cost and benefits of incentives, and other potential trade-offs. For example, providing discounts to winners can increase participation and competition but reduce profits. Offering rewards to non-winners can enhance satisfaction and retention but decrease the motivation of higher bidders and auction efficiency [50]. Addressing credit issues can ensure future benefits and honesty but may lead to lock-in effects and reduced competition [51]. Therefore, designing the optimal incentive scheme for IoT applications requires a deep understanding of the auction environment and participants' preferences, along with the ability to evaluate various scenarios and outcomes.

C. Application Scenarios in IoT

Edge Computing: A common challenge in IIoT is the limited computational capability of devices, where edge computing is a promising solution. In practice, edge resource allocation involves a multi-layer structure, posing challenges due to incomplete information between layers. To address this property, Ling et al. [12] proposed a hierarchical auction mechanism for edge computing in blockchain-empowered IoT. They conducted ascending clock auctions in both top-markets and sub-markets. Resource providers bid in the top-market, intermediaries purchase accordingly, and end users bid in the sub-market, ensuring fair and reasonable pricing.

Baranwal et al. [52] addressed the elimination of trusted third parties and tackled challenges such as IIoT device mobility, edge server heterogeneity, false guarantees, result latency, and server responsiveness. They introduced a decentralized auction-based resource allocation mechanism using consortium blockchain and smart contracts. Their system encourages truthful bidding from edge resource providers through incentives and calculates IIoT device satisfaction based on various quality parameters. The proposed mechanism ensures sealed bids, no bidder impersonation,and immutable auction results.

Data Sharing: Cai et al. [53] proposed a hierarchical data auction model implemented through smart contracts to maximize the overall social welfare of all participants. Data sharing among IoT devices is typically subjected to limitations caused by multi-layer communication networks. This mechanism designs a three-layer data auction model, including data agents and corresponding data allocation and pricing rules, and considers the impact of data transmission cost.

Electricity Trading: Han et al. [3] proposed a double incentive trading mechanism that combines blockchain and IoT technology, considering the external costs of producers and the efficiency of consumers in blockchain-based electricity trading. By combining these factors with bid prices, they obtain a priority value for transactions. Wang et al. [54] then proposed a decentralized electricity trading model for higher frequency demand based on blockchain and continuous double auction (CDA) mechanisms. Buyers and sellers first complete market matching, and due to frequent market price fluctuations, they adopt an adaptive aggressive strategy to adjust quotes timely according to market changes. CDA can quickly achieve market equilibrium, is suitable for the decentralized nature of microgrids, and does not require centralized control. It utilizes the dynamics of the free market to balance supply and demand and has relatively low computational costs.

Task Collaboration: Cheng et al. [50] proposed an auction-based incentive mechanism for task collaboration among IoT devices. A core feature of IoT applications is the ability to perform collaborative tasks using data from different IoT managers. However, the success of tasks relies heavily on the number of actively participating IoT managers. Managers who continuously fail to win bids might exit the auction, reducing overall effectiveness. To address this, Cheng et al. utilized a virtual credit mechanism to compensate managers who failed in previous auctions and introduced a dropout recruitment plan to attract them back. This approach ensures sufficient participation and prevents incentive cost explosions.

Crowdsourcing: Liang et al. [51] proposed a grade-based task sorting (GTS) algorithm to determine the service priority of heterogeneous crowdsourcers to motivate their cooperative behavior. Workers submit bids for interested subtasks and pay deposits to suppress malicious bidding. Miners verify bids and deposit transactions and select workers for each subtask based on crowdsourcers' requirements and platform goals. Selected workers perform their assigned subtasks. Miners verify task completion and update the grade values for each system entity. Miners calculate payments to selected workers according to the payment structure designed by the system designer and receive rewards from crowdsourcing. Finally, miners return deposits to crowdsourcers after deducting their payments.

VI. Vision

Blockchain technology enhances transparency and security by eliminating centralized intermediaries, which is vital for the decentralized IoT architecture. It enables secure data exchanges among IoT devices from various service providers. Smart contracts automate incentives, ensuring fair resource distribution while lowering operational costs. Furthermore, blockchain's immutability secures the authenticity of IoT transactions and data, critical for smart cities and IIoT applications. This section examines the future potential of blockchain-based incentive mechanisms in IoT, comparing and emphasizing their advantages and applications.

A. Evaluation of Shapley Value-Based Mechanisms

Advantages: The Shapley value provides a fair method of profit distribution, suitable for scenarios where multiple IoT devices collaborate to complete tasks. The Shapley value-based incentive mechanism is highly effective in distributing rewards based on contributions, which incentivizes active participation and improves the quality and efficiency of task completion, especially when the parties are in cooperation.

Challenges: Calculating the Shapley value is usually computationally intensive, especially when a large number of IoT devices are involved. Assessing the contribution of each device becomes more difficult, making this incentive mechanism less suitable for scenarios with many participants. Additionally, accurately evaluating each IoT device's contribution is challenging. If the evaluation is not comprehensive enough, the actual contribution and the calculated Shapley value may not align, which even discourages device participation.

Future Development: Distributed computing and optimization algorithms can reduce computational complexity. Introducing more precise contribution assessment methods can enhance the effectiveness of Shapley value mechanisms in IoT.

B. Evaluation of Stackelberg Game-Based Mechanisms

Advantages: Stackelberg game models can simulate dynamic interactions among IoT devices, considering the diverse interests of buyers, sellers, and multiple parties. This approach optimizes by modeling complex scenarios from each party's perspective and the leader-follower structure effectively coordinates device interactions, reflecting IoT transactions.

Challenges: Designing high-precision game models and strategies is complex and requires a deep understanding of behaviors of all the participants. Accurately predicting complex decisions is challenging, and models often assume complete information, which may not be achievable in all scenarios. Additionally, traditional Stackelberg game models rarely consider the reputation issues of IoT devices, reducing their effectiveness in addressing the free rider problem [55].

Future Development: Incorporating reputation management is essential to enhance system trust and cooperation, particularly to address the bad point problem. Integrating this with blockchain technology can record and verify participants' behaviors, ensuring transparency and reliability. Additionally, incorporating machine learning and artificial intelligence can optimize game strategies and decision-making processes.

C. Evaluation of Auction-Based Mechanisms

Advantages: Auction mechanisms, through the choice of auction methods, processes, and leading parties, can increase the revenue of buyers and sellers. Among all the auction mechanisms, reverse auctions, double auctions, and hierarchical auctions are widely used for IoT applications, exhibiting high flexibility and efficiency in resource allocation and IoT data transactions, with each process favoring different parties.

Challenges: Auction mechanisms may lead to speculative behaviors, affecting system stability, and may result in cost escalation issues [56]. Participants who frequently lose may give up cooperation, and those who exit weaken price competition, leading to increased incentive costs, as remaining managers may raise their bids to earn more profits. Therefore, designing effective auction mechanisms requires considering multiple factors and choosing different auction methods based on specific scenarios. Currently, most blockchain platforms' smart contracts cannot support overly complex logic for predefined rules, as each step consumes significant resources.

Future Development: Future Development: Integrating blockchain technology can enhance the efficiency and security of auction mechanisms by ensuring transaction transparency and credibility. Two fundamental components in the integration of blockchain and IoT are the consensus mechanism and the incentive structure [57]. With well-designed smart contracts, blockchain-based incentive models can automate the auction process, reducing human intervention and enhancing transaction efficiency and fairness. This automation can lead to more reliable and tamper-proof transactions, promoting wider adoption and trust in IoT ecosystems. Furthermore, continuous advancements in blockchain scalability and security can further optimize these mechanisms, making them more robust and adaptable to various IoT applications.

D. Comparative Analysis of Incentive Mechanisms

Advantages: Each mechanism offers unique strengths tailored to specific IoT applications. SV-based mechanisms prioritize fairness, ideal for collaborative environments where contribution-based rewards are essential. Stackelberg game-based mechanisms are best suited for structured IoT systems with hierarchical dynamics, leveraging the leader-follower paradigm for optimized decisions. Auction-based mechanisms, by contrast, offer high flexibility and efficiency, making them advantageous in competitive resource allocation scenarios.

Challenges: Despite their advantages, each mechanism faces unique challenges. Shapley value-based mechanisms are computationally intensive, especially when dealing with large-scale IoT networks. Stackelberg game-based models require intricate design and precise behavioral assumptions, making them difficult to implement in real-world scenarios with incomplete information. Auction-based mechanisms, while efficient, can lead to speculative behaviors, which may reduce system stability and increase operational costs.

Future Development: The future potential of these mechanisms depends on technological advances. SV-based mechanisms can achieve better scalability through distributed computing and refined contribution assessment. For Stackelberg game-based mechanisms, incorporating reputation and AI-driven optimization introduces more robustness. Auction-based mechanisms can benefit from blockchain integration, using smart contracts to enforce rules and enable automated, transparent, and secure transactions.

VII. Conclusion

In this survey, we explored the application and potential of blockchain-based incentive mechanisms in the Internet of Things. We categorized these mechanisms into three main types: Shapley value-based, Stackelberg game-based, and auction-based. Each type's theoretical foundations, modeling processes, and current IoT applications were summarized. We highlighted how these mechanisms can transform IoT applications by fostering greater collaboration and enabling more secure and efficient systems. With ongoing development and refinement, these mechanisms are poised to realize their full potential across diverse IoT scenarios, driving innovation and enhancing the functionality of IoT ecosystems.

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