Decentralized On-Demand Energy Supply for Blockchain in Internet of Things: A Microgrids Approach

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***Abstract*— Currently, blockchain technology has been widely used due to its support of transaction trust and security in next generation society. Using Internet of Things (IoT) to mine makes blockchain more ubiquitous and decentralized, which has become a main development trend of blockchain. However, the limited resources of existing IoT cannot satisfy the high requirements of on-demand energy consumption in the mining process through a decentralized way. To address this, we propose a decentralized on-demand energy supply approach based on microgrids to provide decentralized on-demand energy for mining in IoT devices. First, energy supply architecture is proposed to satisfy different energy demands of miners in response to different consensus protocols. Then, we formulate the energy allocation as a Stackelberg game and adapt backward induction to achieve an optimal profit strategy for both microgrids and miners in IoT. The simulation results show the fairness and incentive of the proposed approach.**

***Index Terms*— Blockchain, energy supply, Internet of Things (IoT), microgrids, next generation society.**

I. Introduction

As a new form of distributed peer-to-peer encryption storage application, blockchain [1] is considered as a subversive innovation of computing models causing global new technological innovations and industrial changes [2]. Satoshi Nakamoto proposed blockchain in the groundbreaking paper "Bitcoin, a Peer-to-Peer Electronic Cash System" published in 2008 [3]. Blockchain is a distributed ledger maintained by network-wide nodes [4]. Due to its ability to solve transaction trust and security, blockchain can be used to record transactions, data, medical records, and identity management, i.e., It has been widely used in the logistics industry, smart healthcare, smart home, real estate, and insurance industry fields [5]. The consensus mechanism of the blockchain enables mutual trust between nodes. For example, the consensus mechanism most commonly used in blockchains is Proof-of-work (PoW) [6], which has become the mainstream approach in cryptocurrency, such as Bitcoin and Ethereum [7]. With high security, PoW consumes lots of power for computation. Although many other consensus protocols have been proposed to reduce PoW's energy consumption, most of them are still based on PoW's hybrid consensus mechanism, which requires the calculation of a puzzle and consumes the corresponding energy.

With the development of Internet-of-Things(IoT) [8], mobile transactions in next generation society have continued to grow globally in recent years [9]. Due to the ability to solve transaction trust, blockchain has become a new approach to ensure security [10]. Blockchain in IoT increases the scalability of blockchain in decentralized wireless networks [11]. While the computational performance of mobile devices improves, the applicability of blockchain technology for smart IoT applications, such as smart homes and smart factories, for example, has become the trend of the blockchain research. As a new research topic of blockchain, there have been many mobile blockchain-related practical implementations. FiiiLab proposed the first mobile blockchain token FiiiCoin powered by its own consensus mechanism delegate proof of capacity (DPoC) in 2018. Supported by the mobile payment POS terminal FiiiPOS, FiiiCoin can be mined by IoT devices such as mobile phones [12]. IFMChain is the third generation of mobile public chain product proposed by Instinct Company, which is the first mobile blockchain that supports access to mobile devices [13]. Besides, there have been some mobile blockchain APP projects. For instance, Phoneum is a mobile-only cryptocurrency, which enables all mobile users to participate in the economy based on the blockchain [14]. Recently, Bitmain also announced that they would launch a new mobile mining pool ANTBOX.

However, the computation and power consumption of IoT devices are important challenges restricting the application of blockchain. At present, some studies have introduced mobile edge computing (MEC) for challenging computational tasks. MEC migrates storage and computing processes from the cloud to the edge of the network [15]. Computing and data storage can be distributed to the edge near IoT terminals,

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sensors, and users, which eases the computational requirements while optimizing the network service architecture [16]. However, the energy consumption challenge of blockchain in IoT still exists.

With the development of blockchain, the consumption of electricity is currently increasing. For example, it is estimated that the global electricity consumption of Bitcoin is increasing by about 1–32 TWh per year, while 32 TWh is equivalent to the annual electricity consumption of Denmark. New studies are starting to use proof of stake (PoS) [17] and proof of activity (PoA) [18], which are more energy efficient and can be a viable alternative to the extended blockchain.

Most of the energy currently used for mining comes from centralized environment-unfriendly fossil fuels [19]. In order to satisfy the distributed needs of mining and reduce the impact on the environment, decentralized renewable energy is also needed as a means of powering the mobile blockchain. The mobile blockchain has a strong geographical distribution while having a large demand for energy. Here, the microgrids can realize the large-scale application of distributed renewable power and achieve a stable supply of multiple energy sources. Microgrids have the potential to realize a distributed efficient power supply for IoT-based blockchain using renewable energy.

In response to these aspects, we propose a decentralized on-demand energy supply approach based on microgrids to provide decentralized on-demand energy for mining in IoT devices. The microgrids can realize the unified deployment and allocation of distributed renewable energy to miners in IoT. On the one hand, users (miners) receive rewards through mining a new block and purchase energy from the microgrids. The microgrids perform real-time scheduling and decision-making according to the user's energy consumption to ensure that the system benefits and maximizes smooth operation. The contributions of this paper are summarized as follows.

1) We propose a decentralized on-demand energy supply approach based on microgrids to provide decentralized on-demand energy for mining in IoT devices. The energy supply includes an interaction process and a game process. The microgrids perform real-time scheduling and decision-making according to the miner's energy consumption to ensure that the system benefits and maximizes smooth operation. The energy supply architecture satisfies different energy demands of miners in response to different consensus protocols. To the best of our knowledge, the problem of powering blockchain devices in mobile IoT environments has barely been studied in previous studies.
2) We model the energy allocation as a Stackelberg game between microgrids and miners in IoT. We apply backward induction to achieve optimal profit strategy for both of them. The simulation results show the fairness and incentive of the proposed approach.

The rest of this paper is organized as follows. Section II discusses the related works. Section III discusses the architectural principles of the system and describes the system architecture of the energy supply for blockchain in IoT based on the microgrids. Section IV introduces the energy allocation using a Stackelberg game model. We evaluate the performance of our proposed strategy in Section V. Eventually, we draw some conclusions in Section VI. Besides, we propose the direction of work that can be studied in the future.

II. Related Works

There have been many studies that concentrate on addressing the high-energy consuming challenge caused by PoW [20]. Some researchers have modified the PoW algorithm or combined it with PoS. UnitedBitcoin [21] implements a hybrid consensus protocol that is split between PoW and PoS. In UnitedBitcoin, on average, 50% blocks will be mined by PoS, and 50% blocks will be mined by PoW. PPCoin [22], which was officially released by Sunny King on August 19, 2012, is a combination of two types of proof. PoW-based mining is used in the early stage to ensure fairness. The PoS protocol is adopted in the later stage to ensure network security. PoA also combines PoS with PoW [18]. The node must have a known and authenticated identity, and the node obtains the right to secure the network by placing this identity and, finally, gets the block reward. Research in [23] proposes a blockchain-based architecture to provide secure data record in the cloud environment that uses the PoS protocol. Xue *et al.* [24] propose proof of contribution (PoC), which reduces electricity consumption by effectively rewarding the daily labor contributions of all community miners. Ethereum released the Casper implementation specification in April 2018 [25], which is a hybrid consensus protocol as a transition from PoW to POS.

With the development of IoT [26], mobile blockchain becomes a new research topic in the field [27]. Luong *et al.* [28] consider computing off-loading in mobile blockchain by two off-loading approaches, off-loaded to the nearby MEC nodes or mobile users. Research in [29] considers the same problem by a social welfare maximization problem. They discuss the pricing problem by modeling an auction-based market model, which includes miners, blockchain owner, and MEC providers. Li *et al.* [30] propose a computing resource management approach of mobile blockchain by formulating a Stackelberg game to guarantee the benefit of miners and edge service provider. Liu *et al.* [31] consider mobile video streaming scenario based on MEC-enabled mobile blockchain. These studies all concentrate on the computing resource management of blockchain in IoT but ignore the energy consumption of mobile blockchain [32].

Blockchain could be a secure transaction guarantee of the microgrids. Based on the blockchain, smart contracts that control energy consumption and power generation have the potential to support all types of existing energy and new energy markets [33]. Di Silvestre *et al.* [34] consider some technical approach to solve the transaction of energy in microgrids using the blockchain. They implement blockchain to establish a trust system between consumers. The proposal in [35] tries to achieve proportional-fairness control of distributed energy in microgrids by a smart contract based on the blockchain. Liu *et al.* [36] propose data coins and energy coins for blockchain to realize multiple transactions in the electronic vehicular environment. The blockchain is

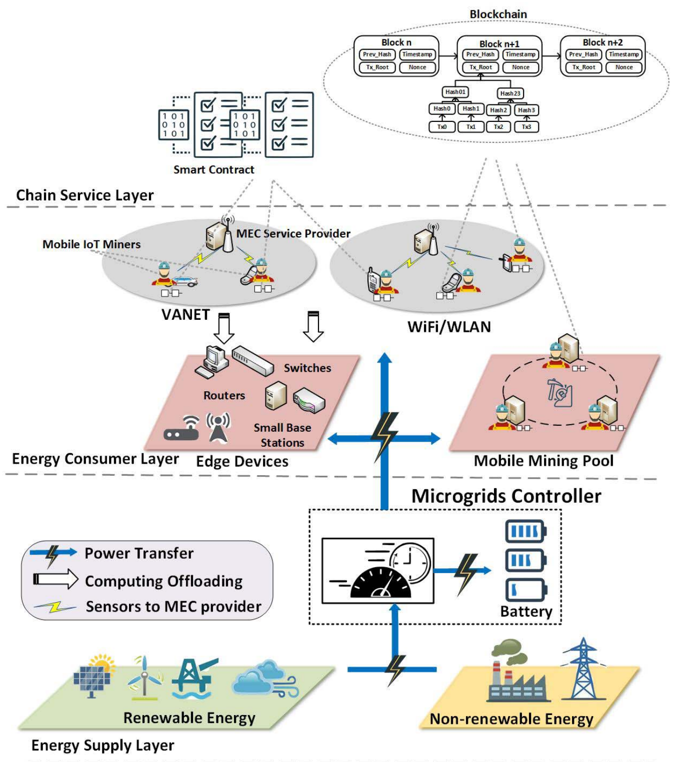

Fig. 1. Architecture of the proposed system.

implemented to store smart contracts that achieve proportional fairness. However, all these studies about blockchain and microgrids concentrate on how to use blockchain to ensure secure transactions in the microgrids but no research proposes how to use microgrids to provide energy for blockchain.

In this paper, we propose a decentralized on-demand energy supply approach based on the microgrids to provide decentralized on-demand energy for mining in IoT devices. The strengths of this system contain these two aspects: first, our proposal provides efficient decentralized environment-friendly energy for IoT-blockchain. Second, our proposal formulates the game between miners in IoT and the microgrids. We realize the equilibrium of the game and maximize the benefits.

III. Proposal of System Architecture

We propose the new system architecture in this section, as shown in Fig. 1. First, we introduce the architectural principles of energy supply architecture for blockchain in IoT based on the microgrids. We propose our system according to these principles. In Section III-B, we give an overview of our architecture. Then, we provide the details of the components of these two subsystems: microgrids and blockchain in IoT.

A. Architectural Principles

1) Stochasticity: Both microgrids and IoT-blockchain behave randomly. Distributed energy as the unstable energy supply is related to regional environments, such as wind power, hydropower, and solar power. On the other hand, the mobility of IoT devices leads to load instability. Blockchain miners using IoT devices can make energy requests to different microgrids. This causes the load request in the system to be unstable. The supply and the load instability require dynamic feedback and real-time deployment of the system.

2) Multi-Energy Supply and Storage: IoT-blockchain requires stable and continuous energy to support computing. Due to the instability of distributed energy, it is necessary for the system to design a hybrid energy source to ensure stable and continuous power to support mining for blockchain. Microgrids need to integrate distributed energy from different sources. Besides, the subsystem requires traditional fossil energy generation as an aid or alternate. Renewable energy is mixed with non-renewable energy to provide energy to the system. Due to load instability, excess energy needs to be stored in the battery. Due to the extra cost of storing energy, microgrids may require a higher price to get the same amount of resources. Energy, communication costs, and tokens in blockchain systems may serve as a means of closed-loop circulation.

3) Multi Processing Modes and Consensus Protocols: Considering the computing power of the devices and the environment in which they are located, for IoT-blockchain miners, there exist two modes of processing. In mode 1, miners use IoT devices to perform computing tasks locally when the following conditions hold: 1) mining IoT equipment in smart homes can be easily recharged and 2) there are no mobile edge service providers available near the IoT-blockchain devices. On the other hand, in mode 2, miners off-load the computing tasks to nearby MEC providers. The MEC providers accept a range of mobile IoT devices and provide computing power to solve mathematical calculations for miners. The blockchain relies on consensus protocols to build a trust network. Most of the consensus protocols, now, proposed are based on PoW's hybrid protocols, which have basic demands for power. Different consensus protocols have different energy demands.

4) Game Between Service Provider and Multi-Miners With Limited Energy: When energy is limited, there is a competition between multiple miners who purchase energy from the microgrids. Multiple users will offer different prices to the microgrids to purchase energy. The benefit of the miners is related to the rewards for mining and the cost of purchasing energy. A game is formulated between multiple users in the restricted environment. The goal of the game is to maximize the income of everyone. In this case, the system should consider multiple factors to balance this game. The benefits of the microgrids are determined by the cost and the price paid by the miners. The cost of the microgrids includes transmission costs, repair costs, and power facility protection fees, which consists of three main components: power generation costs, power supply costs, and electricity sales costs. There are cooperation and interest interaction between the microgrids and the miners. The user's goal is to maximize the profit from mining. From the perspective of energy providers, they focus on how to determine energy distribution to maximize their own interests. The system should obtain a balance among members of different roles.

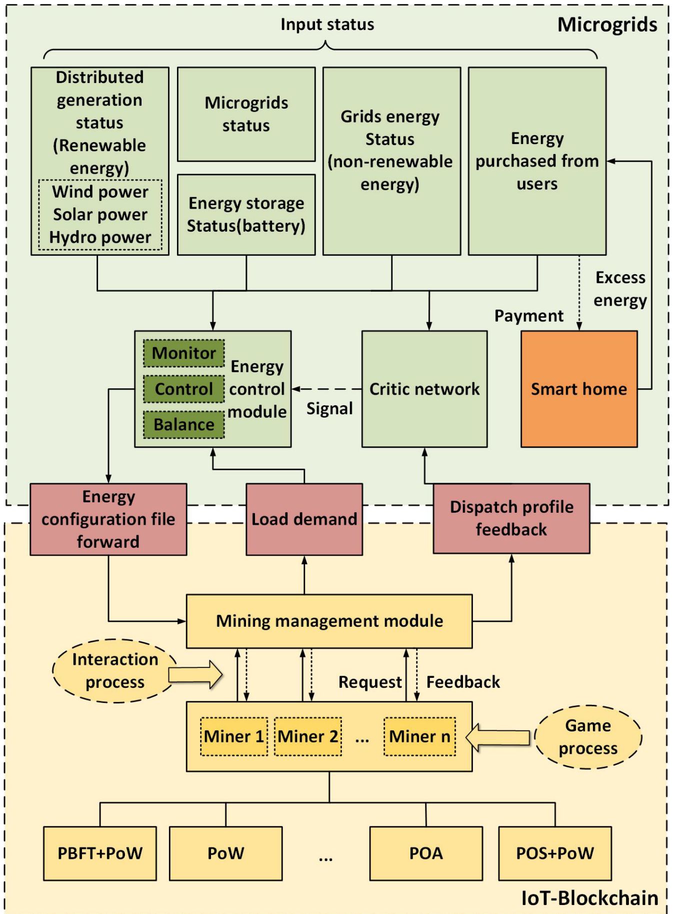

Fig. 2. Microgrids-based energy supply for miners in IoT.

B. Microgrids-Based Energy Supply

In this section, we first propose an overview of our system architecture. Then, we introduce the details of each part of the architecture.

We propose a decentralized on-demand energy supply approach based on the microgrids, as shown in Fig. 2. The goal of this system is to achieve decentralized management of distributed renewable energy through microgrids in order to provide a stable and efficient environment-friendly energy supply for blockchain applications on geographically distributed IoT devices. The microgrids integrate, store, and manage geographically concentrated distributed energy, providing environment-friendly energy for mining in IoT devices. Blockchain applications deployed in IoT devices compete by mining and probabilistically acquire rewards. The miners selectively adjust the demand for energy to the microgrids. There are two subsystems in our proposed architecture.

The goal of the microgrids is to dynamically provide a stable output of energy. There have been many studies on microgrid adaptive dynamic energy management systems. We apply a smart microgrid energy management system using adaptive dynamic programming (ADP) [37]. Through such an energy management strategy, we can improve the reliability and stability of the system, reduce the cost of power generation, and extend the life of the system. This system includes two networks: the critic network and the action network. The action network (energy control module) achieves the approximate optimal strategy of microgrids. The critical network provides dynamic performance feedback to the action network in order to achieve the target state, which is one of the inputs of the action network. Other inputs of the action network include three parts: energy status, microgrids status, and load demand status. Load demand status refers to the current demand of the load. Energy status consists of four parts. The main source of energy is distributed energy, which means that renewable energy includes hydropower, wind power, and solar power, i.e., besides, non-renewable energy (fossil energy) is needed as an alternative energy source. In addition, the system also requires an energy storage device such as a battery. Users in IoT, such as smart homes, can sell excess power from self-generation to the microgrids, which is another source of energy of microgrids. From the above-mentioned considerations, the energy source of the microgrids has four main parts: distributed generation (renewable energy), energy storage, grids energy (non-renewable energy), and energy purchased from users. The details of these components are presented in the following part.

1) *Distributed Generation (Renewable Energy):* Distributed energy sources include a mix of multiple renewable energy sources. Energy status, such as hydropower, wind power, and solar power, is one of the inputs to smart microgrids scheduling.
2) *Energy Storage:* In order to ensure a stable output of the microgrids, we need to set up energy storage devices. Due to the instability of distributed renewable energy and IoT-blockchain miners, the energy storage device acts as a battery to replenish and assist the microgrids. The battery stores excess power when the distributed energy supply is sufficient or when the number of miners in the area is small. In order to facilitate the scheduling of battery energy, the energy storage state is also an input to the intelligent microgrids energy dynamic scheduling strategy. In order to extend the battery life, the system minimizes that the number of times the battery is charged/discharged and extends the single charge and discharge time.
3) *Grids Energy (Non-Renewable Energy):* In order to prevent power outages and insufficient resources, the system needs fossil energy as an energy aid. To maximize the use of distributed energy and the minimal use of fossil energy, the energy status of grid energy is used as an input to the microgrids dynamic energy management strategy.
4) *Energy Purchased From Users:* Blockchain guarantees point-to-point power trading in the microgrids. IoT users such as smart homes may be able to generate electricity to satisfy their power needs and sell excess power to the microgrids. The microgrids purchase electricity at an appropriate price and store it in the energy storage devices as one of the sources of energy.

Inputs of the critic network include two parts: input status and dispatch feedback. Input status consists of energy status, microgrids status, and load demand status. Dispatch feedback of the system refers to the output energy of microgrids. The critic network helps the action network to improve performance and achieve optimal dynamic planning strategies. The energy control module controls and adjusts the energy in the microgrids dynamically based on the input and feedback signals from the critic network.

In the mining management module, there exist two processes. In the interactive process, miners who need energy send energy requests to the surrounding microgrids. The microgrids make decisions based on the system energy status and the load status and give feedback to the miners. Then, in the game process, the energy and payment interactions between the miners in IoT and the microgrids are realized.

The existing consensus protocols have different energy requirements, and we satisfy the energy demand of different consensus protocols. We maximize the use of energy through the benefit game among different miners. For instance, under the hybrid consensus protocol of PoS and PoW, each miner has a certain probability to be selected as the miner of the next excavation block. When a miner who needs energy sends a request to the microgrids, the mining management module would make decisions whether it allows the system to provide energy for the miner according to the system energy status and load demand. Then, the mining management module would send feedback to the miner. Miners who are permitted to be powered by the microgrids have different energy demands. Therefore, each miner has a different energy demand for the microgrids. Each member will propose an energy unit price according to different needs. Members earn different profits due to different incomes and expenses. The system, therefore, needs to provide a strategy to achieve energy distribution in a profitable situation. In Section IV, we propose the game between the members in IoT and the energy provider.

In order to implement a dynamic energy management strategy, the microgrids require the load demand for IoT devices and dispatch profiles as complementary inputs to the system. On the other hand, the microgrids need to provide energy configuration components to help the system to achieve energy allocation for members. The purpose of the collaboration between two subsystems is to maximize the benefits of the system-wide role while providing a stable and reliable energy input for mobile blockchain miners.

IV. Model and Problem Formulation

A. Game Model

In our game model, we consider mobile blockchain in IoT devices using PoW consensus, which is supported by the microgrids with renewable energy. There are three entities in the system: blockchain miners, MEC providers, and microgrids. Mobile blockchain miners in IoT devices put the transaction records into a block and calculate a puzzle to obtain the right of a new block. Miners could earn tokens by producing new blocks. The power consumed by miners per unit time is related to the proportion of the calculated power. Limited to the computing capacity, miners off-load the computation task to nearby MEC providers that are located geographically. MEC providers calculate the hash value for miners. The process

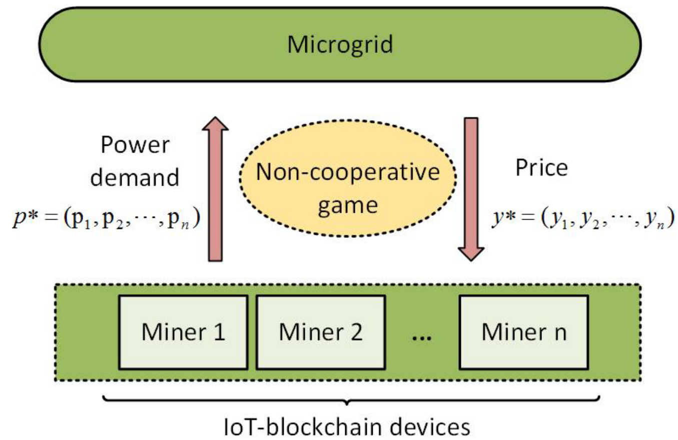

Fig. 3. Game model between miners and microgrids.

of computing has a large demand for energy. To meet the requirement, miners purchase energy from the microgrids for MEC providers. The price of electricity purchased is proposed by microgrids. Besides, microgrids operation requires a lot of costs, including power generation costs and maintenance costs, i.e., we finally consider the behavior of two entities in the system model: miners and microgrids. In our model, miners include IoT-device users and MEC. MEC that off-loaded computing tasks can be regarded as a miner who owns higher computing capacity. Meanwhile, MEC has a demand for energy powered by the microgrids. Therefore, the model in this paper only considers two players—miners and microgrids.

B. Problem Formulation

In the system model, the mobile blockchain miners using IoT devices to record transactions and achieve the mining process are represented as a set of nodes $\mathbb{B}$, which are denoted as $\mathbb{N} = \{1, 2, \cdots, n\}$. The profit of miners is determined by two factors: 1) reward, which is given by distributing the block producing process, and 2) payment, which is the price paid to the microgrids for the electricity needed for mining. The amount of electricity required by each user is different, and the price of electricity proposed by the microgrids is different. Therefore, there is a non-cooperative game between the users' benefits, and the user dynamically adjusts the requested electricity to maximize the self-revenue. For the microgrid, it focuses on the comprehensive pricing strategies of different users to maximize benefits. To solve the problem, we consider the interaction between the microgrid and the mobile IoT-blockchain miners as a Stackelberg game. The microgrid could be considered as a leader in the game who proposes a non-uniform pricing strategy for different miners. Miners could be considered as followers who decide their demand for electricity according to the price. Therefore, we consider our game model as $\mathbb{G} = \{S^B_{B_i \in B}, S_M; U^B_{B_i \in B}, U_M\}$, which is described in the following.

1) $S^B_{B_i \in B}$is the strategy space of miners $\mathbb{B}$, which is defined as the energy demand on miners. Let $\mathbb{P} = \{p_1, p_2, \ldots p_n, i \in N\}$ denote the energy that each

miner would purchase from the microgrids. We have $S^B_{B_i \in B} = \{p_i, i \in N, p_{\min} \le p_i \le p_{\max}\}$. S_M is the strategy of microgrids, which is the proposed price to each miner. The strategy space is defined as $S_M = \{y_i, i \in N, 0 \le y_i \le y_{\max}\}$.

2) $U^B_{B_i \in B}$is the utility function of miners $\mathbb{B}$, which is determined by a reward of producing a new block and energy cost. U_M is the utility function of microgrids, which is determined by electricity fee and operating cost.

The objective function of miner's sub-game can be described as follows:

$$\max_{p_i} \; U_{B_i}(p_i)$$
$$s.t. p \;\in [p_{\min}, p_{\max}]. \tag{1}$$

We represent $y* = (y_1, y_2, \ldots, y_n)$ and $p* = (p_1, p_2, \ldots, p_n)$. Then, the objective function of microgrid's sub-game can be described as follows:

$$\max_{y^*} \; U_M(y^*, p^*)$$
$$s.t. y \;\in [0, y_{\max}]. \tag{2}$$

These two sub-games consist of the Stackelberg game.

C. Utility Function Formulation

In the model, we consider that the device is installed in a CPU. The amount of electricity consumed by a device is related to the frequency of the CPU, which refers to the CPU clock cycle, which is the number of operations per second. The energy consumption relationship is shown as follows [38]:

$$\mathrm{P} = CV^2 f. \tag{3}$$

Here, P represents energy consumption. C can be simply regarded as a constant, which is determined by factors such as the process. V is the voltage, while f defines the main frequency of the CPU. Frequency is positively correlated with computational power, which is denoted as w. In the blockchain, the computation power refers to the hash frequency, which is the number of times a hash can be calculated per second. In our model, we assume that the frequency is linearly related to the computational power as the following equation presented [39]:

$$f = h \times w. \tag{4}$$

By substituting (4) into (3), we have the relationship between the energy demand and computation power that is $P = Kw$, where $K = hCV^2$.

The relative energy demand of miner i is denoted as $\eta = (p_i/(\sum_{j \in N} p_j))$, which is linearly related to the relative demand of computation power. The process of successfully mining a new block follows the Poisson distribution. Therefore, the probability of successfully appending a new block and obtaining the tokens is determined by

$$\Pr_i = \eta e^{-\lambda z t_i} \tag{5}$$

where z is a constant determined by a delay factor. t_i is the size of blocks, which means the number of transactions included in the new block.

The miners' benefit consists of tokens and transaction fees from mining. The current transaction fee represents less than 5% of the revenue. Thus, in the model, we only consider tokens. Let T denote the tokens that a miner could win by mining a new block successfully. We can define the utility function of miners as follows:

$$U_{B_i}(p_i) = T \frac{p_i}{\sum_{j \in N} p_j} e^{-\lambda z t_i} - y_i p_i. \tag{6}$$

The profit of microgrids is determined by electricity fee and operating cost. Costs can be classified into fixed costs, variable costs, semi-fixed costs, and semi-variable costs depending on their nature. Final costs can be classified into fixed costs a and variable costs by. According to the production cost of the classical production function, when the output exceeds a certain relevant range, the unit cost of the cost function and the unit variable cost nonlinearly change. Therefore, we can assume a quadratic cost function for microgrids in our model. a, b, and c can be seen as cost-related constants. Thus, we can define the utility function of microgrids as the following function:

$$U_M = \sum_{i \in N} y_i p_i - \left[a\left(\sum p_i\right)^2 + b \sum p_i + c \right]. \tag{7}$$

V. Game Equilibrium of Miners and Microgrids

In Section IV, we form the Stackelberg game with two sub-games. In this section, we analyze the Nash equilibrium of the game. Under the premise of roughly predicting the energy demand of miners, the microgrid provides electricity price strategies for different users. The miners observe the electricity price strategy to dynamically adjust their own needs and maximize their own interests. We adopt the backward induction approach to find the demand equilibrium of the miners' sub-game and, thus, get the Nash equilibrium of the whole system game.

A. Miner's Energy Demand Sub-Game

Definition 1: In the game $\mathbb{G} = \{S^B_{B_i \in B}; U^B_{B_i \in B}\}$, $S^B_{B_i \in B} = \{p_i, i \in N, p_{\min} \le p_i \le p_{\max}\}$ is the strategy space of miners B, which is defined as the energy demand of miners. The energy demand set of miners $\mathbf{p}^* = (p_1, p_2, \cdots, p_n)$ is the Nash equilibrium of the game if the strategy S_{B_i} of miner i is the best response to the strategy of other miners $(S_{B_1}, \cdots, S_{B_{i-1}}, S_{B_{i+1}}, \cdots S_{B_n})$, which means that for every miner $i \in N$, $p_i \in [p_{\min}, p_{\max}]$, $U_i(p_i, P_{-i}, \mathbf{y}^*) \ge U_i(p_{ij}, P_{-i}, \mathbf{y}^*)$, where P_{-j} is the demand strategy of miners excluding p_i.

Theorem 1: A Nash equilibrium exists in $\mathbb{G} = \{S^B_{B_i \in B}; U^B_{B_i \in B}\}$.

Proof: p_i is continuous in $[p_{\min}, p_{\max}]$. Then, we find the first derivative and the second derivative for the utility function with respect to p_i as the following:

$$\frac{\partial u_i}{\partial p_i} = \frac{T e^{-\lambda z t_i} \sum_{i \neq j} p_i}{\left(\sum_N p_i\right)^2} - y_i \tag{8}$$

$$\frac{\partial u_i^2}{\partial^2 p_i} = \frac{-2Te^{-\lambda z t_i}\sum\limits_{i\neq j} p_j}{\left(\sum\limits_N p_j\right)^3} < 0. \tag{9}$$

Thus, $U_i(p_i, P_{-i}, \mathbf{y}^*)$ is a strictly concave function with respect to p_i. A Nash equilibrium exists in the sub-game $\mathbb{G} = \{S^B_{B_i\in B}; U^B_{B_i\in B}\}$, $S^B_{B_i\in B} = \{p_i, i\in N, p_{\min}\le p_i \le p_{\max}\}$. The proof is completed. Therefore, for any miner $i\in N$, the model can find the best profit strategy, and the best strategy is unique when $p_i \in [p_{\min}, p_{\max}]$.

Theorem 2: The Nash equilibrium in $\mathbb{G} = \{S^B_{B_i\in B}; U^B_{B_i\in B}\}$, $S^B_{B_i\in B} = \{p_i, i\in N, p_{\min}\le p_i\le p_{\max}\}$ is unique.

By solving $((\partial u_i 0/(\partial p_i)) = ((Te^{-\lambda z t_i}\sum\limits_{i\neq j} p_i)/((\sum\limits_N p_i)^2)) - y_i = 0$, we have

$$p_i = \sqrt{\frac{T\sum\limits_{i\neq j} p_j e^{-\lambda z t_i}}{y_i}} - \sum_{i\neq j} p_j$$
$$p_i \in [p_{\min}, p_{\max}]. \tag{10}$$

When the following condition holds:

$$Te^{-\lambda z t_i} > y_i \sum_{i\neq j} p_j. \tag{11}$$

If $Te^{-\lambda z t_i} < y_i \sum\limits_{i\neq j} p_j$, we assume that the demand of miner i is zero, which means that the microgrid would not offer energy for miner i. If $p_i \le p_{\min}$, we set that the demand of miner i is the same as $p_{\min}$, while $p_i \ge p_{\max}$,we set that the demand of miner i is the same as $p_{\max}$.

According to (8), after mathematical deduction, we have the following expression:

$$\sum_N p_j = \frac{N-1}{\sum\limits_N \frac{y_i}{Te^{-\lambda z t_i}}}. \tag{12}$$

Substituting (12) into (10) and mathematically deriving the deformation, we have

$$p_i^* = \frac{N-1}{\sum\limits_N \frac{y_i}{Te^{-\lambda z t_i}}} - \left(\frac{N-1}{\sum\limits_N \frac{y_i}{Te^{-\lambda z t_i}}}\right)^2 \frac{y_i}{Te^{-\lambda z t_i}}. \tag{13}$$

Thus, we can obtain the Nash equilibrium of miner's sub-game $\mathbb{G} = \{S^B_{B_i\in B}; U^B_{B_i\in B}\}$, $S^B_{B_i\in B} = \{p_i, i\in N, p_{\min}\le p_i\le p_{\max}\}$.According to (13), we can obtain a set of dynamic demand strategies of miners. Then, in Section V-B, we would analyze the sub-game of the microgrids, which concentrates on the maximization of the profit of microgrids according to the demand strategies of miners.

B. Microgrid's Sub-Game

By analyzing the Nash equilibrium of miner's sub-game $\mathbb{G} = \{S^B_{B_i\in B}; U^B_{B_i\in B}\}$, $S^B_{B_i\in B} = \{p_i, i\in N, p_{\min}\le p_i\le p_{\max}\}$, the microgrid provides dynamic electricity price strategies for different users to maximize its profit.

Theorem 3: In the game $\mathbb{G} = \{S^B_{B_i\in B}, S_M; U^B_{B_i\in B}, U_M\}$, S_M is the strategy of microgrids, which is the proposed price to each miner. The strategy space is defined as $S_M = \{y_i, i\in N, 0\le y_i\le y_{\max}\}$. There exists a unique Stackelberg equilibrium in the Stackelberg game. The pricing strategy set of microgrid $\mathbf{y}^* = (y_1, y_2, \cdots, y_n)$ could achieve the profit maximization of microgrid and p_i is given by (13) when the following condition holds:

$$\sum_{j\neq i}\left((g_j+g_i)\left(1-\frac{2y_j(N-1)}{g_j\sum\limits_N \frac{y_k}{g_k}}\right)\right) \le 0. \tag{14}$$

Proof: Substituting (12) into (7), we have

$$U_M = \sum_{i\in N} y_i p_i - \left[a\left(\frac{N-1}{\sum\limits_N \frac{y_i}{Te^{-\lambda z t_i}}}\right)^2 + b\frac{N-1}{\sum\limits_N \frac{y_i}{Te^{-\lambda z t_i}}} + c\right] \tag{15}$$

where y_i is continuous in $[y_{\min}, y_{\max}]$. We set $f(y) = \sum\limits_{i\in N} y_i p_i$ and $h(y) = a(((N-1)/(\sum\limits_N ((y_i)/(Te^{-\lambda z t_i}))))^2 + b((N-1)/(\sum\limits_N ((y_i)/(Te^{-\lambda z t_i})))) + c$.

Then, we find the first derivative and the second derivative for $f(y) = \sum\limits_{i\in N} y_i p_i$

$$\begin{aligned}\frac{\partial f(y)}{\partial y_i} &= \frac{(N-1)}{g_i\left(\sum\limits_N \frac{y_k}{g_k}\right)^2}\sum_{j\neq i}(g_j+g_i)\left(-\sum_{k\neq i}\frac{y_k}{g_k}\left(1-\frac{y_j(N-1)}{g_j\sum\limits_N \frac{y_k}{g_k}}\right)\right)\\ &\quad + \frac{(N-1)}{g_i\left(\sum\limits_N \frac{y_k}{g_k}\right)^2}\sum_{j\neq i}(g_j+g_i)\left(\frac{y_k}{g_k}\left(1-\frac{y_i(N-1)}{g_i\sum\limits_N \frac{y_k}{g_k}}\right)\right)\end{aligned} \tag{16}$$

$$\begin{aligned}\frac{\partial^2 f(y)}{\partial {y_i}^2} &= \frac{2(N-1)\sum\limits_{k\neq i}\frac{y_k}{g_k}}{{g_i}^2\left(\sum\limits_N \frac{y_k}{g_k}\right)^3}\sum_{j\neq i}\left((g_j+g_i)\left(1-\frac{2y_j(N-1)}{g_j\sum\limits_N \frac{y_k}{g_k}}\right)\right)\\ &\quad - \frac{2(N-1)}{{g_i}^2\left(\sum\limits_N \frac{y_k}{g_k}\right)^3}\sum_{j\neq i}\left((g_j+g_i)\frac{y_j}{g_j}\left(1-\frac{y_i(N-1)}{g_i\sum\limits_N \frac{y_k}{g_k}}\right)\right) < 0.\end{aligned} \tag{17}$$

Thus, $f(y)$ is strictly concave with respect to y_i.

Then, we find the first derivative and the second derivative for $h(y)$ with respect to y_i as follows:

$$\frac{\partial h(y)}{\partial y_i} = a\frac{2(N-1)^2}{Te^{-\lambda z t_i}\left(\sum\limits_{j\in N}\frac{y_j}{Te^{-\lambda z t_j}}\right)^3} + b\frac{(N-1)}{Te^{-\lambda z t_i}\left(\sum\limits_{j\in N}\frac{y_j}{Te^{-\lambda z t_j}}\right)^2} \tag{18}$$

$$\nabla^2 h(y) = \frac{-2(N-1)}{(\sum\limits_{j\in N}\frac{y_j}{g_j})^3}\begin{bmatrix} \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_1)^2}+\frac{b}{{g_1}^2} & \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_1g_2)}+\frac{b}{g_1g_2} & \cdots & \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_1g_n)}+\frac{b}{g_1g_n} \\ \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_2g_1)}+\frac{b}{g_2g_1} & \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_2)^2}+\frac{b}{{g_2}^2} & \cdots & \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_2g_n)}+\frac{b}{g_2g_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_ng_1)}+\frac{b}{g_ng_1} & \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_ng_2)}+\frac{b}{g_ng_2} & \cdots & \frac{a(N-1)}{3(\sum\limits_{j\in N}\frac{y_i}{g_j})(g_n)^2}+\frac{b}{{g_n}^2} \end{bmatrix} \tag{22}$$

$$\begin{aligned}\frac{\partial^2 h(y)}{\partial {y_i}^2} &= = \frac{-2a(N-1)^2}{3\left(\sum\limits_{j\in N}\frac{y_i}{Te^{-\lambda z t_i}}\right)^4 (Te^{-\lambda z t_i})^2} \\ &\quad + \frac{-2b(N-1)}{\left(\sum\limits_{j\in N}\frac{y_i}{Te^{-\lambda z t_i}}\right)^3 (Te^{-\lambda z t_i})^2}\end{aligned} \tag{19}$$

$$\begin{aligned}\frac{\partial^2 h(y)}{\partial y_i \partial y_j} &= \frac{-2a(N-1)^2}{3\left(\sum\limits_{j\in N}\frac{y_i}{Te^{-\lambda z t_i}}\right)^4 (Te^{-\lambda z t_i})(Te^{-\lambda z t_j})} \\ &\quad + \frac{-2b(N-1)}{\left(\sum\limits_{j\in N}\frac{y_i}{Te^{-\lambda z t_i}}\right)^3 (Te^{-\lambda z t_i})(Te^{-\lambda z t_j})}.\end{aligned} \tag{20}$$

The Hessian matrix of $h(y)$ can be expressed as follows:

$$\begin{bmatrix} \frac{\partial^2 h(y)}{\partial {y_1}^2} & \frac{\partial^2 h(y)}{\partial y_1 \partial y_2} & \cdots & \frac{\partial^2 h(y)}{\partial y_1 \partial y_n} \\ \frac{\partial^2 h(y)}{\partial y_2 \partial y_1} & \frac{\partial^2 h(y)}{\partial {y_2}^2} & \cdots & \frac{\partial^2 h(y)}{\partial y_2 \partial y_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 h(y)}{\partial y_n \partial y_1} & \frac{\partial^2 h(y)}{\partial y_n \partial y_2} & \cdots & \frac{\partial^2 h(y)}{\partial {y_n}^2} \end{bmatrix}. \tag{21}$$

We define $g_i = Te^{-\lambda z t_i}$. Substituting (19) and (20) into (21), we can obtain the Hessian matrix as presented earlier.

We can observe that the diagonal elements of the Hessian matrix $((a(N-1))/(3(\sum\limits_{j\in N}(y_i/g_j))(g_i)^2))+(b/({g_i}^2))$ are all positive. Besides, we can prove that the principle minors are equal to zero.

Thus, U_M is a strictly concave function with respect to y_i when $\sum\limits_{j\neq i}((g_j+g_i)(1-((2y_j(N-1))/(g_j\sum\limits_{N}(y_k/g_k))))) \leq 0$. By substituting the optimal strategy of miners into microgrid's game, the optimal pricing strategy set of microgrid $\mathbf{y}* = (y_1, y_2, \cdots, y_n)$ could achieve the profit maximization of the microgrid. The model could achieve the Nash equilibrium and the Stackelberg equilibrium of the game.

C. Gradient-Based Iterative Algorithm of the Game

According to the above-mentioned analysis, we use the gradient-based iterative algorithm in order to find the Nash equilibrium and the Stackelberg equilibrium of the game. We adopt Algorithm 1 to achieve the optimal strategy of miners and microgrid provider.

Algorithm 1 Gradient-Based Iterative Algorithm to Find Nash Equilibrium and Stackelberg Equilibrium of the Game

Input: $\mathbf{y}^0$
Output: $\boldsymbol{p}^*$, $\boldsymbol{y}^*$, U_M

Initialization:
Select initial input $\mathbf{y}^0 = (y_1^0, y_2^0, \cdots, y_n^0)$, where $y_i \in [0, y_{\max}]$; $k := 0$, precision threshold ζ;
Reapeat
Each participating miner B_i adjust the energy demand p_i according to Eq. (13);
Microgrid provider updates the giving price by exploring gradient-based iterative searching algorithm, i.e.,$\mathbf{y}(t+1) = \mathbf{y}(t) - \varphi \nabla U_M(\mathbf{y}(t), \mathbf{p}^*(\mathbf{y}(t)))$. $\nabla U_M(\mathbf{y}(t), \mathbf{p}^*(\mathbf{y}(t)))$ is the gradient with $\frac{\partial U_M(t)}{\partial y_i(t)}$ based on Eq. (16) and Eq. (18). φ is the step size of given unit prize update. The price strategy will be sent to all participating miners;
$k+1 := k$;
Until $\frac{\|\mathbf{y}^{k+1}-\mathbf{y}^k\|_1}{\|\mathbf{y}^k\|_1} \leq \zeta$; optimal $\boldsymbol{y}^*$ is obtained;
Calculating maximum utility U_M according to Eq. (7);
Output: optimal energy demand $\boldsymbol{p}^*$, optimal price strategy $\boldsymbol{y}^*$ and maximum utility U_M;

VI. Simulation

In this simulation, we compare the performance of our proposed Stackelberg model with several sets of experimental data and analyze the underlying causes. Limited to the low computing capacity and power consumption of IoT devices, it is reasonable for IoT-blockchain miners to join a mining pool. IoT miners devote their computing power to the mining pools. According to the computing capacity and the number of IoT-blockchain miners, the mining capacity of mining pools is

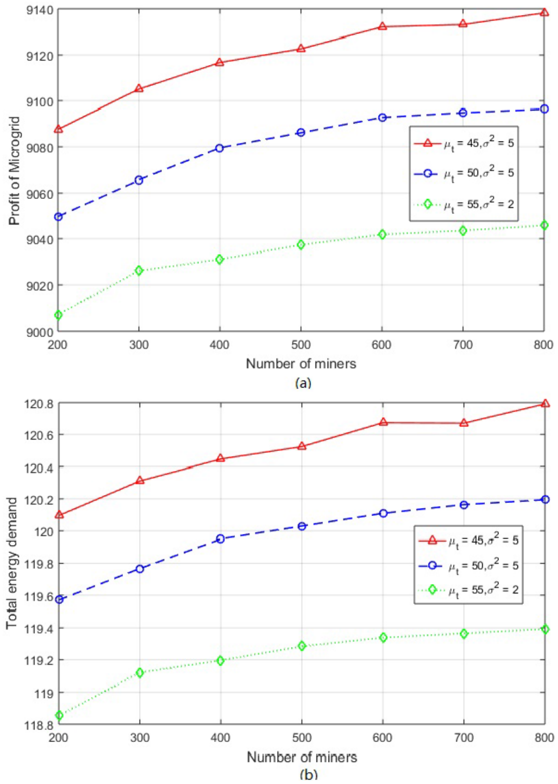

Fig. 4. (a) Benefit of microgrids versus the number of miners. (b) Miners' energy demand versus the number of miners.

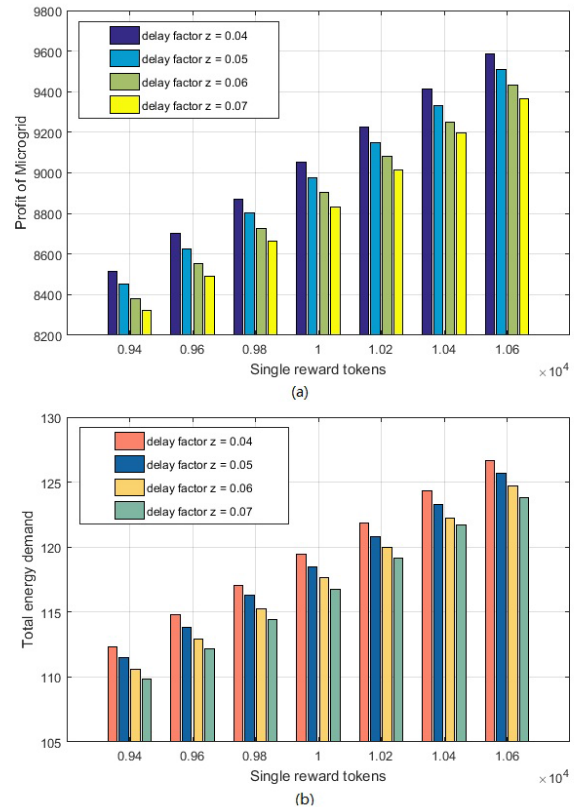

Fig. 5. (a) Benefit of microgrids versus the single reward tokens. (b) Miners' energy demand versus the single reward tokens.

different. In our simulation, we assume that each miner joins a mining pool.

Considering the widespread deployment of IoT devices, the number of IoT miners in a mining pool is much bigger than a traditional mining pool. We assume that one microgrid provides energy for 200–800 IoT miners in different mining pools. The number and the status of IoT devices result in different energy demands for each mining pool. In a mining pool, the strategy of the mining pool to distribute the reward and the strategy of the miner to choose a mining pool is another research, which has been widely studied in many works. Therefore, in this simulation, we only focus on the energy allocation of microgrids. Considering the different demand of mining pools, we set that the range of power demand is $p_{\max} = 150$. Besides, we set that the range of electricity price is $y_{\min} = 0$ and $y_{\max} = 80$. The size of the block obeys a normal distribution $\mu = 50$ and $\sigma^2 = 5$. Other model parameters are set as follows: $z = 5\times10^{-2}$, $T = 1\times10^4$, $a = 0.01$, $b = 3$, and $c = -1$.

First, we consider the impact of the number of miners to the profit of microgrids and the energy demand of miners, as shown in Fig. 4. We can find that when the number of miners participating increases, both the miner's energy demand and the benefit of the microgrids increase. The reason is that when the miners involved increase, there is an incentive for miners, and thus, there is more competition between miners, which leads to more energy demand. Greater energy demand brings more benefits to microgrids. As the size of the block increases, the probability of successfully mining the block decreases, and therefore, the profits of microgrids are correspondingly reduced.

Then, from Fig. 5, we observe that with the increase of single reward token, there is an increase in miners' energy demand and microgrids' benefits. As the reward tokens earned by the miners increased, this became an incentive for the entire game, which increases the miners' energy requirements. As a result, the benefits of microgrids have also increased. Besides, it is shown in Fig. 5 that miners' energy demand and microgrids' benefit decrease when the propagation delay of blockchain increases. When the propagation delay of the blockchain becomes higher, the possibility of successfully mining a new block is reduced. This reduces the enthusiasm of the miners, which leads to a reduction in the miners' energy request. Finally, the benefits of microgrids also declined.

Fig. 6 presents the relationship between the number of miners and the price. When the unit price of energy proposed by the microgrids increases, the energy demand of miners decreases. In contrast, the profits of microgrids increase due to higher unit prices. In addition, with the increase in the number of miners, the profit growth rate of the microgrids has gradually declined. As the number of miners increases, competition among miners becomes more intense. In this case, the opportunity for miners to successfully mine a new block and get rewards becomes smaller. As a result, the energy demands of miners become smaller. Therefore, the profits of microgrids are also dropped.

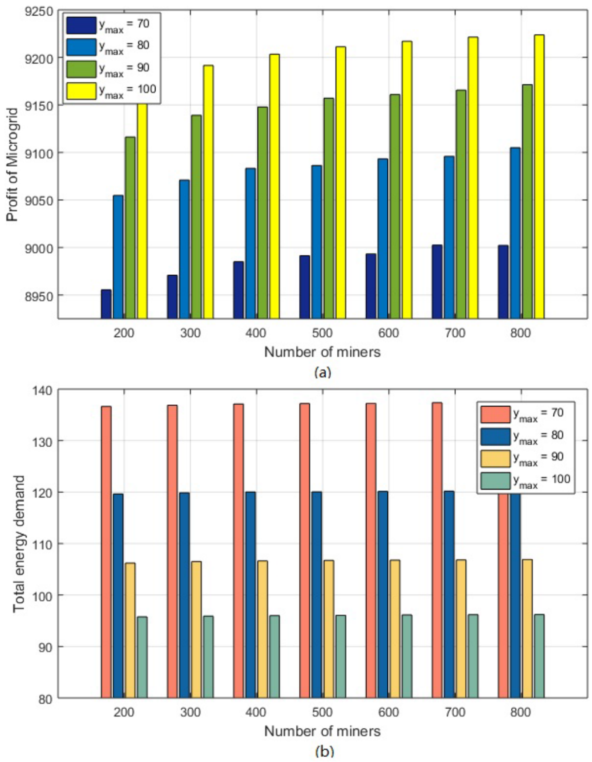

Fig. 6. (a) Benefit of microgrids versus the price of energy. (b) Miners' energy demand versus the price of energy.

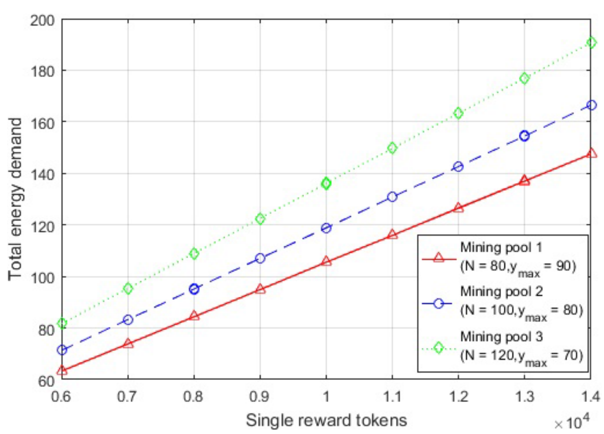

Fig. 7. Energy demand of different mining pools versus the single reward tokens.

Besides, considering the difference between mining pools, we explore a case study of three different mining pools. We set mining pool 1 of 80 miners with the upper limit of price $y_{\max} = 90$, mining pool 2 of 100 miners with the upper limit of price $y_{\max} = 80$, and mining pool 3 of 120 miners with the upper limit of price $y_{\max} = 70$. In our simulation, mining pool 3 has the biggest scale of miners with the lowest price of energy provided by a microgrid. From Fig. 7, we observe the demand of different mining pools. With a larger scale of a mining pool, the mining tasks of the mining pool get bigger, which causes a higher demand for energy. Due to the policy and restricts of price, the performance of different mining pools shows an incentive of miners. When the upper limit of price decreases, there is an incentive for mining pools, which causes bigger demands.

In addition, we also simulate the relationship between the power generation cost of the microgrids and the energy demand of miners. Since the cost of microgrids is a quadratic cost function, the change of cost is not determined by a single variable. We suspect that the profit of the microgrids is related to both these three values of a, b, and c. We have not given specific changes in this paper.

VII. Conclusion

In this paper, we have proposed a decentralized on-demand energy supply architecture for miners in IoT, using microgrids to provide renewable energy for mining in IoT devices. The energy management framework satisfies different energy demands in response to different consensus protocols. Then, we model the game between the microgrids and the miners as a Stackelberg model. We apply backward induction to achieve an optimal profit strategy for both of them. The simulation results show that our strategy supports the fairness of the game between different roles and show a strong incentive to encourage collaboration among microgrids and miners in IoT. In future studies, we would consider energy allocation among different consensus protocols. We will also consider the energy allocation between multi-microgrids suppliers and multi-miners. Besides, the security issues of our proposal should be considered. The combination of energy blockchain and microgrids energy supply is also our research direction in the future.

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