A Dynamic Resource Allocation Algorithm Based on Auction Model in Mobile Blockchain Network

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***Abstract*—Blockchain has been widely used in many fields such as bitcoin, smart contract, supply chain. However, because of the high requirement of computation and energy resource in mining process, blockchain application is restricted in mobile environment. In this paper, we introduce edge servers offered by Edge Service Provider into mobile blockchain network. Thus mining task can be offloaded from mobile devices to the edge server. Since there is competition among users, we propose an auction-based model for edge server resource allocation. Moreover, in order to maximize the revenue of all mobile users, we design a mechanism to achieve the allocation strategy and pricing rule for Edge Service Provider. Considering different resource demands, bids and usage time, we use Benders decomposition to get the dynamic resource allocation strategy. We evaluate the performance of the proposed auction model through extensive simulation. Results show that dynamic allocation can solve the resource allocation problem for Edge Service Provider and will get higher revenue with more winners than fixed allocation.**

***Index Terms*—mobile blockchain; resource allocation; Benders decomposition**

I. Introduction

In the last ten years, cryptocurrencies has noticed a significant growth [1]. As the core of cryptocurrencies, the blockchain technology has been widely studied. Blockchain is an emerging technology with decentralized, tamper-proof features that guarantee a secure record of transactions [2]. Through a decentralized consensus mechanism, blockchain implements a secure and trust-free decentralized database management to enable transactions that are not dependent on third parties like central banks [3]. Blockchain plays a key role in many areas, such as smart contract [4], finance [5], supply chain [6] and so on. According to several surveys [7], with the implementation of the blockchain solution, the revenue of enterprises will reach 20$ billion by 2025.

Blockchain is actually a distributed accounting system. To ensure data integrity and validity in the blockchain, *mining* [8] is introduced into blockchain network. Mining is a computational process to decide the winner who achieves the billing right. In particular, participants in the blockchain, called *miners*, obtain billing rights by solving a computationally difficult problem to connect the previous block to the current block, which is called Poof-of-Work(PoW). PoW is widely used because it can solve the problem of verifying trust in a decentralized system [9]. After the PoW is resolved, the result will be broadcast to other miners in the network for validation. If most miners agree to reach the consensus, the new block is successfully added to the chain. At the same time, the successful miner will be given a reward as an incentive to solve PoW.

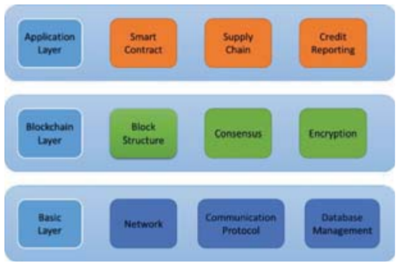

Fig. 1: Blockchain architecture

The Blockchain architecture can be divided into three layers, as shown in Figure 1. Blockchain-based applications can be deployed in application layer. Blockchain layer includes the structure of the block, the consensus algorithm and the encryption method, which offers service for applications. Basic Layer is the backbone of the blockchain and defines the network structure, such as P2P networks, communication protocols between nodes and database management principles.

However, there is a general problem with the application of the blockchain at present, which does not support the mobile environment. The application of the blockchain requires a third-party to provide mobile services, which is violating the design principles of decentralization. The reason why mobile blockchain applications are rarely deployed in resource-limited environment such as Internet of Things(IoT) and mobile devices is that the high demand for computational capacity and storage availability of the mining process, i.e. solving PoW puzzle. It is worth noting that the computational power of the edge servers scattered on the mobile side has been greatly improved. Therefore, we introduce the edge server, which is provided by Edge Service Provider(ESP), into the mobile blockchain network and offload the computing tasks from the mobile device to the edge server, thus solving the problem of insufficient computing power of the mobile device. Compared with the cloud service center, edge node is closer to mobile users and can obtain lower transmission delay. Primarily, we investigate and study the issue of ESP computation resource allocation and pricing during the offloading process. Auction is a process of buying and selling goods by bidding on available

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resources. Auction plays an important role when demand is higher than the amount of resources. Buyers and sellers are free to provide valuations for the resources and the reach an agreement on the payment of resources in the end. Auction is an important method to solve the problem of resource allocation. Former researches [10] about resource allocation issue mostly focus on the static method, which means the resource will be allocated static and resulting in the reduction of resource utilization. The problems in static allocation are:

i. Resource allocation contracts are always beneficial to suppliers. In some cases, the user and vendor instances do not match.

ii. The utilization of resource will be reduced.

These problems can be overcome by dynamic resource allocation, which provides financial benefits to ESP and computing resource to mobile users. Dynamics is not only reflected in the fact that resources are allocated to users on demand, but also the usage time applied by a mobile user is dynamic.

So in this paper, we mainly discuss the dynamic resource allocation strategy in auction. In order to maximize the revenue of all mobile users, we propose an auction model and turn the problem into an optimization problem under constraints. Through Benders decomposition, we solve the multivariate mixed linear integer programming problem to get the dynamic resource allocation strategy. We simulate the performance of the model and compare it with the fixed resource allocation scheme from multiple perspectives. It is demonstrated that higher revenue of miners can be obtained by dynamic resource allocation strategy.

The contribution of this paper lies in three aspects:

- We introduce the edge server into the mobile blockchain network and propose an auction model to solve the resource allocation problem.
- We use Benders decomposition algorithm and optimized Vickrey Auction pricing model to get the dynamic resource allocation strategy with reasonable pricing rule.
- Through performance simulations and comparison experiments, we prove the feasibility and effectiveness of the dynamic allocation strategy.

The rest of this paper is organized as follows. Section II reviews related work. Section III raises the problem and describes it in mathematical formula. Section IV presents the algorithm to the maximum revenue of all users and gives the theoretical analysis. The experimental simulation results and analysis are shown in Section V. Section VI summarizes the paper.

II. Related Work

In recent years, there are many studies about the combination of edge server and blockchain. In [11], authors introduce edge server to provide local data processing with low latency into Internet of Vehicles. Additionally, blockchain is used in the system to solve the problem of personal information security and privacy. Authors in [12] investigate the resource allocation problem in three-layer edge computing networks. Based on cost efficiency, they propose a double-matching resource allocation strategy of edge server and use DA-DMS algorithm to solve the problem. The combination of edge server and blockchain has been widely discussed, especially the resource allocation problem. Authors in [13] propose a lightweight blockchain model and offload the consensus process to the edge service. In particular, they use two-stage Stackelberg game to study the resource allocation strategy and prove the equilibrium by capitalizing on the variation inequality.

As one of the pioneer work, authors in [14] propose the underlying design of the mobile blockchain, including database design and mining process implementation. The consensus algorithm is PoW and the mining process is calculating the hash number to obtain the billing right. Specially, they offer Android core module of mobile blockchain. In [15], authors combine the mobile blockchain with the edge computing. For the first time, the edge server is used to realize the mobile mining task, which realizes the offloading of computation tasks. However, authors only use the game theory to analyze the game process between users and the ESP, and do not propose a reasonable resource allocation strategy. Auction model is introduced to solve the resource allocation problem in [16], which can make it possible to get the analytical solution. This paper presents a new computation resource allocation model based on combinatorial double auction mechanism. In [17], authors mainly discuss two offloading methods, nearby access point and a group of nearby users. Through alternating direction method of multipliers based algorithm, they developed an optimization plan for joint offloading decision and caching strategies. Authors in [18] analyze the system architecture of the blockchain network and deeply discuss the design of the distributed consensus system and the incentive mechanism at the same time. Particularly, this paper shows the mathematical principles in the mining process, which helps a lot in this paper. In [19], authors propose an auction-based edge server resource market of the edge service provider. They maximize the social welfare through greedy selection of resource allocation strategy and Vickrey Auction pricing rules, while guaranteeing the truthfulness, individual rationality and computational efficiency.

The above methods prompot us to study the optimal mechanism of edge server resource allocation in mobile blockchain networks. In particular, in order to motivate more users participating in mining process, we maximize the total revenue of all users and employ the dynamic resource allocation in auction model, which can increase ESP resource utilization.

III. Problem Formulation

In this section, we introduce the mining process and the combination between mobile blockchain and edge server at first. Then we analyze the process of the resource allocation based on auction model. Due to the limitation of the edge server resource, mobile users have to compete to obtain resource. With certain allocation strategy and pricing rule, ESP selects several users as winners, who will pay the price and get the resource. Finally, we describe the mining process by mathematics and summarize the user revenue formula.

A. Mobile Blockchain Mining Process

Mobile blockchain is not only used to support p2p-based mobile applications, but also employed to solve the trust issues in mobile payment. Each miner on the mobile blockchain listens to the transactions generated on the chain, and puts transaction records into its own trading pool. At a certain point of time, the miner will select some records and put them into the block according to their priorities. Using consensus algorithm, i.e. PoW, miners achieve a nonce through solving a mathematical problem. While mining the block, the miner propagates the result to the blockchain network and gets a certain amount of bitcoin as a reward. The more computation power that user has, the sooner the user calculates the result and gets the reward. So the mining process is similar to the speed race. However, it is found that calculating this math problem on a mobile device is very difficult because the computation capacity of mobile device is limited [15]. In order to offload the mining task, we introduce edge server in mobile blockchain. In the following, we analyze the process of resource allocation between mobile users and ESP using auction model.

B. Edge Server Resource Auction

As is shown in Figure 2, we consider the mobile blockchain network including one ESP and a certain amount of users denoted by $N = \{1...N\}$. Each mobile user runs mobile blockchain application and competes to get computation resource. We have the following assumption:

Assumption 1: The total computation resource of ESP is M and it is limited. M is smaller than the sum of all mobile users' demand

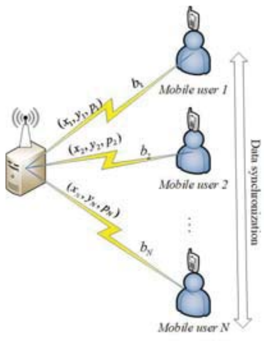

Fig. 2: Mobile blockchain system

Due to Assumption 1, it is unable to satisfy the needs of all users, so ESP has to launch an auction to realize resource allocation. Firstly, ESP informs users about its service and resource limitation. Then, users submit their bids. The bid of user u_i is denoted by a 3-tuple $b_i = (v_i, q_i, t_i)$, where v_i is the price at which u_i is willing to pay for the service, q_i is the quantity of resource that u_i apply for, t_i represents the usage time that u_i need. While receiving all users' bids $b = (b_1, b_2, ..., b_N)$, ESP will select a set of users $y = (y_1, y_2, ..., y_N)$ as winners and notify mobile users the resource allocation $x = (x_1, x_2, ..., x_N)$ as well as the prices $p = (p_1, p_2, ..., p_N)$. Among them, y_i determines whether $u_i$will be allocated resources, and x_i represents the amount of resources allocated, which is the dynamic meaning of this paper. At the end of the auction, winners pay the conditional prices and get the computation resource. The auction process is shown in Figure 3.

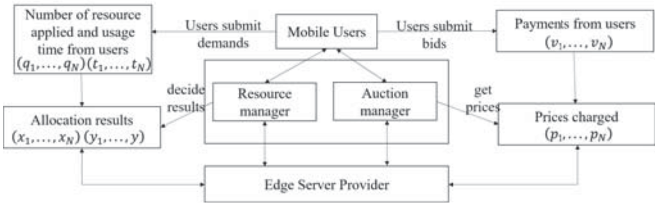

Fig. 3: Auction process

C. Mobile Blockchain Mining

Miners compete to solve PoW puzzle in the mining process to propagate the block and get reward. Since mining is becoming more and more difficult, many miners have to concentrate their mining resources to form a mining pool. However, this will cause 51% attack problem that affects the decentralization of the blockchain because of the concentration of computational power. So, we assume that miners mine blocks individually [20], which is called solo mining. Each calculation has a corresponding computing difficulty, labeled D, which determines the difficulty of finding a legal block.

According to the analysis of the block generation process, the mining difficulty D has a very important impact on the results. Mining is actually a violent guessing, and how many times to guess relying on the difficulty of the whole network consensus. Taking Bitcoin as an example, the generation of each block is 10 minutes, which is the time it takes to calculate the nonce that meets the requirements.

$$nonce <= \frac{2^{256}}{D} \tag{1}$$

while difficulty D increases, the nonce will be easier to calculate, so the block generation time will be reduced. In order to maintain a fixed average generation time of the block, it is necessary to adjust the difficulty of mining. The difficulty is adjusted according to the average output time of 2016 blocks generated before. As more and more miners participate in mining, the computational power is increasing, and this guessing game will be achieved faster theoretically. Under the premise that all nodes are working normally, we make an idealized assumption about the mining process, and believe that the difficulty of mining is only related to the number of miners.

In mobile blockchain network, in order to maintain a constant calculation cycle, the mining difficulty D will vary with the number of users. The fewer the number of users, the lower the difficulty is. The minimum is a fixed value D_0, when the number of user increases, the difficulty also becomes higher. We can fit the mining difficulty D and the number of users N into an exponential function curve [8]:

$$\mathrm{D} = D_0 e^{\varepsilon N} \tag{2}$$

The generation of block is modeled as a Poisson process [21] with parameter λ in unit time. We can conclude several assumptions:

Assumption 2: Whether one calculation produces a legal block can be considered as a random event, and any hash calculation is independent of each other.

Assumption 3: The nNonce in Bitcoin provides 2^{32} possible values, which is the target of miners mining for. Combining nNonce with mining difficulty D, we can achieve the probability of $\frac{1}{2^{32}D}$ to produce a legal block.

Assumption 4: The computation power of u_i, which means the number of hash calculation per second, is determined by the allocated resource x_i only.

Thus, we can obtain the rate at which u_i mines the block in unit time with allocated computational resource x_i is $\lambda = \frac{x_i}{2^{32}D}$, which is the Poisson distribution parameter [17]. Considering the usage time t_i, the number of block that u_i may mine can be described as follows:

$$E(X_i) = \lambda \cdot t_i = \frac{x_i}{2^{32}D} \cdot t_i \tag{3}$$

The revenue that miners obtain by mining a block is actually an incentive mechanism of the blockchain network. The purpose of incentive mechanism is to encourage the miners to participate in the safe operation of the blockchain system through economic balance, and prevent tampering with the general ledger. In mobile blockchain, incentives includes issuance incentives and distribution incentives.

The first user who mines the block and broadcasts to the network will achieve a fixed reward R, which is the issuance incentives. Besides, each block contains some transactions, in which there are some transaction fees. The more transaction fees, the faster the transaction will be packaged into the block. All transaction fees in the block will be given to the miner as a reward as distribution incentives. We represent the number of transactions of each miner by $s = (s_1, ..., s_N)$, and thus the miner's distribution incentives t is determined by the transaction fee rate r_i and the size of transactions of the block s_i.

So the reward of u_i is described as follows:

$$T_i = \mathrm{R} + \mathrm{t}_i = \mathrm{R} + \mathrm{r}_i \cdot s_i \tag{4}$$

From what we discussed above, the profit of u_i with the resource of x_i in time t_i can be summarized as follows:

$$w\left(\mathrm{i}\right) = \frac{x_i}{2^{32} D_0 e^{\varepsilon N}} \times t_i \times (\mathrm{R} + \mathrm{r}_i \cdot s_i) \tag{5}$$

IV. Auction Model and Solution

In this section, in order to encourage more users to use mobile blockchain, we propose an auction-based market model to solve the problem of ESP resource allocation, with the goal of maximizing the total revenue of all users. In particular, we use Benders decomposition algorithm to get the optimal resource allocation strategy, while getting the pricing rules through optimized Vickrey Auction pricing mechanism.

A. Revenue of Mobile Users

Considering the cost paid by the user, we can describe the net income of u_i as follows:

$$pure\,(i) = \frac{x_i}{2^{32} \cdot D_0 e^{\varepsilon N}} \times t_i \times (\mathrm{R} + \mathrm{r}_i \cdot s_i) - v_i y_i \tag{6}$$

While receiving all mobile users' bids $b_i = (v_i, q_i, t_i)$, ESP will select winners under resource allocation strategy and pricing rule with the goal of maximizing the revenue of all users. Therefore, designing such an auction model becomes the solution of the following problem:

$$max: \quad \sum_{i=1}^{N} \frac{\mu x_i}{2^{32} \cdot D_0 e^{\varepsilon N}} \times t_i \times (\mathrm{R} + \mathrm{r}_i \cdot s_i) - \sum_{i=1}^{N} v_i y_i \tag{7}$$

$$s.t. \begin{cases} 0 \le x_i \le q_i & (8) \\ \sum_{i=1}^{N} x_i \le \sum_{i=1}^{N} q_i y_i & (9) \\ \sum_{i=1}^{N} x_i \le M & (10) \\ y_i \in \{0,1\} \quad \forall i \in N & (11) \end{cases}$$

The objective function (6) represents the difference between income and expenditure of all users through mining and we expect to get the allocation strategy $x = (x_1, x_2, ..., x_N)$ and $y = (y_1, y_2, ..., y_N)$ by maximizing (6). Constraint (7) indicates that the number of resource allocated for each user is not greater than the number of resource requested, constraint (8) defines the relationship between continuous variable x and 0-1 variabley, constraint (9) indicates that the total quantity of computation resource for allocation is M.

Our goal is to solve this multivariate mixed linear integer programming problem and the method is shown in Algorithm1.

B. Resource Allocation Strategy

As is shown in Lines 4-18, we use Benders decomposition to get the optimal resource allocation strategy, which can transform the general mixed linear integer programming problem into one Nonlinear Programming (NP) and one Mixed-Integer linear Programming (MILP), where NP is called sub-problem and MILP is called master-problem.

1) Sub-problem: In our case, the sub-problem is a linear problem with binary variables y. So the sub-problem can be expressed as follows:

$$\varphi\left(\mathrm{y}\right) = \min \sum_{i=1}^{N} v_i y_i \tag{12}$$

$$\text{s.t.} \quad (8)\,,\ \ (10)$$

Since it is a traditional linear optimization problem, we can use many methods to obtain the result such as Dinkelbach Algorithm.

Algorithm 1 User Profit Maximization Auction

Input: Mobile users' bids $b = (b_1, b_2...b_n)$, $b_i = (v_i, q_i, t_i)$
Output: Computation Resource allocation strategy $x^* = (x_1, ..., x_n)$, $y^* = (y_1, ...y_n)$ and ESP pricing strategy $p^* = (p_1, ..., p_n)$

1: **for** each $i \in N$ **do**
2: $\quad x_i = 0, y_i = 0, p_i = 0$
3: **end for**
4: **Initialization:**
5: $\mathrm{UB} = \inf,\ \mathrm{LB} = -\inf, \varepsilon = 10^{-4}$
6: **while** $|\mathrm{UB} - \mathrm{LB}| > \varepsilon$ **do**
7: $\quad$ solve sub problem
8: $\quad$ **if** Unbounded **then**
9: $\quad\quad$ Get unbounded ray $\overline{u}$
10: $\quad\quad$ Add cut $-y^T \overline{u} \leq 0$ to master problem
11: $\quad$ **else**
12: $\quad\quad$ Get extreme point $\overline{u}$
13: $\quad\quad$ Add cut $-(y^T)\overline{u} \leq z$ to master problem
14: $\quad\quad$ $\mathrm{UB} := \min\left\{\mathrm{UB}, f^T \overline{y} + (-\overline{y})^T u\right\}$
15: $\quad$ **end if**
16: $\quad$ solve master problem
17: $\quad$ $\mathrm{LB} := \min\limits_{y}\{\mathrm{z}|\mathrm{cuts}, y \in Y\}$
18: **end while**
19: **for** each $i \in N$ **do**
20: $\quad$ **if** $y_i == 1$ **then**
21: $\quad\quad$ **for** each $j \in N$ and $y_j == 0$ **do**
22: $\quad\quad\quad$ $\min\limits_{j}\{|j - i|\}$
23: $\quad\quad$ **end for**
24: $\quad\quad$ $p_i = \frac{v_j}{q_j} \times x_i + \alpha \times t_i$
25: $\quad$ **end if**
26: **end for**

2) *Master-problem:* In the master-problem, we assume that the continuous variable x is fixed. After the last iteration, we have obtained the optimal solution for the sub-problem. The master-problem is formulated as follows:

$$\mathit{min:} \qquad -\sum_{i=1}^{N} \frac{\mu x_i}{2^{32} \cdot D_0 e^{\varepsilon N}} \times t_i \times (\mathrm{R} + \mathrm{r}_i \cdot s_i) + \varphi(\mathrm{y}) \quad (13)$$

$$\text{s.t.} \quad (7), \ (8), \ (9)$$

C. Payment Rule

The corresponding payment is to set certain prices for the winners. Based on Vickrey Auction pricing strategy [22], our pricing strategy has two steps as is shown in Lines 19-26. In the first step, system will search all users and find the nearest u_f who failed in the auction for each winner. The second step decides the final payment of winner by the bid of u_f. Firstly, we calculate the bid density of u_f:

$$d_f = \frac{v_f}{q_f} \qquad (14)$$

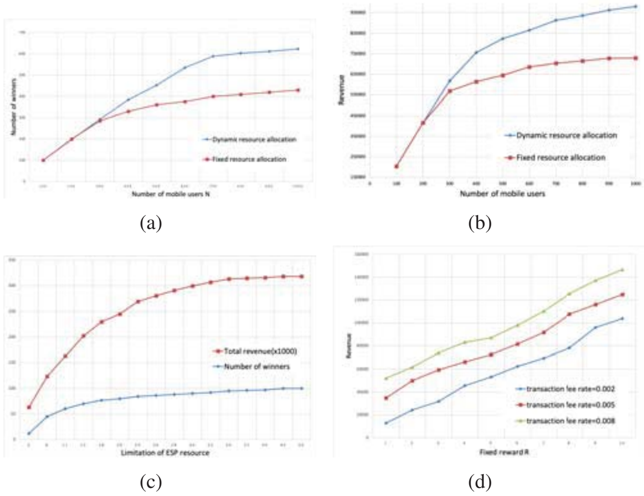

Fig. 4: Comparison of two methods and simulation of the model. (a) Comparison of winners number. (b) Comparison of revenue of miners. (c) Impact of ESP resource. (d) Impact of fixed reward and transaction fee rate.

For example, u_j is the winner and u_f is the nearest failure user. The payment of u_j is determined by d_f and q_j. So the formulation of p_j can be described as follows:

$$p_j = d_f \times x_j + \alpha \times t_j = \frac{v_f}{q_f} \times x_j + \alpha \times t_j \qquad (15)$$

The α is a parameter and $\alpha \cdot t_j$ is the punishment item. The longer time to apply, the more payment that the winner has to pay.

V. PERFORMANCE EVALUATION

In this section, firstly we compare the revenue of all users and the number of winners obtained by different methods. Then we obtain the user benefits under different resource caps by numerical simulation, and explain the impact of different parameters on the performance of the proposed model. The experiment is implemented on Matlab.

A. Comparison with other algorithms

We compare the user revenue calculated by the model proposed in this paper with the method in [19] at first. The parameters of the model is set as $\mu = 10^{12}, \varepsilon = 0.01, \alpha = 0.1$ [15]. We vary the number of the mobile users N from 100 to 1000. We assume the size of the block mined by miner s_i follows the normal distribution $\mathrm{N}\left(\mu_t, \sigma^2\right)$ where $\mu_t = 800,\ \sigma^2 = 100$.

1) *The number of winners:* We fix the total available computation resource of ESP $M = 10^4$, and the fixed reward $R = 10$, transaction fee rate $r = 0.01$. Using the fixed resource allocation method as a comparison, we show the number of winners obtained by two methods in Figure 4(a). We observe that when the number of mobile users is small, the two methods are almost the same. But when it increases, the dynamic resource allocation method gets significantly more

winners than fixed resource allocation. When $N > 860$, both methods converge to stabilize, and the dynamic method is 40% more than the original method.

2) The revenue of all miners: Figure 4(b) shows a comparison of the total revenue of the miners between dynamic resource allocation method and fixed resource allocation method when the number of mobile users increases. We set $R = 10, r = 0.01$. As the number of mobile users grows, so does the revenue. It can be seen that the revenue of dynamic allocation grows faster than fixed allocation method, which is because of the high resource utilization. However, if the users participating in the mining reaches a certain number, revenue will towards stability because of the resource limitation of ESP.

B. Effect of algorithm parameters

We vary the limitation of ESP computation resource M from 500 to 5000, fixed reward R from 1 to 10, transaction fee rate r in [0.002, 0.005, 0.008]. The parameters of the model is set as $\mu = 10^{12}, \varepsilon = 0.01, \alpha = 0.1$. We fix the number of mobile users $N = 100$.

1) The impact of ESP resource limitation M: In Figure 4(c), we set R=10,r=0.01. It is shown that when the limitation of ESP resource increases, the revenue of miners and the number of winners increases overall. However, both of them will tend to be smooth in the end. That is because with the growth of M, mobile users demand of resource will be satisfied and finally all users will be winners. The rapid increase of revenue at the beginning is due to the rapid growth of users. However, the revenue will tends to stabilize while M is large.

2) The impact of fixed reward R and transaction fee rate r: As is shown in Figure 4(d), we simulate the relationship of the revenue of miners with the fixed reward R and transaction fee rate r. We fix N=10, M=2000. It is obviously that the revenue of miners increase with R when the transaction fee is fixed, and they are almost linear. Also, we can see that the more transaction fee, the more revenue.

VI. Conclusion

In this paper, we have combined edge server with mobile blockchain and investigated the edge server resource management. In particular, we have proposed an auction mode to dynamically allocate edge server resource with the target of maximizing the revenue of all mobile users. Through Benders decomposition algorithm, we have achieved the dynamic resource allocation strategy. Basic on this, we have proposed the reasonable resource management solution, including the optimized Vickery Auction pricing rule. Further, the feasibility and effectiveness of the allocation strategy have been proved by theoretical analysis and experiment simulation. The comparison experiments have shown that higher revenue and more winner number can be achieved by dynamic resource allocation. In addition, we have conducted several simulation results of the model performance to help mobile users gain more revenue.

For the future work, we will consider about the network that has several edge service providers and the corresponding resource allocation strategy and pricing rule.

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