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Joint Mining Offloading and Computing Resource Optimization in Mobile Blockchain System

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***Abstract*—Mobile edge computing is considered as a promising solution to mobile blockchain system, where mobile nodes with limited computing capability may participate in the mining process by offloading the computing intensive mining tasks to nearby edge service providers (ESPs). However, malicious ESP will dishonestly perform miners' mining tasks, which harms miners' interests. We consider blockchain mining and computing offloading services jointly, and model the interaction between the ESP and miner nodes as a two-stage Stackelberg game. Then, we obtain the optimal edge computing demand and the corresponding price of each miner by solving the Nash equilibrium of the game iteratively with gradient descent method. Simulation results show that the more computing power ESP has, the more computing services it will provide for miners. When the revenues coefficient of ESP on vehicular services increases, ESP will provide more computing resources for vehicular services to obtain maximum benefits.**

***Index Terms*—blockchain, edge computing, computing offloading**

I. Introduction

As a distributed ledger technology (DLT) with advanced cryptography, blockchain can achieve peer-to-peer transactions in a secure and tamper-proof manner in trustless environment without relying on a trusted central authority, and thus it has received extensive applications in many application areas, such as finance, supply chain, government and medical data sharing, etc [1]–[4]. Consensus is the key to guarantee consistency and security in blockchain technology. In public blockchain, such as bitcoin system [5], the proof-of-work (PoW) [6] consensus is most commonly adopted. With PoW consensus, each participating node is required to solve a computation-intensive mathematic puzzle to find a feasible nonce that satisfies the target difficulty, and the node who finds the nonce will broadcast the results to other nodes for verification. Once most of the nodes validate the results, a new block will be generated and appended to the chain with a mining reward given to the first winner.

Even though blockchain is a promising solution for many applications, it cannot be readily applied in mobile scenarios due to the limitations of the proof like consensus. Generally, the available computing resources on mobile devices (e.g., smartphones and unmanned aerial vehicles) are very limited, and cannot support the computing intensive block mining tasks. Edge computing [7] has been proposed as a new solution for many emerging applications, by moving the computing capability near to the end users. Thus, edge computing brings new opportunities for mobile blockchain system [8].

The combination of mobile edge computing (MEC) and blockchain network is regarded as a promising solution for mobile blockchain system [9]–[13]. To help the mobile devices in reaching consensus and storing data, an architecture of blockchain network combining with edge server was introduced in [9]. Because the network computing resources determine the efficiency of the blockchain system, how to obtain computing resources and incentivize device participation will be the driving force. The authors in [10] focused on the incentives for rational miners to purchase computing resources and formulated a two-stage Stackelberg game between edge service providers (ESPs) and miners. Many researchers have also worked on solving the privacy and security issues during the offloading of computing tasks. The optimal offloading strategy and security issues for mobile nodes were studied in [11]. The authors in [12] modeled the interaction of miners and blockchain platform as a two-stage Stackelberg game, and studied how to incentivize more miners to join in blochchain. Note that the work in [12] did not consider the block propagation delay in the block verification process, and a modified system utility function were considered by considering the block verification delay in [13].

The authors in [14] developed an optimal auction for edge computing resources allocation based on deep learning. An auction-based edge computing resources allocation mechanism for ESPs was proposed to maximize the social welfare in [15]. Then, the game model of multiple leaders and multiple followers was also considered in many articles. A multi-operator multi-user Stackelberg game to analyze the interaction among the UE and multiple operators was developed in [16]. In addition, the author in [17] simulated the computing resource allocation process as a two-stage starckelberg game process, and considered the joint optimization of the revenue of cloud/fog computing service provider (CFP) and the miners. Considering multiple edge servers, the pricing strategy based an alternating direction method of multipliers (ADMM) was presented in [18]. The authors in [19] proposed a dynamically pricing strategy in non-orthogonal multiple access (NOMA) resource allocation.

The above researchers proposed a two-stage Stackelberg game and an auction-based edge computing resources allocation mechanism at the same time. But it is worth noting that most works above have investigated the computing resource allocation of ESPs in a mobile blockchain system with the assumption that ESPs are trustworthy. However, under current revenue model, ESP is much likely to collude with some miners

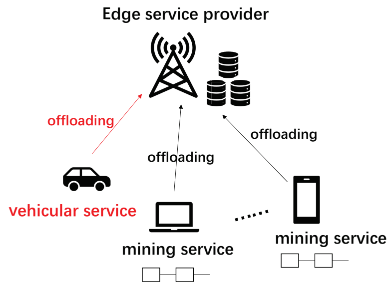

Fig. 1: Edge computing in the mobile blockchain system.

to obtain more revenues. The collusion of the ESP and miners will cause severe security threats to the blockchain system. The authors in [20] proposed a reward sharing scheme to mitigate potential colluding miners in the mobile blockchain system. Considering the collusion issue in computing offloading, the authors in [21] and [22] proposed a nonce ordering mechanism to provide fair computation resource offloading. The ESP maps the nonce sequence submitted by all users into a merged nonce sequence, and provides hash computing services for the merged sequence. However, the above researchers only considered the model in which ESP uses all computing power for miners' computing tasks. For the completeness of the experimental results, we need to consider whether the ESP will simultaneously provide computation for other devices.

In this paper, we propose a model in which ESP provides both vehicular services and mining services. We also consider that the malicious ESP may not perform the miner's mining task with a certain probability. We consider the influence of the computing power in the blockchain network and ESP uses the remaining computing resources for other computing tasks. In particular, we use the two-stage Stackelberg game to model the interaction among the ESP and miners. Then, we solve the Nash equilibrium of the game using gradient descent method iteratively. The simulation results show that the more computing power ESP has, the more computing services it will provide for miners. When the revenues coefficient of ESP on vehicular services increases, ESP will provide more computing resources for vehicular services to obtain maximum benefits. In addition, as the increase of the probability of not performing mining tasks, the revenues of ESP increases.

The rest of this paper is arranged as follows. The system model is described in Section II. In Section III, we analyze the game between ESP and miners, and deduce Nash equilibrium. The simulations and discussions are given in Section IV. In Section V, we draw the conclusions.

II. System Model and Problem Formulation

A. System Model

As shown in Fig. 1, we consider a MEC aided mobile blockchain network, where miners perform block mining tasks to earn rewards. Due to the limitation of computing capability, miners need to offload their Hash computing tasks to the ESPs. In addition, ESP also provides computing resources for vehicular services for data analysis and data storage. We consider the impact of other miners' computing power in the blockchain on the ESP offloading strategy. We consider a scenario with one ESP and multiple miners. Denote the set of miners as $\mathcal{N} = \{1, 2, ..., N\}$. The ESP dynamically changes the unit price of computing resource for each miner, and then broadcasts the prices to miners, so that miners decide their optimal purchase amount of computing resource to maximize their revenues. ESP only uses part of the computing power to assist miners in mining, and the remaining part of the computing power is used for vehicular services for data analysis and data storage. Note that, to facilitate the theoretical analysis, we ignore the synchronization issues and the communication overhead.

B. Problem Formulation

Because ESPs and miners maximize their respective revenues, we model their interactions as a game model. Hence, we adopt a two-stage Stackelberg game, where the ESP and miners act as leader and followers, respectively. In the upper stage, the ESP dynamically adjusts the unit computing resource price to maximize its revenue. In the lower stage, according to the price given by the ESP, each miner decides the optimal purchase amount of computing resource to get maximum revenue.

Assuming that the total computing power of other miners in the blockchain system is ω_b. We considered that the total revenue of the miner is composed by the remaining mining reward minus the cost of purchasing computing resources. Denote the set of computing resource purchased by each miner and the corresponding prices as $\boldsymbol{\omega} = \{\omega_1, \omega_2, ..., \omega_N\}$ and $\mathbf{p} = \{p_1, p_2, ..., p_N\}$, respectively. Then, the i-th miner's cost on purchasing computing resources is given by $p_i\omega_i$. The successful mining rewards from the blockchain platform include both fixed reward R and transaction dependent variable rewards rs_i, where r is transaction fee rate and s_i is the block size of the i-th miner. In addition, we consider the impact of block verification delay, which is related to the block size. The delay of block verification is given by $\exp(-\tau s_i)$ [23], where τ is the delay factor. Then, the probability of successful mining is given by [13]

$$k_i = \frac{\omega_i}{\sum\limits_{j\in\mathcal{N}} \omega_j + \omega_b} \,. \tag{1}$$

Considering the propagation delay of block verification, the mining reward is given by [13]

$$R_i = (R + rs_i)e^{-\tau s_i} \,. \tag{2}$$

Thus, the revenue of the i-th miner is given by

$$U_i = R_i \frac{\omega_i}{\sum\limits_{j\in\mathcal{N}} \omega_j + \omega_b} - p_i\omega_i \,. \tag{3}$$

Assuming that the total computing power of ESP is ω_a, the part of the computing power used for vehicular services is

$\omega_0 = \alpha\omega_a$, where α is the ratio of the computing power used by ESP for vehicular services. Due to the influence of various factors such as service quality, the incomes obtained by ESP for data storage and data analysis of vehicular services are $a\ln(1+b\omega_0)$, where a and b are the coefficients. The unit computational cost is c. For the ESP, the revenue can be defined as the profit by providing computing services to miners plus the income from vehicular services minus the computational cost. Therefore, the revenue function of the ESP can be defined as follows:

$$U_s = \sum_{j\in N} p_j\omega_j + a\ln(1+b\omega_0) - c\left(\sum_{j\in N}\omega_j + \omega_0\right). \quad (4)$$

Then, the profit maximization problem of the two sides can be modeled as the following problems.

Problem 1. *For each miner in the lower stage, the optimization problem can be formulated as:*

$$\max_{\omega_i} U_i(\omega_i|\boldsymbol{\omega_{-i}}, p_i), \quad (5)$$

where ω_i is the computing capability of the i-th miner and $\boldsymbol{\omega_{-i}} = \boldsymbol{\omega}\backslash\{\omega_i\}$.

Problem 2. *The problem in the upper stage (ESP side):*

$$\begin{aligned} &\max_{\mathbf{p}} U_s(\mathbf{p}, \boldsymbol{\omega}), \\ &s.t. \sum_{j\in\mathcal{N}}\omega_j + \omega_0 \le \omega_a. \end{aligned} \quad (6)$$

where p_i is the unit price of computing resources for the i-th miner.

III. Stackelberg Game Analysis

In this section, we analyze Stackelberg game and deduce the optimal strategies of ESP and each miner.

The equilibrium point of Stackelberg game (SE) is a Nash equilibrium (NE) between the leader (ESP) and followers (miners). At the NE point of the game, players can not change their strategies to obtain greater profit without damaging the profit of other players. In this paper, the SE point (ω_i^*, p_i^*) is defined as follows:

Definition 1. *Let ω_i^* and p_i^* be the optimal computing resources purchased by the i-th miner and the corresponding price, respectively, where $\boldsymbol{p^*} = \{p_1^*, p_2^*, ...p_N^*\}$. The point (ω_i^*, p_i^*) is the Stackelberg NE point if it satisfies the following conditions:*

$$U_s(\boldsymbol{p^*}, \boldsymbol{\omega^*}) \ge U_s(\boldsymbol{p}, \boldsymbol{\omega^*}), \quad (7)$$

$$U_i({\omega_i}^*|\boldsymbol{\omega^*_{-i}}, \boldsymbol{p^*}) \ge U_i(\omega_i|\boldsymbol{\omega^*_{-i}}, \boldsymbol{p^*}), \quad (8)$$

where $\boldsymbol{\omega^*_{-i}} = \boldsymbol{\omega^*}\backslash\{\omega_i^*\}$.

Next, we use the method described above to sovle the equilibrium point of the game. First, given the computing resource prices profile, we solve the optimal computing resource demands of miners in the lower stage. Subsequently, we deduce the optimal computing resource prices of ESP in the upper stage.

A. Lower stage (miners side) analysis

Before solving the equilibrium point, we first prove its existence and uniqueness in the miners' sub-game through the following proposition.

Proposition 1. *The NE point in the miners' sub-game exists and is unique.*

Proof. The first and second order derivatives of the miners' revenue function (3) can be written as follows:

$$\frac{\partial U_i}{\partial \omega_i} = R_i \frac{\sum\limits_{j\in\mathcal{N}\backslash\{i\}}\omega_j + \omega_b}{(\sum\limits_{j\in\mathcal{N}}\omega_j + \omega_b)^2} - p_i, \quad (9)$$

$$\frac{\partial^2 U_i}{\partial {\omega_i}^2} = (-2)R_i \frac{\sum\limits_{j\in\mathcal{N}\backslash\{i\}}\omega_j + \omega_b}{(\sum\limits_{j\in\mathcal{N}}\omega_j + \omega_b)^3} \le 0. \quad (10)$$

Therefore, the miners' revenue function is strictly concave, and there must exist a unique ω_i^* which is the Nash equilibrium point in the miners' sub-problem. To ensure the positivity of the utility function U_i, we have $R_i/\sum_{j\in\mathcal{N}}\omega_j > p_i$. Let the equation in (9) be zero, we can get the optimal computing resource demand is:

$$ {\omega_i}^* = \begin{cases} 0 & , if \frac{R_i}{\sum\limits_{j\in\mathcal{N}}\omega_j + \omega_b} < p_i \\ G(1-\frac{p_i}{R_i}G) & , else \end{cases}. \quad (11)$$

where

$$G = \frac{(N-1) + \sqrt{(N-1)^2 + 4\omega_b\sum\limits_{j\in\mathcal{N}}\frac{p_j}{R_j}}}{2\sum\limits_{j\in\mathcal{N}}\frac{p_j}{R_j}}. \quad (12)$$

Theorem 1. *The unique Nash equilibrium for the i-th miner is given by*

$${\omega_i}^* = G(1-\frac{p_i}{R_i}G), \forall i. \quad (13)$$

Proof. According to (9), for each miner i, we have

$$\frac{\sum\limits_{j\in\mathcal{N}\backslash\{i\}}\omega_j + \omega_b}{(\sum\limits_{j\in\mathcal{N}}\omega_j + \omega_b)^2} = \frac{p_i}{R_i}. \quad (14)$$

Then, we take the summation of (14) for all miners yields, we have

$$\sum_{i\in\mathcal{N}}\frac{\sum\limits_{j\in\mathcal{N}\backslash\{i\}}\omega_j + \omega_b}{(\sum\limits_{j\in\mathcal{N}}\omega_j + \omega_b)^2} = \sum_{i\in\mathcal{N}}\frac{p_i}{R_i}, \quad (15)$$

then we get

$$\frac{(N-1)\sum\limits_{j\in\mathcal{N}}\omega_j + N\omega_b}{(\sum\limits_{j\in\mathcal{N}}\omega_j + \omega_b)^2} = \sum_{i\in\mathcal{N}}\frac{p_i}{R_i}. \quad (16)$$

According to (9), we have

$$\sum_{j\in\mathcal{N}}\omega_j=\frac{(N-1)+\sqrt{(N-1)^2+4\omega_b\sum\limits_{j\in\mathcal{N}}\frac{p_j}{R_j}}}{2\sum\limits_{j\in\mathcal{N}}\frac{p_j}{R_j}}-\omega_b\,. \quad (17)$$

By substituting (14) into (17), by simple transformations, we can obtain the Nash equilibrium for the i-th miner as shown in (13).

B. Upper stage (ESP side) analysis

For any price by the ESP, each miner has a unique Nash equilibrium point, so the ESP's revenue can be maximized by setting a reasonable price.

By substituting (13) into (4), we have the ESP's revenue fuction as follow:

$$U_s=\sum_{i\in\mathcal{N}}p_iG(1-\frac{p_i}{R_i}G)-c\left(G-\omega_b+\omega_0\right)+a\ln\left(1+b\omega_0\right)\,. \quad (18)$$

Let $K=1+\sum\limits_{t\in\mathcal{N}\backslash\{i\}}p_t$, $X=\sum\limits_{j\in\mathcal{N}}p_j-c$, $J=\partial G/\partial p_i$, $H=\partial^2G/\partial {p_i}^2$, $W=\sum\limits_{j\in\mathcal{N}}\frac{p_j^2}{R_j}$. Then we caculate the first order and second order derivatives of (18), which are given as follows:

$$\frac{\partial U_s}{\partial p_i}=GK-2\frac{p_i}{R_i}G^2+XJ-2GJW\,, \quad (19)$$

$$\frac{\partial^2U_s}{\partial {p_i}^2}=KJ-2\frac{G^2}{R_i}-8\frac{p_i}{R_i}GJ-2W\left(J^2+H\right)+XH+J\,. \quad (20)$$

Because $G\geq 0$, $J\leq 0$, $H\geq 0$, we can get $\frac{\partial^2U_s}{\partial {p_i}^2}\leq 0$. So $U_s(\mathbf{p})$ is a strictly concave function, and there is a unique optimal price that maximizes ESP's revenue. Because the Problem 2 is a convex optimization problem, we can deal with Problem 2 with Lagrange multiplier. Then we can get the Lagrangian of the Problem 2 as:

$$L(\mathbf{p},\lambda)=U_s\left(\mathbf{p}\right)+\lambda(G-\omega_b+\omega_0-\omega_a)\,. \quad (21)$$

where λ is a nonnegative Lagrange multiplier with the constraint $\sum\limits_{j\in\mathcal{M}}\omega_j+\omega_0\leq\omega_a$.

Thus the KKT conditions that the optimal solution needs to satisfy are as follows:

$$\frac{\partial L(\mathbf{p},\lambda)}{\partial\mathbf{p}}=\begin{cases}GK-2\frac{p_1}{R_1}G^2+XJ-2GJW+\lambda J=0\\ GK-2\frac{p_2}{R_2}G^2+XJ-2GJW+\lambda J=0\\ \ldots\ldots\\ GK-2\frac{p_N}{R_N}G^2+XJ-2GJW+\lambda J=0\end{cases}, \quad (22)$$

$$\lambda\geq 0\,, \quad (23)$$

$$\lambda(G-\omega_b+\omega_0-\omega_a)=0\,. \quad (24)$$

Then we have two cases as follows:

case 1. When $\lambda=0$, we have $G-\omega_b+\omega_0-\omega_a\leq 0$. By substituting $\lambda=0$ into (22), we can derive that $\frac{\partial L(\mathbf{p},\lambda)}{\partial\mathbf{p}}=0$. Because $J\leq 0$, we have $\frac{\partial L(\mathbf{p},\lambda)}{\partial\mathbf{p}}>0$. This contradicts the presumption. Thus, the asumption that $\lambda=0$ does not hold.

case 2. When $\lambda>0$, we have $G-\omega_b+\omega_0-\omega_a=0$. With (22) and (24), we can solve the optimal value of $U_s^*(\boldsymbol{p})$.

Then we use Bisection method to iteratively solve the optimal unit price. Through constant iterations until $\left\|\mathbf{p}(t+1)-\mathbf{p}(t)\right\|_1<\varepsilon$, with the precision threshold ε. Since the revenue function $U_s(\mathbf{p})$ is concave on each p_i, thus $\mathbf{p}^*$ exists and is unique. The optimal price is the NE solution, $\mathbf{p}^*=\mathbf{p}(t)$. In summary, $\boldsymbol{p}^*$ is the unique NE solution. The distributed algorithm to find the NE points of miners and ESP is summarized in Algorithm 1.

Algorithm 1: Nash equilibrium calculation algorithm for miners and ESP.

1: **Initialization:**
   Set initial input $\mathbf{p}=\{p_1,p_2,......p_N\}$, $\lambda=\lambda_0$, $t\leftarrow 1$, precision threshold ε;
2: **repeat**
3: Each miner i decides its computational demands μ_i^* as shown in (13) ;
4: ESP obtains the optimal price $\mathbf{p}^*$ and Lagrange multiplier λ by solving (22) and (24) with Bisection method. Then ESP sents the unit computing resource price to all miners;
5: **until** $\left\|\mathbf{p}(t+1)-\mathbf{p}(t)\right\|_1<\varepsilon$
6: **Output:** optimal demand $\boldsymbol{\mu}^*$ and optimal price $\boldsymbol{p}^*$.

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, we conduct simulations to verify the effectiveness of the proposed scheme. Specifically, we consider one ESP, one vehicle and 100 miner nodes ($N=100$) in this scenario. The simulation process is done using MATLAB. The simulation parameter values are in the TABLE I.

TABLE I: Default Parameter Values

Parameters	**Values**
Mining reward, R	50
Profit coefficient, a	20
Profit coefficient, b	0.5
Transaction fee rate, r	0.01
Delay factor, τ	0.001
Reward sharing factor, α	$[0,1]$

The impact of the ratio of ESP's computing resources on the average revenues of miners, the revenue of ESP are evaluated in Figures. 2-5, respectively. In Fig. 2, we can observe that the average revenues of miners gradually decreases with the increase of the ratio of ESP's computing resources in the total, α. When α increases, the proportion of computing resources used by ESP to provide computing services to miners decreases, and the computing power that miners can purchase decreases. The lower probability of successful mining by miners leads to a decrease in the total revenue of miners. In addition, when

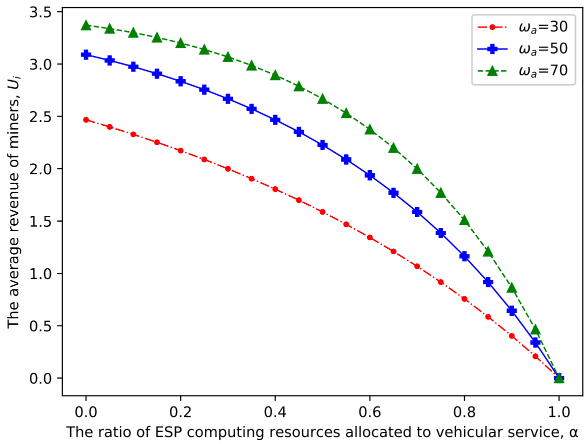

Fig. 2: The average revenues of miners vs. the ratio of ESP's computing resources allocated to vehicular service.

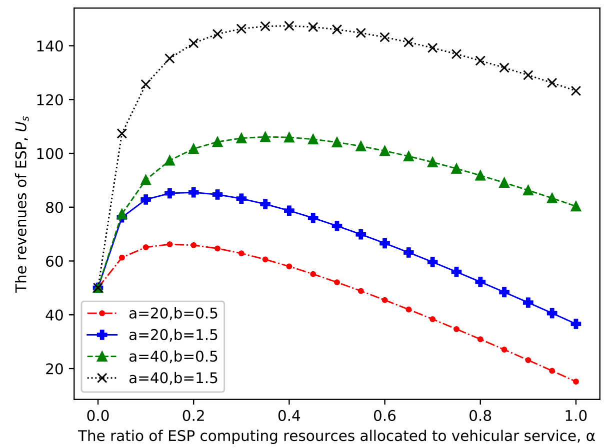

Fig. 4: The revenue of ESP vs. the ratio of ESP's computing resources allocated to vehicular service.

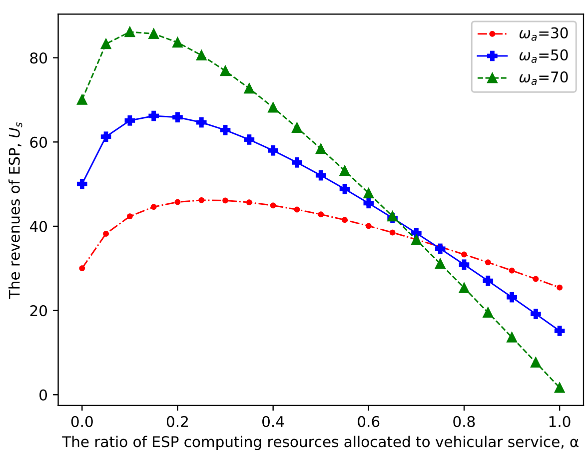

Fig. 3: The revenue of ESP vs. the ratio of ESP's computing resources allocated to vehicular service.

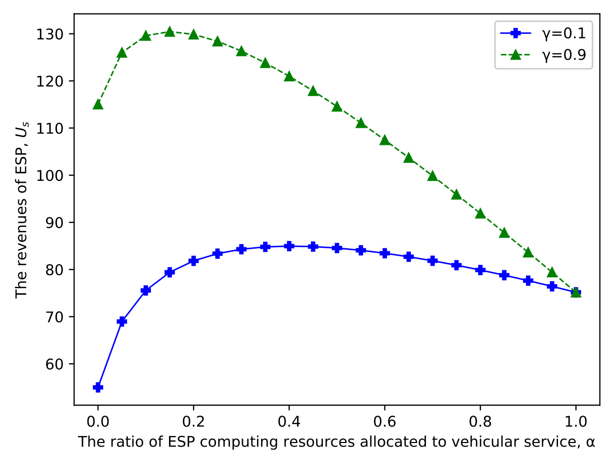

Fig. 5: The revenue of ESP vs. the ratio of ESP's computing resources allocated to vehicular service.

the total computing resource of ESP increases, because the ratio of ESP's computing resources in the total unchanged, the number of computing power purchased by each miner increases, resulting in a increase in the average income of miners.

As shown in Fig. 3, as the ratio of ESP's computing resources in the total α increases, each revenues curve of ESP has a maximum value. As the total computing power of ESP ω_a increases, the proportion of computing resources used by ESP for mining tasks increases. This is because when the computing power of ESP is high enough and the total computing power of other users in the blockchain network remains unchanged, the more computing services ESP provides to miners, the higher the probability of successful mining. This incentivizes miners to buy more computing resources from ESP. In additon, because more computing power leads to more computing costs, when the computing power of ESP used for vehicular services gradually increases, at a certain point α, ESP income decreases.

In Fig. 4, for fixed the ratio of ESP's computing resources in the total α, as the revenue coefficient of vehicular services a and b increase, the revenues of ESP and the optimal computing power distribution ratio increase. This is because that under the condition that other conditions remain unchanged, as the revenue coefficient a increases, the revenue of ESP on vehicular services increases, so that ESP will provide more computing services for vehicular services to maximize its revenues.

However, the previous pictures are based on the honesty and credibility of ESP. In order to study the revenues of ESP when the ESP is untrustworthy, we introduce the probability of not performing mining tasks, γ. We consider a model where ESP does not perform the miner's mining task with the probability

γ. As shown in Fig. 5, the revenues of ESP increases with the increase of the probability γ. This is because that when the ESP does not perform the mining tasks of the miners, the computing cost of the ESP decreases. When the probability γ increases, ESP will provide more computing power for miners to buy, so as to obtain more revenues and reduce computing costs.

V. Conclusion

In this paper, we have proposed the optimal computing resource allocation strategy in mobile blockchain network, considering both mining services and other computing services. We have modeled the interaction among the ESP and miner nodes as a two-stage Stackelberg game and obtained the optimal edge computing demand and the corresponding price of each miner by solving the Nash equilibrium of the game. We have compared the revenues of ESP under different proportions of vehicular services and mining services. Simulation results show that the more computing power ESP has, the more computing services it will provide for miners. When the revenues coefficient of ESP on vehicular services increases, ESP will provide more computing resources for vehicular services to obtain maximum benefits. In addition, as the increase of the probability of not performing mining tasks, the revenues of ESP increases.

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