Blockchain Based Spectrum Sensing: A Game-Driven Behavior Strategy

Pei Lv[1,2] ,Hangsheng Zhao[1] ,Jianzhao Zhang[2]
1. Nanjing University of Posts and Telecommunications, Nanjing, China
2. The Sixty-third Research Institute, National University of Defense Technology, Nanjing, China
lvpei_1123@163.com, zhaohs@njupt.edu.cn, jianzhao63s@nudt.edu.cn
Corresponding Author: Hangsheng Zhao Email: zhaohs@njupt.edu.cn

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***Abstract*—Spectrum sensing is an important step of *Dynamic Spectrum Access (DSA)*. However, the existing sensing technology are limited by the scarcity of sensing nodes, the narrow sensing range, and the security issues. In this paper, *Crowd Sensing (CS)* is used to collect sensed data with a large number of mobile devices equipped with sensors to ensure reliability and sensing range. In order to solve *single point of failure* caused by the vulnerability of the *cluster* in CS, we used the characteristics of blockchain (i.e. de-centralization and de-trust) to ensure the security and correctness of the spectrum trading process. Specifically, a Blockchain Based Spectrum Sensing (BBSS) system is proposed, in which requester recruit sensing workers to involve in spectrum sensing, sensing workers obtain benefits by participating in spectrum sensing and miner verifies and packages transactions into the blockchain. In particular, the recruitment and sensing worker's response is modeled as a Reward-Sensing-time game, and the strategy of requester is the total reward *R*, and the strategy of sensing worker is the sensing time t. We proved that both of them can adopt strategies to maximize their own benefits. Simulation results show that requester benefit increases with the growing number of sensing workers, but the amplification is smaller and smaller. A certain sensing worker who adopted strategy can achieve larger benefit compared with random allocation of sensing time when the number of sensing workers is smaller (less than 500) in the system.**

Keywords*—*crowd sensing; dynamic spectrum access; specrtum sensing; blockchain

I. Introduction

With the large-scale deployment of 5G network, a large number of devices are connected to the Internet of Things (IoT), resulting in an increasing scarcity of spectrum resources [1]. *Dynamic Spectrum Access* (DSA) is widely recognized as an effective way to improve the spectrum utilization [2], and spectrum sensing is an important step of DSA. However, there exist three problems to be solved in real-world scenarios. Firstly, the sensing results of individual user are unreliable due to fading and shadowing effects [3]. Secondly, individual user is limited by the sensing range, which reduces the spatial coverage of spectral data. Thirdly, individual user is vulnerable to malicious attacks which will result in the failure of sensing task [4]. Therefore, the key to the practical application of DSA is to solve the reliability, validity and security issues of individual user sensing.

Crowd Sensing (CS) [5], as an emerging sensing technology, has received wide attention recently. CS utilizes a large number of mobile devices equipped with sensors (such as smartphones, tablets, vehicle-equipped wireless devices, etc.) to opportunistically sense and upload data to the *Sensing Task Publisher* (requester), which receives the sensed data and distributes rewards to the mobile device (collectively referred to as the sensing worker). CS is characterized by a large number of sensing workers and high mobility. On the one hand, multi-worker participation ensures the reliability and security (i.e. less likely to be attacked). On the other hand, utilizing the mobility of sensing worker can greatly improve the scope of sensing [6]. However, most of the existing CS technologies rely on the *cluster* to process the sensed data and generate the perception results. The *cluster* may suffer from malicious nodes attacks which cause single point of failure [7]. In addition, since the sensed data contains privacy data such as its own geographic location information, it requires all the sensing workers involved in CS trust each other [8].

Blockchain is a growing list of encrypted records, referred as *blocks* usually [9]. Blockchain enables the nodes in the chain to implement untrusted peer-to-peer transactions by utilizing data encryption, time stamps, distributed consensus and incentive mechanisms, so as to solve the problems of high trust, low efficiency and unsafe data storage in the centralized system [10]. With the rapid growth of research and application of blockchain, it is considered as the fifth generation of Internet disruptive technology after mobile Internet [11]. To be brief, blockchain can be used as a distributed, open, and unmodifiable *ledger* [12~13], which is a decentralized accounting system consisting of credit records and the liquidation of credit records in essence [14]. Blockchain enables distributed recording of data and storage [15]. This technology enables each node to record and read public accounts, and all the nodes jointly monitor and ensure its correctness.

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In view of these advantages, a large number of scholars have introduced blockchain technology into spectrum management. H. Zhang considered the applicability of blockchain in CBRS (Citizens Band Radio Service) spectrum sharing system [16]. He believed that utilizing the advantage of de-trust and decentralization of blockchain can help reduce the transaction cost in CBRS through automating the process of signing contracts, agent and data exchange. Kotobi and Bilen presented a blockchain-based spectrum sharing protocol [17]. In this paper, *primary user* auctions the idle spectrum to the *secondary user*, who earns access to the spectrum by paying encrypted currency. Both auctions and payments are recorded in the blockchain. Like bitcoins, encrypted currencies can be obtained by exchanging traditional legal currencies or helping maintain blockchains. The simulation results show that the performance of the proposed protocol is better than that of the traditional spectrum sharing protocol in moderate and severe fading scenarios. [18] puts forward the concept of *spectrum sensing as a service*, which aims to implement spectrum sensing by recruiting *helper nodes*. Recruitment information is published through *smart contract* running on the blockchain. The *helper nodes* are rewarded after completing the sensing task and the blockchain is updated through *miners*. The simulation results show that the algorithm can effectively identify malicious attacks and motivate more *helper nodes* to participate in spectrum sensing on the basis of guaranteeing system benefits.

Existing research mostly focused on reducing transaction costs in spectrum sharing systems [16~17] by taking advantage of the de-centralization and de-trusting characteristics of blockchain without considering the benefits of *secondary users*. Some assumed that the *helper nodes* randomly choose whether to participate in spectrum sensing or not while ignoring the intelligence of the *helper nodes* themselves [18], i.e. intelligently choose whether to participate and how to participate in spectrum sensing. In this paper, we combined blockchain and CS to model spectrum sensing. To be specific, it is modeled as a Reward-Sensing-time game, in which requester and sensing worker strategically choose sensing reward and sensing time to maximize their own utilities.

II. Blockchain Based Spectrum Sensing

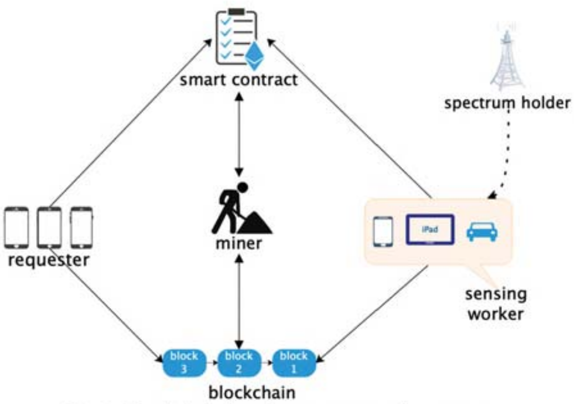

Fig. 1. blockchain based spectrum sensing system

Considering the spectrum sensing system shown in Fig. 1, the Blockchain Based Spectrum Sensing (BBSS) system mainly consists of six parts: spectrum holder, requester, sensing worker, miner, smart contract and blockchain. ***Spectrum holder*** has the ownership and priority over spectrum, it has the incentive to rent the idle spectrum to get benefits. ***Requester*** can bid the spectrum once it accurately knows the state of spectrum holder (occupied or idle). Therefore, requester acts both as a *claimant* for broadcasting spectrum sensing tasks and a potential *tenant* for spectrum holder's idle spectrum. ***Sensing worker*** (such as smartphone, tablet, vehicle-equipped wireless device, etc.) accepts the sensing task published by requester, and gets certain reward after completing the task through its own sensor. By utilizing many sensing workers and their mobility, the resolution and coverage of spectrum sensing can be greatly improved. ***Smart contract*** is the *credential* for requester to publish a sensing task, which contains information about the sensing task, such as task reward, upper and lower bounds of detection probability and false alarm probability, and spectrum bidding information. ***Miner*** plays a role in verifying the quality of sensed data, broadcasting and packaging completed transactions in the system. Miner is not specific in the system. Miner should get a solution to a mathematical problem by trial and error. The first miner to get an approximate solution will have the opportunity to obtain the right of accounting and become *miner of this transaction*. The proof of work (trial and error) consumes a lot of energy, so *miner of this transaction* will receive a certain reward when it completes its task, and the remaining miners who are not *miner of this transaction* will also receive a small reward to motivate them to participate in accounting. ***Blockchain*** acts as a *ledger* to store the transaction information between the requester, sensing workers and miner.

Thanks to the de-centralized structure of the blockchain (each miner in the chain has the opportunity to participate in accounting), BBSS helps alleviate the single point of failure of the *cluster* in traditional CS. In addition, each of the miners in the blockchain owns a copy of the complete transaction information to improve the stability. Moreover, the transaction information on the blockchain is encrypted by public-private key pairs, and its reverse decryption is almost impossible, which can greatly improve the information security. In BBSS systems, smart contracts are used to handle requester's sensing requests instead of centralized server. Smart contracts are essentially unmodifiable code running on a blockchain. Once the preset conditions are met, smart contracts will be automatically executed. This mechanism also helps ensure the rights of the sensing workers, such as preventing malicious behavior. (i.e. the requester receives a perception result and refuses to pay a fee)

Blockchain based spectrum sensing is accomplished through the following five steps:

step 1: The requester publishes sensing tasks in the form of smart contracts. The requester specifies the Service Level Agreements (SLA) in the smart contract, which includes the total reward for the task (i.e. the total reward shared by all sensing workers), the sensed data quality requirements, lower and upper bounds of the detection probability and the false alarm probability.

step 2: The sensing workers look up the sensing tasks and report their own *sensing strategy*. *Sensing strategy* mainly includes the level (such as sensing time, sampling rate, etc.) of the sensing task. On the one hand, long sensing time and high sampling rate require more energy and should be paid more. On the other hand, the sensing worker should be paid more than the cost of itself.

step 3: Miner becomes *miner of this transaction* in way of proof of work and broadcasts the results to the sensing workers. Sensing workers participating in the task upload the data by calling the *specific functions* of the smart contract after completing the task. The data upload process requires a fee for the sensing worker, which in fact is pre-existing in the blockchain before the sensing task is accepted. This mechanism can effectively mitigate DDoS (Distributed Denial of Service) and false reporting attacks on malicious workers [19]. (*miner of this transaction* hereinafter referred to as miner).

step 4: Miner verifies the sensed data and packages transactions into blockchain. Miner processes the sensed data according to the pre-set SLA in smart contract. Processing the sensed data mainly includes generating the sensing results, such as using the principle of large numbers to determine whether the spectrum is occupied or not (i.e. if more than half of the sensing workers think the spectrum is occupied, the spectrum is occupied). Miner packaged the transaction into the blockchain and received a certain reward. Overall, the sensing worker is rewarded for sensing high-precision data, and the miner is rewarded for packaging transactions, both of which benefit from the BBSS system. In addition, both benefits of them are unmodified code in smart contracts, reward distribution does not require third-party participation, so the BBSS system can encourage more sensing workers and miners to join in.

step 5: The requester accepts the perceived results and decides whether to continue the task. Once the requester accepts the perceived results, if it is satisfied with the perceived results, it can choose to terminate the task and recover the remaining remuneration and broadcast the termination decision to all miners and sensing workers, which stop working immediately upon receiving the command. If the requester is not satisfied with the perceived results, the requester can choose to continue the task and continue to receive the perceived results.

The flow chart of BBSS is shown in Fig.2 (with some details omitted and only the important elements of the system included).

III. Behavior Strategy Based on Reward-Sensing-Time Game

Considering BBSS system discussed in Section II. First,

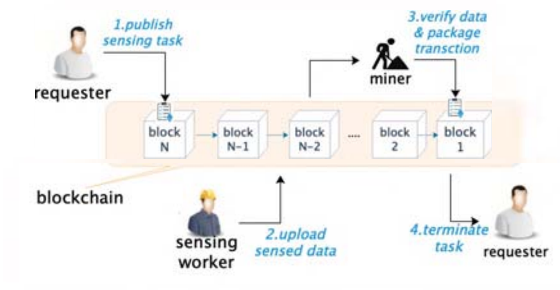

Fig. 2. flow chart of BBSS

a requester with spectrum access requirements publishes a sensing task in the form of smart contract with a total reward of $R > 0$. Then, the ith sensing worker sw_i of set $SW = \{sw_j, j = 1,2, \dots n\}$ reports its strategy t_i (sensing time) based on its own benefit. Specially, $t_i = 0$ means sw_i does not participate in this sensing task. $sw_i's$ sensing cost is $t_i \times k_i$, where k_i denotes $sw_i's$ unit cost. Then $sw_i's$ sensing benefit u_i can be expressed as:

$$u_i = \frac{t_i}{\sum_{j\in N} t_j} R - t_i \times k_i \tag{3.1}$$

The first item in the formula is expressed as the partial reward of sw_i, the second item denotes sensing cost, and the difference between them is expressed as $sw_i's$ benefit. Notice that $k_i \in K, K = \{\beta_1, \beta_2, \dots \beta_l\}$. We use n_j denotes number of sensing workers with cost β_j, so we have $n = \sum_{\beta_j \in K} n_j$. Furthermore, we assume that the sensing worker with the same unit cost adopts the same strategy.

In this system, we assume that sw_i choose $t_i = 0$ with the probability of $f(R)$, and $t_i > 0$ with the probability of $1 - f(R)$:

$$t_i = \begin{cases} 0 & f(R) \\ > 0 & 1 - f(R) \end{cases} \tag{3.2}$$

$f(R)$ is a non-incremental function of the total reward R published by requester, that is, with the increase of R, there are more sensing workers in the system.

The benefit of requester after publishing the task and successfully accessing the spectrum can be written as [20]:

$$u_0 = \lambda \log\left(1 + \sum_{i\in N} \log(1 + t_i)\right) - R - C_{bid} \tag{3.3}$$

The first item in the formula is the revenue of requester's success access to the spectrum (e.g. data transmission), where λ is a system parameter, the $\log(1 + t_i)$ term represents the requester's diminishing return on the work of sensing worker with unit cost β_i, and the outer log term reflects the requester's diminishing return on sensing workers. The second item is the total reward paid by the requester to the sensing workers and the third item is the rental of the spectrum together with the fee of miner.

In this model, the goal of requester is to set the optimal value of R to maximize (3.3) while $sw_i \in SW$ intelligently determines the sensing time t_i to maximize sensing benefits (3.1). This model can be modeled as a *Stackelberg game*. In particular, we refer to BBSS as Reward-Sensing-time game. This game is divided into two phases: a) requester releases total sensing reward R. b) $sw_i \in SW$ make its own strategy t_i to maximize sensing benefits.

Therefore, in Reward-Sensing-time games, requester is the leader and sensing worker is the follower. Both of them are players. And the strategy of requester is total reward R, $sw_i's$ is the sensing time t_i. The requester can predict the strategy of the sensing worker to set the optimal value of R to maximize its own benefits. Let $t = (t_1, t_2, \dots, t_n)$ as a strategy set for all the sensing workers, t_{-i} denoted as strategy set except sw_i, so $t = (t_1, t_2, \dots, t_n)$ can be rewritten as $t = (t_i, t_{-i})$.

In the Reward-Sensing-time game, we define the Nash Equilibrium (NE):

Strategy set for all the sensing workers $(t_1^{ne}, t_2^{ne}, \dots, t_n^{ne},)$ is the Nash Equilibrium for the Reward-Sensing-time game, if and only if, for any sensing worker $sw_i \in SW$ satisfied:

$$u_i(t_i^{ne}, t_{-i}^{ne}) \geq u_i(t_i, t_{-i}^{ne}) \tag{3.4}$$

where $t_i \geq 0$, u_i is the sensing benefit defined in (3.1). Nash Equilibrium infers that sensing workers cannot increase its own benefits by changing the current strategy. The existence and uniqueness of the Nash Equilibrium enables the requester to choose R by predicting the strategy of the sensing worker to maximize its own benefits.

A. Behavior Strategy of Sensing Workers

In order to study $sw_i's$ optimal strategy $B_i(t_{-i})$, we calculate the derivatives of u_i with respect to t_i:

$$\frac{\partial u_i}{\partial t_i} = \frac{-Rt_i}{(\sum_{j\in N} t_j)^2} + \frac{R}{\sum_{j\in N} t_j} - k_i \tag{3.5}$$

$$\frac{\partial^2 u_i}{\partial t_i^2} = -\frac{-2R\sum_{j\in N, j\neq i} t_j}{(\sum_{j\in N} t_j)^3} < 0 \tag{3.6}$$

Notice the second derivative of u_i is negative, then u_i is convex function in t_i. Therefore, $B_i(t_{-i})$ exists and is unique given R and t_{-i}. Note that when $t_{-i} = (0)$, sw_i can set $B_i(t_{-i})$ to a small positive number, in which case, sw_i can obtain rewards close to R. As a result, we only consider $\sum_{j\in N, j\neq i} t_j > 0$.(i.e. at least two sensing workers participate in spectrum sensing). Let the first-order derivative to be zero, we can get:

$$t_i = \sqrt{\frac{R\sum_{j\in N, j\neq i} t_j}{k_i}} - \sum_{j\in N, j\neq i} t_j \tag{3.7}$$

If (3.7) is positive, $sw_i's$ optimal strategy $B_i(t_{-i}) = t_i$. If (3.7) is negative, sw_i choose not to participate in spectrum sensing. Therefore, we can get:

$$B_i(t_{-i}) \begin{cases} 0 & if \;\; R < k_i\sqrt{\sum_{j\in N, j\neq i} t_j} \\ \sqrt{\frac{R\sum_{j\in N, j\neq i} t_j}{k_i}} - \sum_{j\in N, j\neq i} t_j, & else \end{cases} \tag{3.8}$$

From the above analysis, we can design Nash Equilibrium algorithm based on Reward-Sensing-time game. Notice that, $t_i^{ne} = \frac{(n_0-1)R}{\sum_{\beta_k\in K_W} n_k\beta_k}(1 - \frac{(n_0-1)\beta_j}{\sum_{\beta_k\in K_W} n_k\beta_k})$,

Algorithm 1: Computation of the NE

Sort the unit costs in K, $\beta_1 < \beta_2 < \beta_3 \dots < \beta_l$;
$K_W \leftarrow \emptyset$;
Let $j \in [1, l]$ be the smallest such $\sum_{k=1}^{j} n_k \geq 2$;
$j \leftarrow j + 1$;
while $j \leq l$ *and* $\beta_j < \frac{\beta_j + \sum_{k=1}^{j-1} n_k\beta_k}{\sum_{k=1}^{j-1} n_k}$
 if $n_j > 0$ **then** $K_W \leftarrow K_W \cup \{\beta_j\}$;
 $j \leftarrow j + 1$;
end
$n_0 \leftarrow \sum_{\beta_k\in K_W} n_k$;
for each $\beta_j \in K_W$ **do**
 $\tilde{t_j} = \frac{(n_0-1)R}{\sum_{\beta_k\in K_W} n_k\beta_k}(1 - \frac{(n_0-1)\beta_j}{\sum_{\beta_k\in K_W} n_k\beta_k})$
end
$PSW \leftarrow \{i | k_i \in K_W\}$;
for each $i \in N$ **do**
 if $i \in PSW$ **then** $t_i^{ne} = \tilde{t_j}$, such that $k_i = \beta_j$;
 else $t_i^{ne} = 0$;
end
return $t^{ne} = (t_1^{ne}, t_2^{ne}, \dots, t_n^{ne})$

where K_W is the cost set of sensing workers which participate in the sensing task.

Proof. Let $n_0 = |PSW|, n_0 \geq 2$, where PSW is the set of sensing workers which participate in the task. We use $\bar{t}$ instead of t in (3.5) and PSW instead of N. Considering $\sum_{j\in N} t_j = \sum_{j\in PSW} \bar{t}$, we have:

$$\frac{-R\overline{t_i}}{(\sum_{j\in PSW}\overline{t_j})^2} + \frac{R}{\sum_{j\in PSW}\overline{t_j}} - k_i = 0,\; i \in PSW \tag{3.9}$$

sum all the $i \in PSW$ in (3.9), we can get:

$n_0R - R = \sum_{j\in PSW}\overline{t_j} \cdot \sum_{j\in PSW} k_j$, hence, we have:

$$\sum_{j\in PSW}\overline{t_j} = \frac{((n_0-1)R)}{\sum_{j\in PSW} k_j} \tag{3.10}$$

substitute (3.10) into (3.9), and consider $\overline{t_j} = 0$ ($j \notin PSW$), we have:

$$\overline{t_j} = \frac{(n_0-1)R}{\sum_{\beta_k\in K_W} n_k\beta_k}(1 - \frac{(n_0-1)\beta_j}{\sum_{\beta_k\in K_W} n_k\beta_k}) \tag{3.11}$$

B. Behavior Strategy of Requester

As the leader in the Reward-Sensing-time game, requester can predict the strategy of the sensing worker after the total reward R is published. Therefore, requester can determine an optimal R to maximize its own benefit u_0.

Substituting the optimal strategy of sensing workers calculated by Algorithm 1 into (3.3). We can get:

$$u_0 = \lambda \log\left(1 + \sum_{i \in N} \log\left(1 + \overline{t_j}\right)\right) - R - C_{bid} \qquad (3.12)$$

where

$$\overline{t_j} = \begin{cases} \frac{(n_0-1)R}{\sum_{\beta_k \in K_W} n_k \beta_k}\left(1 - \frac{(n_0-1)\beta_j}{\sum_{\beta_k \in K_W} n_k \beta_k}\right) & if\ \beta_j \in K_W \\ 0 & if\ \beta_j \notin K_W \end{cases} \qquad (3.13)$$

where u_0 is a concave function of $R\left(R \in [0, \infty)\right)$ and $u_0 = 0$ when $R = 0$, u_0 goes to $-\infty$ when R goes to $+\infty$. Hence, there exists R^* to make u_0 the maximum.

IV. PEARFORMANCE EVALUATION

For the strategy based on Reward-Sensing-time Game discussed in Section III (hereinafter referred to as game strategies), we assume that the sensing worker's unit cost is uniformly distributed between $[1, k_{max}]$. In addition, we assume that the number of sensing workers increases from 100 to 1000 with an increment of 100 and the system parameter $\lambda = 10$.

running time: We first evaluate the trend of running time with the number of sensing workers, as shown in Fig. 3. We can see that the running time of the game strategy is almost linear with the number of sensing workers. For $O(nlogn)$ is required to compute the classification of the sensing worker (i.e. whether participating in sensing or not) and $O(n)$ is required to compute the optimal strategy (algorithm line14-line16), so the algorithm complexity is $O(nlogn)$. It is important to note that once the sensing worker classification is complete, the optimal strategy can be computed from similar expressions to improve the efficiency of the algorithm.

requester benefit: Fig. 4 shows the impact of number of sensing workers and k_{max} on requester benefit. We can see that as the number of sensing workers increases, requester benefit tends to increase, but the amplification is getting smaller and smaller. This is because, while more sensing workers can bring more benefits, the cost also increases. We can also note that when the number of sensing workers is the same, the higher the k_{max}, the lower the requester benefit. This is because the higher the k_{max}, the more discrete distribution of the cost set. According to the *while loop* in Algorithm1, if all the sensing workers have the same unit cost, then all the sensing workers will satisfy the *loop* condition and participate in spectrum sensing. When the unit cost becomes more discrete, the sensing worker has a higher probability of violating the *loop* condition, so there will be fewer sensing workers in the system, and thus the reward of the requester will be reduced.

sensing worker benefit: To study the benefit of a certain sensing worker in our system (we select sensing worker no.58, hereinafter referred to as sw58). As shown in Fig. 5, as more and more sensing workers join in spectrum sensing, sw58's benefit decreases as more competitors participate. We also compare the benefits of sw58 with different strategies: in the first part of Fig. 5, the number of sensing workers in the system is smaller, sw58 faces less competition, as a result, it can obtain higher benefit than random strategy. As the competition in the system increases, sensing worker is more competitive. Even though the worker takes the game strategy, the income still accounts for a small part of the total income, so the benefit is smaller than that of random strategy. As a result, game strategies are more practical with fewer sensing workers.

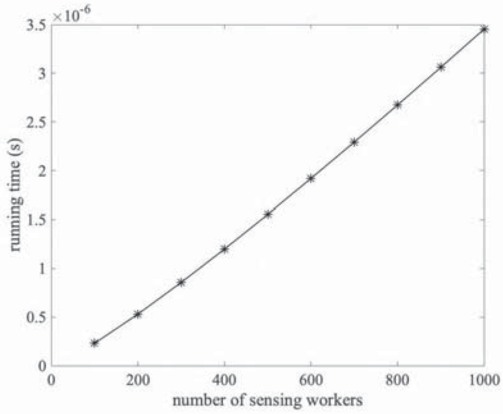

Fig. 3. running time versus number of sensing workers

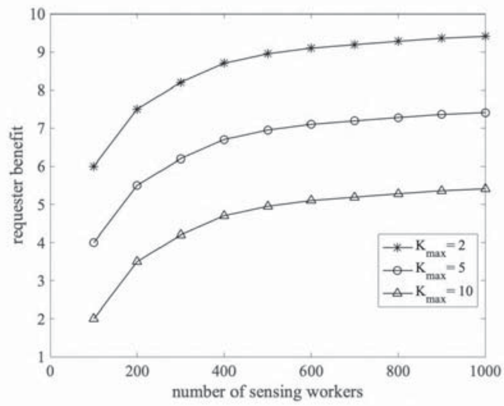

Fig. 4. requester benefit versus sw number and k_{max}

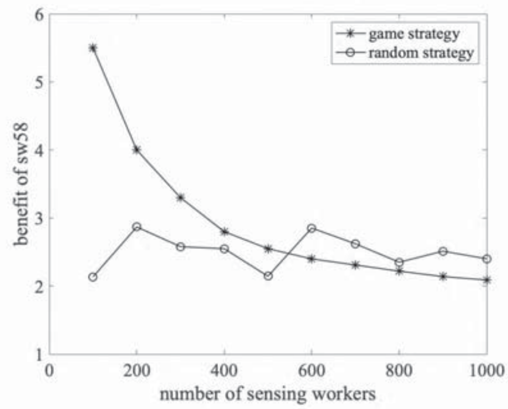

Fig. 5. benefit of sw58 with different strategies

V. CONCLUSION

To solve the reliability, validity and security problems in existing spectrum sensing, Blockchain Based Spectrum Sensing (BBSS) system is proposed in this paper. In the system, the requester first publishes the sensing task in the form of smart contract. Thereafter, the sensing worker strategically decides to how to participate in spectrum sensing (i.e. how much time should be spent in the task). Finally, the miner verifies the sensed data and packages the transaction into a blockchain. In the BBSS system, the reliability and validity of spectrum sensing can be solved by the large number and mobility of sensing workers, while the security problem can be solved by the feature of smart contract in the blockchain. In particular, we model the behavior of requester and sensing worker (i.e., publishing sensing tasks and accepting tasks) as a strategy based on the Reward-Sensing-time game in which requester is the leader and sensing worker is the follower. Sensing worker's behavior strategy is sensing time t while requester's behavior strategy is total reward R. We proved that each of them has its own optimal strategy and design an effective algorithm to find the optimal strategy for the sensing workers.

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