A Blockchain Enhanced Coexistence of Heterogeneous Networks on Unlicensed Spectrum

Hanwen Zhang, Supeng Leng, Yunkai Wei, Jianhua He

Abstract*—Due to the forecasted fast increasing cellular traffic and the already highly congested licensed spectrum, it is critical to exploit and utilize the unlicensed spectrum resources for the fifth-generation (5G) and beyond networks. A challenging problem is the coexistence of 5G and other networks with fair, reliable, and efficient sharing of the unlicensed spectrum. In this paper, we propose a blockchain-enhanced distributed spectrum sharing scheme for coexisting multiple operators and multiple WiFi APs. We design a novel lightweight and efficient consensus mechanism, named Proof of Strategy (PoG). In this consensus mechanism, the problem of spectrum sharing is used as a consensus puzzle, and the part of the unlicensed spectrum is used as the 'fee' of miners. With such a design, the computing overhead of the consensus process is expected to be reduced significantly. We develop a non-cooperative game to analyze the behavior of the miners and obtain a symmetric Bayesian Nash equilibrium under the uniform distribution of mining cost estimation. It can be found mathematically and experimentally that the strategy of the winner tends to maximize the system revenue by sharing the unlicensed spectrum resource. Furthermore, to reduce the impact of heavy interactions on system throughput, the operation of WiFi APs in the proposed scheme can be adaptively switched between 'contention mode' and 'blockchain mode' according to the network traffic load. The dynamic behavior is constructed as an evolutionary game, and the existence and uniqueness of equilibrium points are proved by theoretical analysis. Simulations demonstrated the fairness and effectiveness of the proposed blockchain-based scheme and the mode switching method for distributed spectrum sharing by heterogeneous wireless networks.

***Index Terms*—Blockchain, Spectrum Sharing, Unlicensed Spectrum**

I. INTRODUCTION

With the fifth-generation (5G) cellular networks starting to be rolled out globally, it is expected that cellular network traffic will increase at a fast pace. According to the latest Ericsson Mobility Report, the total global mobile data traffic (excluding the traffic generated by fixed wireless access) is estimated to reach around 65 EB per month by the end of 2021, and is projected to grow by a factor of around 4.4 to reach 288 EB per month in 2027. The scarcity of licensed spectrum poses key challenges to delivering sustained performance and the desired quality of service to connected mobile users [2] [3]. Due to the fast increasing cellular traffic and the already highly congested licensed spectrum, it is critical to exploit and utilize the unlicensed spectrum resources for 5G and beyond networks.

As WiFi and other networks have been using the unlicensed spectrum, a challenging problem for the coexistence of the heterogeneous wireless networks is fair, reliable, and efficient sharing of the unlicensed spectrum. This problem becomes worse due to the Covid-19 pandemic as there are increasing home working and competing indoor traffic from cell and WiFi networks. The coexistence problem of unlicensed heterogeneous networks has attracted great interest from industry and academia. 3GPP has successively launched LTE-unlicensed (LTE-U) [4], licensed assisted access (LAA) [5] and NR-unlicensed (NR-U) [6] as solutions to the coexistence problem.

Despite the existing work on the coexistence of heterogeneous wireless networks, there are still many technical challenges to be tackled to efficiently use the unlicensed bands for the coexisting networks. Several works [7] [8] [9] focus on adjusting the parameters and mechanisms of the cellular system to ensure fairness for the WiFi networks, and cellular systems are even required to learn and predict the traffic patterns of WiFi networks [10] [12] [13]. However, these schemes can only achieve limited fairness, as channel access is entirely controlled by the cellular system. In addition, even the cellular system can guarantee the fairness of WiFi networks by using contention-based MAC protocol, it may result in low efficiency of the cellular system. Coordination of multiple cellular networks with unlicensed spectrum was investigated by [9] [14]. But there is very little reported on the coordination among multiple cellular networks and WiFi networks. It is very difficult for traditional WiFi networks to coordinate with each other, due to those random and scattered mobile users. IEEE 802.11ax offers opportunities for coordination by using cellular-like protocols to schedule WiFi transmissions from the APs [15]. However, how to design an appropriate coordination mechanism between WiFi APs and cellular systems remains an open issue. On the other hand, massive nodes (such as IoT devices) in next-generation mobile networks present many challenges to the traditional centralized network management in terms of reliability and administrative cost. It is very difficult to meet the expectations of multi-stakeholders in heterogeneous networks. Most existing works on distributed

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spectrum sharing schemes [16] [17] [11] change the single-center approach to the multi-centers approach. However, these local centers can not solve the reliability problem, instead, they bring management problems as the network expands. Even a few works implemented user-based distributed mechanisms [18], the spectrum management is still affected by a third party with a vulnerable structure.

As a disruptive technology, Blockchain [19] has found many applications for virtual currency and decentralized system management [20] [21]. The features of blockchain including decentralization, transparency, immutability, availability, and security, make it perfectly suitable for distributed decision making by multiple untrusted unities. Hence, it is widely regarded as a powerful tool for distributed spectrum sharing for wireless networks. However, one of the barriers to the application of blockchain to unlicensed spectrum sharing is the excessive communication and computing overheads and the latency on the consensus processes. Conventional consensus mechanisms such as proof-of-work (PoW) and proof-of-stake (PoS) consume excessive computing power resulting in low efficiency on resource use. Existing lightweight consensus algorithms, such as proof of reputation [22], still require additional overhead. In addition, compared with traditional models, the transaction confirmation delay of blocks will reduce throughput if spectrum resources are idle. Therefore, how to make efficient blockchain-based consensus on spectrum sharing under various situations is a challenge. Furthermore, in the existing consensus mechanisms, the objectives of the consensus processes are independent of the distributed spectrum sharing problem, which means separate spectrum allocation and scheduling decisions are to be made even a consensus is reached. Even several researchers conducted the combination approaches of blockchain and spectrum sharing, most of them [23] [24] [25] [26] follow the bitcoin model, ignoring the requirements of lightweight and highly efficient consensus processes of future IoT scenarios.

Motivated by the aforementioned research problems, in this article, we propose a new blockchain-enhanced distributed unlicensed spectrum management for heterogeneous wireless networks, which may not have full trust in each other. More specifically, we propose a novel lightweight consensus mechanism, named Proof of Strategy (PoG), which combines with the processes of consensus and distributed spectrum allocation. With the new PoG consensus mechanism, miners (coexisting networks) who work out a fair spectrum allocation strategy with the maximal global system revenue will be the winner of the consensus. It can be proved that the global revenue of the proposed strategy is close to the global revenue that can be achieved by a central spectrum allocation system.

The contributions of the paper are summarized as follows:

- We propose a multi-operators multi-APs distributed spectrum management scheme for unlicensed spectrum sharing, where blockchain is firstly introduced into unlicensed spectrum management among cellular systems and WiFi networks. With the proposed scheme, fair spectrum sharing among untrusted heterogeneous wireless networks is achieved while maintaining high efficiency of spectrum utilization.
- A lightweight consensus mechanism PoG is designed for the spectrum sharing task. Miners propose spectrum allocation solutions that may allocate more spectrum to themselves as a reward for mining, and the miner with the greatest global revenue will win. This process is modeled as a non-cooperative game. The equilibrium points indicate that it is optimal but does not require any additional spectrum for competing with other potential winners. In other words, the spectrum allocation solution that seeks to maximize global revenue becomes the best strategy for all miners. By setting the spectrum sharing problem as the consensus puzzle, extra computing overhead unrelated to the distributed spectrum sharing can be avoided. Simulation results demonstrate the effectiveness and fairness of the proposed distributed spectrum sharing scheme and the PoG consensus mechanism.
- To reduce the effect of complex interactions on throughput, we investigate the transaction validation delay and design a mode switch algorithm for WiFi APs, which can switch between 'contention mode' and 'blockchain mode' according to network conditions. In this way, the unnecessary overhead caused by waiting for transaction validation with unused spectrum is avoided. Based on CSMA/CA MAC protocol, we model the dynamic behavior of APs as an evolutionary game. The existence and uniqueness of Nash equilibrium are proved mathematically and demonstrated by simulation experiments. The simulation also shows that the lower bound of the throughput of the proposed model is the throughput of the CSMA/CA.

The rest of this article is organized as follows. Section II reviews distributed spectrum sharing and blockchain technology for unlicensed spectrum sharing. The distributed spectrum management scheme is presented in Section III. Detailed analysis of the PoG consensus mechanism is provided in Section IV. In Section V, mode switching of WiFi APs is designed and analyzed as an evolutionary game. Performance evaluation and conclusion are presented in sections VI and VII, respectively.

II. RELATED WORK

Several works have been proposed to tackle the coexistence problem of the cellular system and the WiFi networks. Almeida et al. [27] reported that in the absence of any coexistence mechanism, the throughput of Wi-Fi was reduced by 96.63% and that of LTE by 0.49%, with no obvious impact on LTE. A representative work was promoted by 3GPP. Based on R10-12, LTE-U uses carrier-aware adaptive transmission (CSAT) for the coexistence of LTE networks and Wi-Fi networks. Duty cycle (DC) was used to mute LTE so that Wi-Fi can have reasonable access to the frequency band [28]. The channel occupancy rate between LTE-U and WiFi networks is defined by the cellular system, which needs to monitor WiFi network activity for a long time to determine its optimal duty cycle to ensure fair spectrum sharing with WiFi. The CSAT-based scheme schedules periodic 'on/off' periods over which the cellular system enables or disables access to the channel. However, it is unfair for the WiFi network to fully comply with the LTE network arrangement. LAA, as part of Release 13, supports the listen before talk (LBT) mechanism, where the transmitter senses an unlicensed carrier before transmission to avoid conflicts with other LAA or WiFi nodes at a fixed or random contention Windows (CW) [29].

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Based on the above two mechanisms, serval works were been proposed. Deep reinforcement learning or deep neural network was applied in [10] [12] [13] [30] [31], where the cellular system learns the traffic of WiFi to maintain fair coexistence. However, these efforts only focus on tuning the parameters and mechanisms of cellular systems. The size of the regression window of CSMA/CA and LAA was adjusted and optimized in the [7], and the impact of IEEE 802.11ax on the coexistence problem was studied in [8]. However, these research works are still based on a contention model, which is unable to achieve efficiency maximization, and the heterogeneous coordination between WiFi and the cellular system is still lacking.

Blockchain is a disruptive technology for decentralized systems and building trust between untrusted entities. It has been widely used in the field of spectrum sharing. Most of the works have been focused on using blockchain to set up a token trade system between ordinary users or operators. Because of the spectrum sharing problem in a multi-operators wireless communication network in [23], a blockchain trust framework is proposed. A. Okon [24] proposed a blockchain-enabled approach for managing radio spectrum access between operators using smart contracts over small cellular networks. Similarly, a blockchain validation protocol is proposed to implement and ensure spectrum sharing in mobile cognitive radio networks [25]. Blockchain authorization for secure spectrum sharing in 5G heterogeneous networks was considered in [26]. The above work is a simple application of a blockchain ledger, using smart contracts to build a token exchange system between ordinary users or operators. However, due to the heavy computation and communication overhead of the PoW consensus, the existing blockchain solutions are not directly applicable to the spectrum sharing of cell-WiFi coexistence networks. Some existing lightweight schemes are facing difficulties in the design of evaluation mechanisms. For example, the evaluation mechanism of reputation is always subjective in the proof of reputation mechanism. [22] [32] [33] [34].

It can be observed that although great efforts have been made in the above studies, guaranteeing fairness and maintaining high spectrum utilization efficiency are very challenging for the coexistence of cellular systems and WiFi networks. Even if blockchain-based spectrum sharing approaches have been proposed, there is a strong need for a lightweight and efficient consensus mechanism, such as the PoG consensus mechanism proposed in this paper.

III. DISTRIBUTED SPECTRUM MANAGEMENT FRAMEWORK

We propose a collaborative spectrum sharing scheme based on blockchain for heterogeneous networks. The architecture of the proposed framework is illustrated in Fig.1. Subsequently, the detailed design of the proposed consensus mechanism PoG will be presented.

A. System Overview

We assume that there are heterogeneous networks, which comprise mobile users, WiFi APs, and small base stations. Two types of users use the unlicensed spectrum together: Small Base Stations (SBSs) and WiFi Access Points (APs). According to IEEE 802.11ax, the uplink and downlink of WiFi stations are controlled by APs, and APs still compete for spectrum by the CSMA/CA protocol. Hence, it should be noted that ‘user’ in the following paper refers to AP or SBS. In this paper, we consider a densely populated environment, where the SBSs and APs are assumed to be the communication range of each other, such as an apartment. The two SBSs depicted in Fig. 1 points to different stakeholders who may use the same infrastructure.

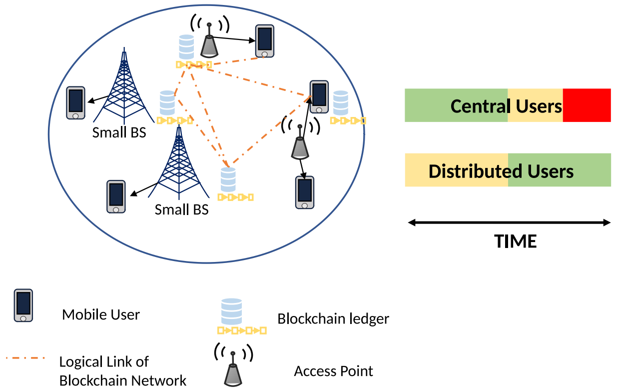

Fig. 1: The Proposed Framework.

We build a spectrum coordination model of heterogeneous users based on blockchain technology and assume participation of all cellular networks in resource coordination is mandatory, and WiFi networks join voluntarily. For ease of expression, WiFi network joining in spectrum coordination is called Blockchain CSMA/CA users (BC Users), while the others are called Conventional CSMA/CA users (CC users). To avoid the situations that a few BC users occupy a large part of resources and ensure that as many users as possible can transfer including CC users, each BC user is allowed to be allocated resources that can trigger an OFDMA transmission within each consensus period. TDMA (time division multiple addresses) is used in our framework.

Building on the idea of Duty Cycle technology of LTE-U, we divided the spectrum usage time into multiple cycles. Considering that many 3GPP members might think that fairness means that cellular nodes and IEEE 802.11 APs should have half the bandwidth [35], each cycle is proportionally allocated to different types of users. As shown in Fig. 1, green indicates the priority of spectrum use for SBSs, yellow indicates only idle, and red indicates forbidden. Cellular networks can use the yellow time slot with no or few competing WiFi networks. Red time slots are reserved for WiFi networks that are not participating in resource coordination.

In the blockchain network, the heterogeneous users will store the results of resource allocation. We use a lightweight strategy-based consensus to achieve distributed allocation, which is introduced in the next subsection. The proposed architecture can adapt to different scenarios as shown below.

Scenario with cellular users only: The proposed scheme can be used to coordinate competition among different stakeholders with only cellular users on the use of the unlicensed spectrum. While providing fair spectrum allocation to untrusted entities, spectrum allocation through mining is shown in Section IV, which can achieve performance close to the globally optimal.

Scenario with WiFi Networks only: When there are no

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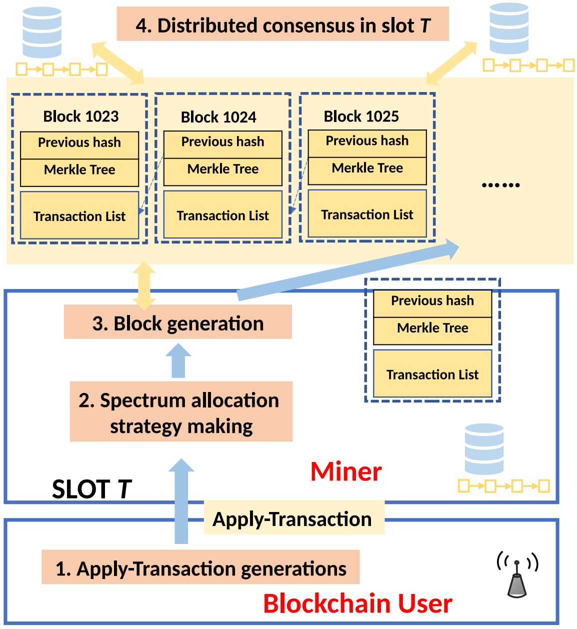

Fig. 2: Consensus Process.

scheduled SBS users, the proposed allocation model gradually degenerates into the conventional contention model.

Scenario with heterogeneous wireless networks: By planning the allocation cycle, we can ensure fairness among different types of networks users. Considering the characteristics of the contention access protocol, we allocate the first part of each cycle to central users. In this way, the CC user is forced to enter the rollback wait count, avoiding the influence of CC users on BC users who use spectrum following the allocated time.

B. Consensus Process

In conventional consensus methods (including classical PoW and PoS), the nodes which solve the puzzles fastest will win the competition and gain the reward. However, in the proposed PoG consensus mechanism [36], the users who solve the puzzle best within the predefined time, i.e., slot T, will win and gain the reward. As illustrated in Fig.2, the main procedures of the proposed consensus can be divided into the following steps: 1) Apply-Transaction generation; 2) Spectrum allocation strategy making; 3) Block generation; 4) Distributed consensus in slot T.

Step 1: *Apply-Transaction Generation:* This operation will be run by all users, who will generate an apply-transaction, including the public key, the network ID, and the type of the used MAC protocol.

Step 2: *Spectrum Allocation Strategy Making:* In every period T, miners (users) will compute an appropriate spectrum allocation strategy based on the information from the transaction pool. We set the consensus period to be the same as the spectrum allocation period. The winning strategy in consensus slot n_t will be executed in slot n_{t+h}, where h is a system parameter that can be configured depending on the actual environment. The incentive for the miner in the traditional blockchain is a coin such as bitcoin, which is directly recorded in the block. However, the incentive is more implicit in our model. Users will gain a different amount of rewards with different spectrum allocation strategies. All users may wish to propose strategies that can benefit themselves more in the form of a new block. Nonetheless, the rule in the consensus process is that the block with the maximum global revenue will win and be added to the blockchain. So the block proposed by greedy users will be unlikely added to the blockchain. To increase the probability of winning, all miners will need to propose a strategy with a trade-off between their interests and global interest. A detailed mathematical model for the analysis of user behavior will be presented in the next section.

Step 3: *Block Generation:* Upon generating their strategy, the miners will generate a new block for the competition in the next slot. The block header contains mainly two parts, the hash value of the last block and the Merkle tree root of the transaction list. Compared to bitcoin, the proposed blockchain has a smaller header with the information of the hash puzzle.

Step 4: *Consensus competition:* Before the end of the current slot, miners broadcast their blocks to the blockchain network. As the blockchain network is built over the local network, the information of new blocks can be transported to every node in a short time. Every node will receive all new blocks before the beginning of the next slot and add the block with the maximum global revenue into the blockchain.

Tamper-proofing is one of the most important advantages of blockchain. Traditional blockchain can help achieve tamper-proofing in two methods. An old block that is in the front of the blockchain is protected by the next new block which stores the hash value of the old block. The new block is protected by a hash-puzzle, which requires plenty of computation power to handle the hash-puzzle and can be verified by all the miners. In our model, the second method is not used as there is no harm if new blocks to be linked are changed. As for the blockhead, the previous hash value cannot be changed and the head of the Merkle is associated with the transaction list. The transaction list stores the spectrum allocation strategy and the global revenue of the block varies with the transaction list. If the global revenue of the block becomes smaller, it will win the consensus process. If the revenue becomes larger, it will be good for the system revenue. In conclusion, there is no need to protect a new block before it is added to the blockchain in our model. But the special method of miner rewarding will make it more difficult for an adversary to benefit from a vicious mining way.

IV. MATHEMATICAL MODEL FOR POG CONSENSUS MECHANISM

The consensus competition in this paper can be viewed as within the same type of users. For example, when a WiFi user is a miner, to improve the probability of winning, the allocation of resources to the cellular users should be made to maximize the global revenue, and vice versa. Considering that the proportion of resources allocated to one type of user is fixed, WiFi users and cellular users can be allocated resources separately. Therefore, the consensus rule can be expressed as the following model.

A. Consensus Mechanism

Like several existing works [37] [38], we assume that the average spectral efficiency is R. Consequently, the total

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transmission quantity of user $i \in N$ is $r_i = Rt_i$, where t_i is the duration of channel occupied by the user i. T is the total amount of available time. The utility $u(r)$ is defined as an α-fair function with $\alpha \in (0, 1)$.

$$u(r) = \frac{r^{1-\alpha}}{1-\alpha}, \tag{1}$$

The utility function may not be consistent with the actual situation of users, but it is introduced to measure the fairness of the users. The proposed consensus rule is to maximize the global revenue, so the miner who proposes a resource allocation strategy with the largest global revenue will be the winner. We first calculate the maximum global revenue, which can be used as assessment criteria for miners.

The global optimization problem can be formulated as the following convex problem:

$$\begin{gathered}\max_t \sum_{i\in N} \frac{(Rt_i)^{1-\alpha}}{1-\alpha} \\ 0 \leqslant \sum_i t_i \leqslant T\end{gathered} \tag{2}$$

We can get the optimal solution t^* when the first derivative is zero, which can be shown as

$$t^* = \frac{T}{|N|} \tag{3}$$

We assume that miners are as self-interested as possible and when they act as decision-makers, they will allocate the spectrum resources in ways that can benefit them. For a general user i, it will set up an optimization problem as follow:

$$\begin{gathered}\max_t \sum_{j\in N} \frac{(Rt_j)^{1-\alpha}}{1-\alpha} \\ 0 \leqslant \sum_j t_j \leqslant T \\ \boldsymbol{t_i = t^* + \beta_i}\end{gathered} \tag{4}$$

where β_i is the extra spectrum resource reserved for user i using before allocation, and it can be regarded as the reward of winning the competition. Similarly, it is also a convex problem, and the optimal solution where the first derivative is zero is as follows:

$$t(\beta_i) = \frac{T - t^* - \beta_i}{|N| - 1} \tag{5}$$

where $t(\beta_i)$ represent the optimal solution of maximizing the global revenue with the constraint of $t_i = t^* + \beta_i$.

The probability of being the winner is closely related to the decay of global revenue brought by β_i. The decay can be described by a decay ratio γ_i as

$$\gamma_i = \frac{(|N|-1)\dfrac{(Rt(\beta_i))^{1-\alpha}}{1-\alpha} + \dfrac{(Rt^* + R\beta_i)^{1-\alpha}}{1-\alpha}}{|N|\dfrac{(Rt^*)^{1-\alpha}}{1-\alpha}} \tag{6}$$

Hence, the comparison of global revenue can be converted into a comparison of γ of the proposed strategies by each user.

B. Non-cooperative Game of Miners

Next, we use the non-cooperative game to model the strategy of miners, specifically the β_i. The determination of a miner is not only affected by the utility, but also by the probability to be the winner in the consensus process. The game is to model the competition among miners, where the game solution is a Nash equilibrium.

Any user can be a miner, which can freely chosen resource allocation strategy on its own. The utility of user i being a winning miner is

$$U_i^W = t^* + \beta_i \tag{7}$$

When the user i is not successful in the consensus process, the utility function will become as

$$U_i^L = E_b \tag{8}$$

where E_b is the average resource of not being a miner and waiting for the spectrum decision from others.

When the strategies of the other users are determined, the best response of user i is

$$\begin{aligned}B(\beta_{-i}) = arg\max_{\beta_i} &\prod_{j\neq i} Prob(\gamma_i > \gamma_j) U_i^W \\ &+ [1 - \prod_{j\neq i} Prob(\gamma_i > \gamma_j)] U_i^L\end{aligned} \tag{9}$$

As the ratio γ_i is a monotone decreasing function of β_i, $\gamma_i > \gamma_j$ can be equivalent to $\beta_i < \beta_j$. Hence, equation (9) cam be rewritten as

$$\begin{aligned}B(\beta_{-i}) =& arg\max_{\beta_i} \prod_{j\neq i} Prob(\beta_i < \beta_j) U_i^W \\ &+ [1 - \prod_{j\neq i} Prob(\beta_i < \beta_j)] U_i^L\end{aligned} \tag{10}$$

Theorem 1. *Under the uniform distribution of mining cost estimation, the symmetric Bayesian Nash equilibrium of the non-cooperative game is*

$$B(\beta_{-i}) = 0 \tag{11}$$

Proof. Player/miner j takes the strategy $\beta_j = \Theta(\cdot)$. With the relationship between the bid of users and the value of the product widely used in the classic auction model, we assume $\Theta(\cdot)$ is a monotonically increasing differentiable function of cost c_i, including computation and communication resource brought by mining. $\Theta^{-1}(\beta_j)$ is the estimated cost when the bid of user j is β_j, that is $\beta_j = \Theta(c_j)$. Based on the classic auction assumptions about the value of goods, we assume the cost of each user is uniformly distributed over $[0, 1]$. Hence the expectations of spectrum resource E_b can be obtained as follows:

$$E_b = \int_0^1 t(\Theta(c_j)) dc_j) \tag{12}$$

As c_j is uniformly distributed over $[0, 1]$,

$$Prob(\beta_i < \beta_j) = Prob(\Theta^{-1}(\beta_i) < c_j) = 1 - \Theta^{-1}(\beta_i) \tag{13}$$

Hence, the best response is

$$\begin{aligned} B(\beta_{-i}) =& \underset{\beta_i}{argmax} \prod_{j \neq i} Prob(\Theta^{-1}(\beta_i) < c_j) U_i^W \\ &+ [1 - \prod_{j \neq i} Prob(\Theta^{-1}(\beta_i) < c_j)] U_i^L \\ =& (1 - \Theta^{-1}(\beta_i))^{n_m - 1} U_i^W \\ &+ [1 - (1 - \Theta^{-1}(\beta_i))^{n_m - 1}] U_i^L \end{aligned} \tag{14}$$

where n_m is the number of miners. The first order condition of the optimization problem is

$$\begin{aligned} -(n_m - 1)(1 - \Theta^{-1}(\beta_i))^{n_m - 2} \frac{d\Theta^{-1}(\beta_i)}{d\beta_i} [\beta_i + t^* - E_b] \\ + (1 - \Theta^{-1}(\beta_i))^{n_m - 1} = 0 \end{aligned} \tag{15}$$

If $\Theta(\cdot)$ is a symmetric Bayesian Nash equilibrium, the solution to the first order condition should be equal to $\Theta(c_i)$.

$$\begin{aligned} -(n_m - 1)(1 - \Theta^{-1}(\Theta(c_i)))^{n_m - 2} \frac{d\Theta^{-1}(\Theta(c_i))}{d\beta_i} \\ *[\Theta(c_i) + t^* - E_b] + (1 - \Theta^{-1}(\Theta(c_i)))^{n_m - 1} = 0 \end{aligned} \tag{16}$$

As $\Theta^{-1}(\Theta(c_i)) = c_i$, the $\Theta(\cdot)$ should satisfy

$$-(n_m - 1)[\Theta(c_i) + t^* - E_b] + (1 - c_i) \frac{d\Theta(c_i)}{dc_i} = 0 \tag{17}$$

which can be solved as

$$\Theta(c_i) = \xi (c_i - 1)^{-n_m + 1} - (t^* - E_b) \tag{18}$$

For $c_i = 0$, user i is assumed to choose to be a miner with no reward required, which is equal to $\xi(-1)^{-n_m+1} = t^* - E_b$. Hence,

$$\Theta(c_i) = (t^* - E_b)[(1 - c_i)^{-n_m + 1} - 1] \tag{19}$$

Combining equation (12) and (19), we can obtain $E_b = t^*$. As a result,

$$\Theta(c_i) = 0 \tag{20}$$

Even if we use a looser but still reasonable assumption of $E_b < t^*$ instead of equation (12), we can find that $\Theta(c_i) = 0$ still holds. The reason can be explained as follows. The exception revenue for miner i with $\beta_i = \Theta(c_i)$ is equal to t^*, which is same as the revenue at global maximum point, where $\beta_i = 0$. □

Under the proposed consensus rule, the miners asking for extra compensation may not increase the expected utility, as the probability of not winning the competition increases. $B(\beta_{-i}) = 0$ means that miners will work without claiming excessive reward by proposing greedy strategies. Therefore, the revenue of the distributed decision model will approach the maximum global revenue of the central system.

V. MODE SWITCHING AND ITS MATHEMATICAL ANALYSIS

In the case of sharing unlicensed spectrum bands, users with distributed coordination function (DCF) used in CSMA/CA cannot be forced to join the blockchain system to participate in centralized scheduling. In addition, transaction validation delay often leads to lower throughput during the spectrum idle period. To adapt to various situations, WiFi APs in the proposed framework can switch between 'contention mode' and 'blockchain mode' according to system throughput performance. Based on evolutionary game theory, this section mainly analyzes the mode selection of CSMA/CA users with the aim to improve throughput.

A. Two Work Model

1) Contention Model: In this model, the users will follow the conventional CSMA/CA. The collision probability of each packet can be expressed as with the widely used analytical model [39]:

$$\rho = 1 - (1 - \tau)^{n-1}, \tag{21}$$

where n is the number of contending stations which are assumed to have saturated traffic. Each station transmits a packet with probability τ, given by

$$\tau = \frac{2(1 - 2\rho)}{(1 - 2\rho)(CW_{min} + 1) + \rho CW_{min}(1 - (2\rho)^m)}, \tag{22}$$

where m is the maximum backoff stage and CW_{min} is the minimum backoff window. Based on [39], there is only one solution (τ, ρ) of equation (21) and (22).

Based on τ, the probability of at least one transmitting in a slot can be expressed as

$$P_{tr} = 1 - (1 - \tau)^n. \tag{23}$$

The probability that one user transmits successfully in a slot is shown as follows:

$$P_s = \frac{n\tau(1 - \tau)^{n-1}}{1 - (1 - \tau)^n}. \tag{24}$$

The normalized system throughput can be defined as follows

$$S = \frac{P_S P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr} P_S T_S + P_{tr}(1 - P_S) T_C}, \tag{25}$$

where $E[P]$ is the average payload size of an OFDMA transmission, and the T_S is the average time the channel is sensed busy because of successful transmission. T_C is the average time the channel is sensed busy by each station during a collision. σ is the propagation delay.

However, when the channel is occupied by blockchain users, the CSMA/CA users will detect that the channel is busy and will wait for channel to be available or rollback counting. Therefore, the actual average communication rate R_C is as follows:

$$R_C = min\{0, (1 - \frac{t_B}{T})\} S \tag{26}$$

where T is the time of the blockchain schedule cycle, and t_B is the time occupied by blockchain users.

2) Blockchain Model: Users under the blockchain model still follow the original MAC protocol, i.e. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) user still waits for Distributed Inter-frame Spacing (DIFS) before communicating. Because of the pre-scheduled time, users in the blockchain mode can conduct channel listening at the proper time, avoiding the detection of a busy and backoff. In blockchain mode, users with the centralized MAC protocol are placed at the front of the scheduling table. Therefore, at the beginning of each scheduling cycle, non-blockchain CSMA/CA users must begin to wait a random backoff time because they detect a 'busy' channel. Since then, the channel continues to be busy, causing its rollback count to be frozen until the blockchain mode user ends spectrum usage. So users in blockchain mode can be thought of as simply waiting for DIFS to begin non-interference transmission. Hence, the normalized system throughput can be defined as

$$R_B = \frac{m_B E(P)}{T}, \tag{27}$$

where m_B is the average number of the packet transmitting under the blockchain mode.

B. Evolution Game Model

The evolutionary game is a mathematical tool developed by biologists for predicting population dynamics [40]. We define an evolutionary game for the users as follow:

- ***Players***: Each CSMA/CA user is a player of the game. In this paper, they can dynamically choose the modes to obtain the highest utility in terms of throughput. The users can gradually change the mode selfishly by observing the action of others.
- ***Strategies***: There are only two strategies to choose, which are 'blockchain mode' and 'contention mode'.
- ***Utility***: The utility is defined as the throughput. The utility of users under the blockchain mode and contention mode is as follows respectively:

$$\begin{aligned} U_B &= R_B \\ U_C &= R_C \end{aligned} \tag{28}$$

In a dynamic evolutionary game, each individual can replicate the strategy used by the others through learning. This process of replication can be modeled by a set of differential equations, i.e., the replicator dynamics. Let the proportion of CSAM/CA users selecting blockchain mode and contention mode be expressed as $x_B = n_B/n, x_C = n_C/n$, where $n = n_B + n_C$ is the total number of CSMA/CA users/stations, and n_B and n_C are the number of CSMA/CA users under blockchain mode and contention mode. In each iteration, the users will adopt the strategy with high utility. Moreover, the game is repeated until the equilibrium is achieved. The speed of the users in learning the strategy is controlled by parameter $\theta > 0$. For a small period, the rate of game evolution is controlled by the replicator dynamics, which is defined as:

$$\begin{aligned} \frac{\partial x_B(t)}{\partial t} &= \theta x_B(t)(U_B - U_C) \\ \frac{\partial x_C(t)}{\partial t} &= \theta x_B(t)(U_C - U_B) \end{aligned} \tag{29}$$

where $x_B + x_C = 1$.

It is noted that there is a special situation where no resource is available for competing users with $U_C = 0$. When this happens, all users will choose the blockchain mode, further deepening the trend. This situation will only happen when there is a huge demand for spectrum resources. In the following, we are going to look at other cases with $U_C > 0$, such as when the system is not overcrowded or the blockchain system has just been launched.

The equilibrium would be obtained as a solution of:

$$U_B = U_C. \tag{30}$$

For the sake of brevity, we will write x_B as x in the following. The equilibrium also can be written specifically as follows:

$$\frac{nxE(P)}{T} = \frac{[T - n_o T_o - nxT_s] P_S P_{tr} E(P)}{T[(1-P_{tr})\sigma + P_{tr} P_S T_S + P_{tr}(1-P_S) T_C]} \tag{31}$$

where $n_o T_o$ is the time occupied by schedule-users.

Based on the unique solution of equation (21) and (22), there is also a mapping from x to (ρ, τ), denoted as $(\rho, \tau) = f(x)$. It can be reduced to the form of a quadratic function as follows

$$\begin{aligned} &Ax^2 + Bx + C = 0 \\ &\quad A = a\tau(1-\rho) \\ &\quad B = b\tau(1-\rho) + (T_C - \sigma)\rho + \sigma \\ &\quad C = c\tau(1-\rho) \\ &(\rho, \tau) = f(x) \end{aligned} \tag{32}$$

The above parameters a, b and c are constants as follows:

$$\begin{aligned} a &= (T_C - 2T_S)n \\ b &= (2T_S - T_C)n + (T_C - \sigma) + (T - n_o T_o) \\ c &= -(T - n_o T_o) \end{aligned} \tag{33}$$

Obviously, according to the fairness of spectrum allocation, the spectrum share reserved for CSMA/CA cannot be zero, with $T - n_o T_S > 0$. With the properties of CSMA/CA, we can know $T_S > T_C > \sigma$. As a result,

$$a < 0, b > 0, c < 0 \tag{34}$$

As the parameter τ and ρ are the probability,

$$A < 0, B > 0, C < 0 \tag{35}$$

Let $y(x) = Ax^2 + Bx + C$, we can know $y(0) = C < 0$, and $y(1) = A + B + C = (T_C - \sigma)\tau(1-\rho) + (T_C - \sigma)\rho + \sigma > 0$. Considering $A < 0$, there is a unique positive zero point at $(0, 1)$, which can be built as the mapping from (ρ, τ) to the zero point x, denoted as $x = g(\rho, \tau), x \in (0, 1)$.

Obviously x is bounded and less than 1. We assume that the blockchain mode carries an upper limit of n', i.e., the upper limit of x is n'/n. We can obtain $y(n'/n) > 0$, as $n_o T_o + n' T_s = T$. That meana the equilibrium is less than the upper limit, but for convenience, we still use $(0, 1)$ in the subsequent analysis.

Theorem 2. ***Existence****: At least one Nash equilibrium exists in the evolution game*

Proof. Obviously, the equilibrium should satisfied $x = g(\rho, \tau), x \in (0, 1)$ and $(\rho, \tau) = f(x)$ simultaneously. Hence, the equilibrium x^* can be solved by

$$x^* = g(f(x^*)) \tag{36}$$

As $g(f(x))$ is a continuous function, there exist at least a point where $x^* = g(f(x*))$, with $g(f(0)) > 0$ and $g(f(1)) < 1$, ☐

Before we prove that the equilibrium point is unique, we will make some lemma as follow.

Lemma 1. *If $(\rho, \tau) = f(x)$ and $(\rho', \tau') = f(x')$ with $x > x'$, there is a relationship that $\tau' > \tau$, $\rho > \rho'$, $\tau(1-\rho) > \tau'(1-\rho')$ and $\tau + \rho - \tau\rho > \tau' + \rho' - \tau'\rho'$*

Proof. As $x = g(\rho, \tau) \in (0, 1)$, we just need consider $x \in (0, 1)$, when we analyse $(\rho, \tau) = f(x)$. We can convert equation (21) to $\tau(\rho) = 1 - (1-\rho)^{1/[n(1-x)-1]}$. The first derivative is shown below:

$$\frac{\partial \tau}{\partial x} = -\frac{nln(1-\rho)(1-\rho)^{1/n(1-x)-1}}{[n(1-x)-1]^2} \tag{37}$$

With $ln(1-\rho) < 0$, we can have $\frac{\partial \tau}{\partial x} > 0$, which means $\tau(\rho|x) > \tau(\rho|x')$. We can obtain $\tau^*(\rho)$ by equation (22), and it is a monotonically decreasing function. When $\tau(\rho_x^*) = \tau^*(\rho_x^*)$, we can get $\tau(\rho_{x'}^*) < \tau^*(\rho_x^*)$. Hence, when $\tau(\rho_{x'}^*) = \tau^*(\rho_{x'}^*)$, we have $\rho_{x'}^* < \rho_x^*$ and $\tau^*(\rho_{x'}^*) < \tau^*(\rho_x^*)$. It can be rewrite as $\tau' > \tau$, $\rho > \rho'$.

We can calculate the first derivative of $\tau(1-\rho)$ and $\tau+\rho-\tau\rho$ as follows

$$\begin{aligned} \frac{\partial(\tau(1-\rho))}{\partial \tau} &= (1 - \tau n(1-x)(1-\tau)^{n(1-x)-2}) \\ \frac{\partial(\tau+\rho-\tau\rho)}{\partial \tau} &= n(1-x)(1-\tau)^{n(1-x)-1} \end{aligned} \tag{38}$$

So, we can get $\tau(1-\rho) > \tau'(1-\rho')$ and $\tau+\rho-\tau\rho > \tau'+\rho'-\tau'\rho'$, when $\tau > \tau'$.

□

Lemma 2. *The intersection point of any two quadratic functions $y(x|\rho,\tau)$ corresponding to $(\rho,\tau) = f(x)$ is unique and less than the intersection point of each of them with the X-axis.*

Proof. In order to analyse the intersection point of $y(x|\rho,\tau)$ and $y(x|\rho',\tau')$, let

$$\begin{aligned} y^* &= y(x|\rho,\tau) - y(x|\rho',\tau') \\ &= A^*x^2 + B^*x + C^* \end{aligned} \tag{39}$$

where

$$\begin{aligned} A^* &= a[\tau(1-\rho) - \tau'(1-\rho)] \\ B^* &= b[\tau(1-\rho) - \tau'(1-\rho')] + (T_C - \sigma)(\rho - \rho') \\ C^* &= c[\tau(1-\rho) - \tau'(1-\rho')] \end{aligned} \tag{40}$$

Same as before, we assume $x > x'$. From Lemma 1, we can obtain

$$A^* < 0, B^* > 0, C^* < 0 \tag{41}$$

and

$$\begin{aligned} y^*(0) =& C^* < 0 \\ y^*(1) =& A^* + B^* + C^* \\ =& (T_C - \sigma)[(\tau+\rho-\tau\rho) - (\tau'+\rho'-\tau'\rho')] > 0 \end{aligned} \tag{42}$$

Hence, there exist unique real solution for $y^*(x) = 0$ at $(0,1)$. Because $A < 0$, $A' < 0$ and $A^* < 0$, the real root at $(0,1)$ is the smaller one. So we can write the general form of the roots at $(0,1)$ as follows:

$$\begin{aligned} x^* &= -\frac{B}{2A} + \frac{\sqrt{\triangle}}{2A} \\ &= -\frac{B}{2A} + \sqrt{(-\frac{B}{2A})^2 - \frac{C}{A}} \end{aligned} \tag{43}$$

where $\frac{C}{A} = \frac{c}{a}$, which is constant, no matter what (ρ,τ) is. Let $l = -\frac{B}{2A}$ and $m = \frac{c}{a}$, we can get

$$x^* = l + \sqrt{l^2 - m} \tag{44}$$

where $l^2 - m > 0$ and $l > 0$, as the existence of real root proved. So,

$$\frac{\partial x}{\partial l} = 1 + l(l^2-m)^{-\frac{1}{2}} > 0 \tag{45}$$

Then we analyse $-\frac{B}{2A}$ of y and y^*

$$\begin{aligned} l_y &= -\frac{b}{2a} - \frac{(T_C-\sigma)\rho + \sigma}{2a\tau(1-\rho)} > -\frac{b}{2a} \\ l_{y^*} &= -\frac{b}{2a} - \frac{(T_C-\sigma)(\rho-\rho')}{2a[\tau(1-\rho) - \tau'(1-\rho')]} < -\frac{b}{2a} \end{aligned} \tag{46}$$

Hence, $x(l_y) > x(x_{y^*})$. □

Lemma 3. *$g(f(x))$ is monotone decreasing function at $(0,1)$.*

Proof. On the basis of Lemma 2, when $(\rho,\tau) = f(x)$ and $(\rho',\tau') = f(x)$ with $x > x'$, the zero point of $y(x|\rho,\tau)$ and $y(x|\rho',\tau')$ is large than the intersection point x^* of them. We have proved above that x^* is unique at $(0,1)$, so $y(x|\rho,\tau) < y(x|\rho',\tau')$ at $x > x^*$, and $y(x|\rho,\tau) < y(x|\rho',\tau')$ at $x > x^*$.

Hence, for x_0 satisfying $y(x_0|\rho,\tau) = 0$, we can get $y(x_0|\rho',\tau') < 0$. Considering $y(1|\rho',\tau') > 0$, the zero point of $y(x|\rho',\tau')$ is at $(x_0, 1)$.

As a result, $g(\rho,\tau) < g(\rho',\tau')$ at $(0,1)$. □

Theorem 3. ***Uniqueness**:The Nash equilibrium of the evolution game is unique.*

Proof. On the basis of Lemma 3, there cannot be multiple intersection points of $g(f(x))$ and $h(x) = x$, because $g(f(x))$ is a monotonically decreasing function and $h(x)$ is monotonically increasing. If there exist two intersection points x_1 and x_2 with $x_1 > x_2$, then $g(f(x_2)) < g(f(x_1)) = h(x_1) < h(x_2)$ and $g(f(x_2)) = h(x_2)$. Obviously there is a conflict. So the intersection point is unique. The solution of $x = f(g(x))$ is unique. □

VI. PERFORMANCE ANALYSIS

In this section, the performance of the proposed blockchain-based distributed spectrum sharing scheme is evaluated by simulations. The simulator is implemented in the Matlab environment. Following [41], the system parameters are determined as Table I. We consider a scenario of a densely populated environment (such as a part of a residential building) with 2 SBSs, and several APs. The SBSs and APs are all in the communication range of each other.

A comparison between the proposed blockchain model without ‘mode switching’ and the non-blockchain model will be presented. Then, we analyze the performance change brought by ‘mode switching’. We analyze the throughput and Nash equilibrium with different consensus periods and the various number of APs. The mining reward, revenue, and reliability of blockchain mode are also considered. We compare the performance of PoS and PoG in terms of computational overhead and spectrum allocation efficiency. In the simulations, we assume that all users choose to act as miners because of the lightweight consensus mechanism.

The period of DC in the convention mode (CM) is the same as the consensus period of the blockchain mode (BM) at period=5ms, and the allocation ratio is the same as 0.5, we compared the throughput of these two. As the network is

TABLE I: Simulation Parameters

Parameter	Value
SIFS	16 μs
DIFS	34 μs
Average Packet Sending Period	108 μs
ACK	28 μs
σ	9 μs
Period Allocation Ratio	0.5
Initial Window	16
α	0.5

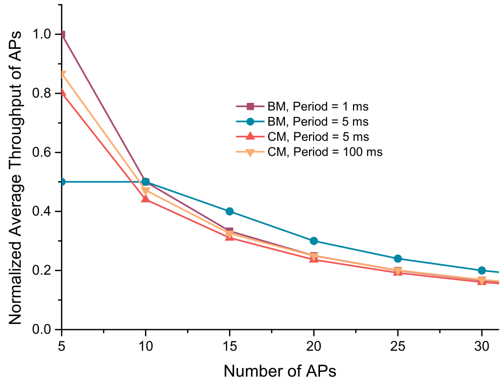

Fig. 3: Normalized throughput of Blockchain Mode and Conventional Mode again the Number of APs.

in a small area, the consensus period should be within a few milliseconds, and 100 ms is a conventional period value of the duty cycle, so we use it for comparison. As illustrated in Fig. 3, the blockchain model based on the proposed Proof of Strategy can perform better when there are many APs and resources are scarce. However, due to the delay of the consensus process, when the number of APs is small, the performance of the conventional DC technology with the same cycle is better. Therefore, to solve this problem, a dynamic switching mechanism has been proposed in Section V.

The average throughput is closely related to the percentage of blockchain users and the total number of users. As shown in Fig. 4, we compare the average throughput of the Switching Mode (SM) with that of the Conventional duty cycle Mode (CM) and Blockchain Mode (BM) without switching. The SM can greatly improve the average throughput of users because the loss from collisions is reduced. Although the throughput of the proposed model declines as the blockchain cycle period increases, it is at least on par with conventional models. Similar to the previous analysis, the larger the number of APs, the more advantages of the BM over the CM can be maintained over a longer blockchain cycle period. SM based on dynamic mode selection can obtain the maximum throughput. Compared with SM at 6ms, SM at 8ms enters blockchain mode more slowly, which also corresponds to Fig. 5.

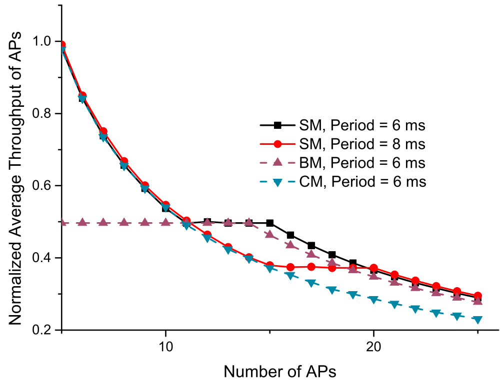

Fig. 4: Average Throughput with Different Number of APs.

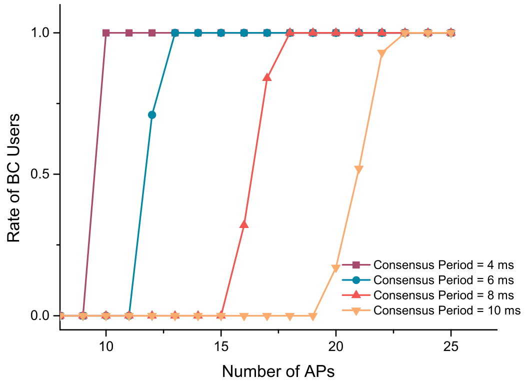

Fig. 5: Nash Equilibrium in Evolutionary Games with Different Number of APs.

As illustrated in Fig. 5, we test the relationship between the proportion of users choosing the blockchain mode and the blockchain cycle, as well as the influence of the number of APs on it. The proportion of blockchain users represents the Nash equilibrium of evolutionary games. In the analysis of the equilibrium point in section V, we proved that the equilibrium point is unique and not equal to 0 or 1, which is different from the simulation results. Because in the process of proof, we used the continuous number of users, but in the simulation it is discrete. Equilibrium points that may not be equal to 0 or 1 in mathematical analysis fall on 0 and 1 in simulation. As the blockchain cycle period increases, the number of users choosing blockchain mode gradually decreases. As the cycle period increases, blockchain users tend to choose the contention mode because the allocation time they need to wait is too long. As the number of APs increases, the throughput in contention mode decreases, allowing blockchain users to tolerate a longer allocation cycle period.

We compare the global utility of the proposed scheme with that of the traditional one under spectrum resource allocation. To better reflect the changes in the strategy of miners, we assume some miners are very radical who believe $E_b = 0$, and removed the miners who chose $\beta = 0$, i.e., all miners who chose the globally optimal strategy. If users with $\beta = 0$ are not removed, the β curve will overlap the X-axis and cannot be observed. As shown in Fig. 6, the two curves overlap very well, when we assume that the revenues of all users are based on the α-fair function. The changes of the corresponding mining

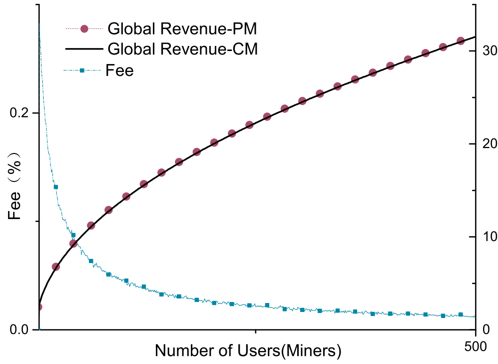

Fig. 6: Global Revenue and Mining Fee.

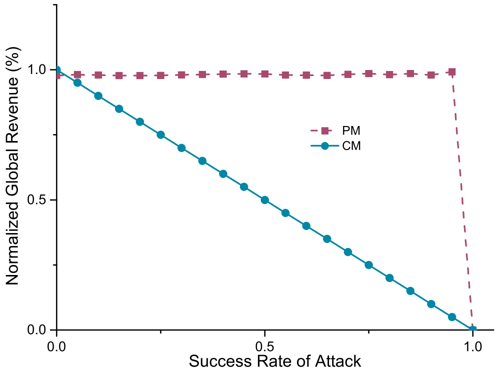

Fig. 7: Reliability of the Proposed Model.

reward for the winning miners are also drawn. It can be seen that even if the users with $\beta = 0$ are removed, the strategy of the winner for the rest of the users gradually approaches 0.

The simulation results are consistent with our proof in Section IV. With the increase of users, the optimal response moves close to 0. Our analysis shows that the expected revenue of miners at this extreme value point is the same as the expected revenue of $\beta = 0$, which is the user revenue under global optimization. The optimal solution of β in the domain is 0 and the extreme point. So, even with a small number of users, there are miners who will choose $\beta = 0$ to increase the stability of revenue.

In addition, we compare the reliability of the proposed model with the centralized resource allocation approach. As shown in Fig.7, it is assumed that there is a malicious attacker, and the success rate of the attacked nodes is shown on the X-axis. In the proposed distributed model, the success rate of attack is represented by the ratio of disabled miner nodes. Similarly, we assume the miners are radical who believe $E_b = 0$. The Y-axis is the mean of the normalized global revenue of several trials, and we can obtain that the revenue of the proposed model is stable until success rare is 1.

Next, we compare the computational overhead and global revenue of the proposed consensus mechanism PoG based scheme with that of the PoW based one in Fig.8. Considering that the investigated scenario is a small local area network,

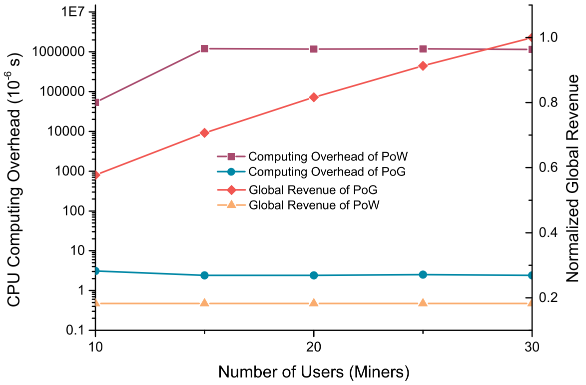

Fig. 8: Computing Overhead and Global Revenue

the block generation period of PoW is assumed to be $50ms$, which means that if the average block generation delay is less than $50ms$, the difficulty of the Hash puzzle will be increased. So there is a change in overhead for 15 users. For a single node, it can be found that the overhead of the proposed model is the same as that with a distributed management architecture without blockchain. However, the conventional PoW model will greatly increase the computational overhead. In addition, we compare the performance of the two consensus mechanisms in spectrum resource sharing. We assume that the winning miner in the PoW can obtain spectrum allocation rights and behave in a greedy manner. Compared with the proposed PoG, PoW performs poorly in spectrum sharing, so it is necessary to introduce an alternative spectrum sharing mechanism to achieve efficient and fair resource sharing.

VII. CONCLUSION

This paper proposed a multi-operators multi-APs distributed spectrum management scheme for unlicensed spectrum sharing. Blockchain is firstly introduced into unlicensed spectrum management among coexisting cellular systems and WiFi networks. More specifically, we propose a lightweight consensus mechanism (Proof of Strategy), which attempts to solve both the consensus problem in the blockchain and the distributed spectrum allocation problem by setting the spectrum allocation problem as the blockchain puzzle to be solved. Extra computation overhead such as solving the hash puzzles in traditional blockchain can be avoided. The behavior of the miners was analyzed by a non-cooperative game, and symmetric Bayesian Nash equilibrium was obtained under the uniform distribution. It was proved that the bid tends to be zero, which was verified by simulations. Furthermore, to reduce the impact of complex user interactions on throughput, a mode switch algorithm was proposed for the WiFi APs, which can dynamically switch between 'contention mode' and 'blockchain mode' according to the network conditions. The dynamic behavior of users was studied as an evolutionary game. The existence and uniqueness of Nash equilibrium for the game were proved mathematically and verified by simulation results. The proposed distributed spectrum allocation scheme can be applied to the distributed autonomous spectrum management in 6G networks. In addition, the theoretic analysis of the blockchain-based spectrum sharing scheme can provide a strong basis for the evaluation and optimization of global revenue in a distributed environment. In the future, we will extend our works with intelligent control and applications of blockchains for distributed spectrum management.

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