An Evolutionary Game Assisted Spectrum Sharing Blockchain Framework for Internet of Vehicles

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***Abstract*—With the significant advance of Internet of Vehicles (IoV), a massive number of vehicular users will connect with the Internet via 5G and the beyond 5G (B5G) networks, which will further worse the spectrum scarcity problem in 5G/B5G networks. Therefore, how to enable dynamical and efficient spectrum resource sharing for IoV users is imperative. To this end, we investigate an evolutionary game enabled spectrum sharing blockchain framework for IoV. Specifically, We use alliance nodes and blockchain framework to assist in the completion of multi-WSP spectrum resource allocation, sharing, and the allocation results storage. We first propose an evolutionary game scheme to allocate the spectrum resource among different WSPs. To reflect the vehicle users' communication demand more appropriately, the vehicle mobility is taken into consideration when defining the payoff of the vehicle users. After completing the spectrum allocation, we illustrate the process of allocation results recording and block generation in our established blockchain verification system, where the transactions ledger of spectrum allocation will be stored in each alliance node in a distributed way. Numerical results exhibit the fast convergence speed of the spectrum allocation approach. Moreover, simulations results from our established hyperledger platform validate the effectiveness and implementability of the investigated spectrum sharing blockchain framework.**

***Index Terms*—Evolutionary game, Multi-WSP, Spectrum Allocation, Blockchain.**

I. Introduction

INternet of Vehicle (IoV) has gradually become common with the advent of the 5G era, the communications and information services among IoV users will become more frequent, and the significantly increase number of vehicles on-board units (OBU) in IoV will produce more communication needs. How to support the massive number of vehicular users with high quality-of-service (QoS) guarantees over the limited wireless spectrum resource is challenging. However, one on hand, the location of the wireless service providers' (WSP) base stations is uneven, and the density in different regions are also different. For a single WSP with the reduced coverage of 5G, it is difficult to meet dense vehicular user needs in all regions. With the scarcity of spectrum resources and the communication problems in a multiple wireless service providers (WSP) assisted IoV environments will gradually become more urgent. Dynamically allocation and scheduling the wireless spectrum resources among WSPs and the massive vehicle users and improving the efficiency of spectrum utilization become an important issue in wireless spectrum sharing and management [1], [2]. However, WSPs lack a neutral institution or a trusted medium that can enable them to cooperate with each other, and the lack of trust between WSPs makes it difficult to implement the allocation of spectrum resources across WSPs [11], [17]-[18].

With the technical development and progress, more and more researches realize that evolutionary game theory is an effective tool to solve resource matching or allocation problems, which is based on the Natural selection theory in biology [1]. Evolutionary game theory is different from traditional game theory. Evolutionary game theory does not require participants to be fully rational, nor does it require complete information, it only lets the participants choose the best strategy at the current time. Armed with evolutionary game theory, the system will become stable and reach convergence step by step in a distributed way. In addition, as for blockchain, it has also attracted huge attentions of many scholars and developers. According to the National Institute of Standards and Technology (NIST) [5], blockchains are immutable digital ledger systems implemented in a distributed fashion (i.e., without a central repository) and usually without a central authority [4], [6]. Blockchain has been widely used in the field of Internet of Things because of its security, trustworthiness, and decentralization [8]-[10], [16].

In this paper, we investigate the Evolutionary Game assisted spectrum sharing blockchain framework for Internet of Vehicles to realize the dynamical and efficient spectrum resource sharing among multiple wireless service providers. For a specific, in this area, each WSP will have different base station locations and numbers, and vehicle users subscribe to different WSPs and access different base stations. We propose a spectrum resource allocation scheme based on evolutionary game, which can integrate the spectrum resources of multiple WSPs and use the evolutionary game scheme to dynamically allocate and share them. To describe the demands of vehicle users more accurately, we take the mobility of the vehicles into consideration. Through this scheme, the spectrum resources can be used more reasonably. In addition, when the spectrum allocation process is completed, we illustrate the process of allocation results recording and block generation in our blockchain system. We use alliance nodes and blockchain framework to assist in the completion of multi-WSP spectrum resource allocation, sharing, and store the allocation results, and make the results of spectrum transactions accessible, traceable, but not temperable in a distributed way. We highlight the novelty and contributions compared with the previous literature works in three-fold:

- We present a dynamical spectrum sharing blockchain framework, which can overcome the problem of sufficient trust lack for executing cooperation, information exchange, and spectrum sharing among multiple wireless service providers.
- We propose an evolutionary game scheme to allocate the spectrum resource among different WSPs, considering the vehicle users communication demands and vehicles' mobility, which will make the model more practical.
- Except for executing numerical simulations on our proposed evolutionary game scheme, we built a blockchain structure to verify the real situation of spectrum data storage and the process of allocation results recording under the hyperledger fabric environment.

The remainder of this paper is organized as follows. Section II describes the system model. Section III presents the evolutionary game enabled multi-WSP spectrum allocation scheme. The simulation results are presented in Section IV. And section V is the conclusion of this paper.

II. System Model

A. Network Framework

As shown in Fig. 1, our system scenario is an area where multiple WSPs coexist. Vehicle users in this area choose an operator to subscribe and access the base station of the operator that is closest to their current location. There are 4 roles exist in our model:

Vehicle user: Vehicle users are the roles that require spectrum resources in our scenario. They choose a WSP to subscribe and choose the base station closest to their location among the base stations of the WSPs. For vehicle users, we use collections to represent collections of vehicle users, i.e. $\mathbb{U} = \{u_1, u_2, \ldots, u_M\}$.

Wireless service provider (WSP): There are N competing WSPs in our scenario. They have different locations and different numbers of base stations in this region. In addition, the frequency band held by each WSP is fixed. We use $\mathbb{N} = \{n_1, n_2, \ldots, n_N\}$ to represent the WSP set.

Base station: Each base station belongs to a WSP. The base station is a direct server that provides spectrum resources for vehicle users. Each base station has a fixed bandwidth. When more users access the base station, each user gets less spectrum resources. The user can choose different base stations to access, but can only access the base stations owned by the currently subscribed WSP. The interference of user communication mainly comes from other base stations in the region from the same WSP. We use b_n^j to represent the j-th base station of the n-th WSP.

Alliance node: The alliance node is the overall manager of each region and is responsible for the information interaction between vehicle users, base stations and WSPs in this region. The spectrum blockchain in our system is composed of alliance nodes. Each region is managed by an alliance node. Each alliance node is outsourced by different companies, which greatly reduces the possibility of collusion. There is no center between the alliance nodes, and each alliance node stores the spectrum resource usage in all regions. Once there is a need, you can query the spectrum transactions at the required time point, and the distributed ledger at each alliance node can prove the correctness of the results, safe and reliable. Alliance nodes can be denote as a set $\mathbb{G} = \{G_1, G_2, \ldots, G_k\}$.

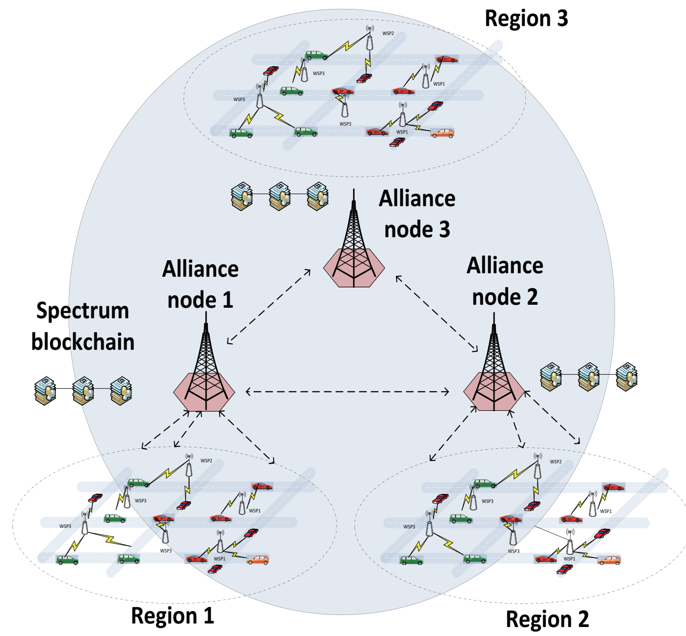

Fig. 1. Multi-WSP spectrum allocation system under a blockchain system.

B. Process of The System

In the area shown in Fig 1, the alliance node integrates the location information and spectrum resources of each operator's base station, combines the current location information of vehicle users, and uses an evolutionary game to allocate spectrum resources. Then, the alliance node sends the spectrum allocation result to the miners selected by the vehicle users to package the data and generate blocks. The blocks verified by the miners will be stored distributed at each alliance node.

We can explain the process described by the model as the following steps:

Step 1. **System initialization**: The alliance nodes collect information of all vehicle users who have spectrum requirements and base stations of multiple WSPs. Each vehicle user and WSPs are provided with a pair of public and private keys, which will be used when they have spectrum transactions.

Step 2. **Spectrum allocation**: The vehicle user chooses to initially subscribe to the WSP, the alliance node integrates the spectrum resources of multiple WSPs, and uses evolutionary game methods to complete multi-WSP spectrum allocation. Under the condition of fast convergence, the rationality and fairness of spectrum resource allocation are guaranteed.

Step 3. **Block generation and profit allocation**: The data of the spectrum transaction is packaged into blocks, and the transaction results are stored as the form of the distributed ledger of each alliance node distributedly. The smart contract (SC) automatically allocates profits corresponding to spectrum resources to various WSPs based on transaction data in the distributed ledger.

III. Evolutionary Game Enabled Multi-WSP Spectrum Allocation Scheme

A. Evolutionary Game Model

The evolutionary game model we built can be divided into the following parts:

Population: The users of each collection choose a WSP to subscribe, and the collection of these users is called a population. Because there are N WSPs, there are N different populations.

Strategy space: For the users in each population, they decide which WSP to access next to get better service. Therefore, their Strategy space can also be expressed as $\mathbb{S} = \{s_1, s_2, \ldots, s_N\}$

Population state: For an evolutionary game, the share of users currently choosing different strategies is expressed as $\mathbf{x} = \{x_{s_1}, x_{s_2} \ldots, x_{s_n}\}$. Obviously, we have $\sum_X x_{s_n} = 1$.

Payoff function: The payoff function π_{s_n} for each strategy is used to quantify the satisfaction or benefits that users can obtain by using strategy space in the current population state. Mathematically, the payoff function of an individual user can be illustrated as a mapping: $\pi_{s_n} : x \rightarrow payoff$

In our scenario, we use λ_{W_n} to denote the base station density of the n-th WSP in this area, and λ_u to denote the density of vehicle users. After the vehicle users select the WSP they subscribe, they choose to access the base station from this WSP which is closest to his location at the current time. Then the expected signal to noise ratio (SINR) $\bar{\gamma}$ of the vehicle users at current time t can be expressed as

$$\bar{\gamma} = \mathrm{E}\left[\frac{P_{W_n} h_j \left(D^t_{W_i^{b_n^j}}\right)^{-\alpha}}{\sum\limits_{k \neq j} P_{W_n} h_k \left(D^t_{W_i^{b_n^k}}\right)^{-\alpha} + \sigma^2}\right], \tag{1}$$

In equation (1), P_{W_n} denotes the transmit power of the base station of WSP_n, α is the path-loss expont. σ^2 denotes the Additive White Gaussian Noise (AWGN) power density, h_i is the effect of Rayleigh fading, and $D^t_{W_i^{b_n^j}}$ denotes the distance between the vehicle user i and the accessed base station of WSP_n (i.e. b^j_n) at time t. The source of the noise is divided into two parts. The first part is the interference caused by other base stations of the same WSP to the vehicle users, and the second part is white Gaussian noise. By defining the signal-to-noise ratio, we can get the expected user rate $\bar{R}(t)$ of vehicle users through the Shannon formula at time t:

$$\bar{\mathrm{R}}(t) = \mathrm{E}\left\{B_i(t)\log_2[1 + \gamma_i(t)]\right\}. \tag{2}$$

B. Payoff Function for Vehicle Users Considering Mobility

Different from static cellular users, vehicles have high-speed mobility when communicating. The traditional user rate cannot fully express the communication needs of the vehicle during driving. Combining the expected driving path of the vehicle, we propose a vehicle user payoff function based on the expected driving path.

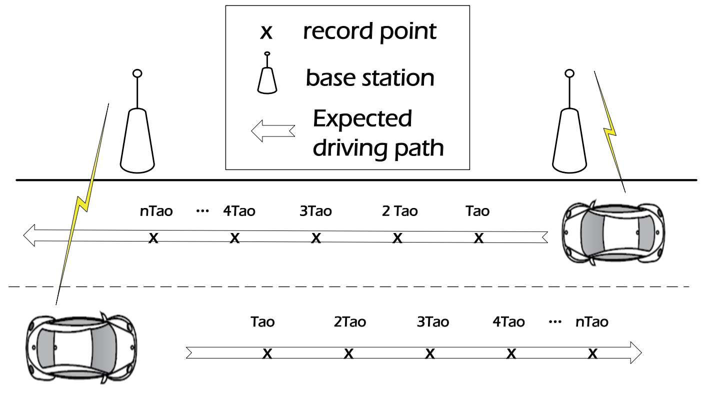

Fig. 2. Illustration of vehicle expected driving path.

As shown in Fig (2), when the spectrum allocation evolutionary game starts, the vehicle user i has the Expected driving path L_i at the speed v_i. In order to more accurately reflect the communication needs of vehicle users, we also consider the expected driving path of the vehicle while considering the current location of the vehicle.

We assume that the vehicle users are at the starting point of the expecting driving path, and time $t = 0$ at the starting point. The vehicle users will move along their expected driving path, and they will reach our first record point at the time $t = \tau$, and they will reach our second record point at the time $t = 2\tau$, etc. We select the first A record points for consideration. In other words, when the vehicle users are at the starting point, each of them estimates his locations at future moments in preparation for the calculation of his payoff. We denote the number of record points A as the length of record points. And combined with (1) and (2), the expected payoff function in each strategy can be expressed as follows:

$$\pi_{s_n} = E\left\{\frac{1}{A+1}\sum_{t=0}^{A} B_{s_n}(t)\log_2[1 + \gamma_{s_n}(t)]\right\}, \tag{3}$$

where

$$\gamma_{s_n}(t) = \frac{P_{W_n} h_j \left(D^t_{W_{s_n}^{b_n^j}}\right)^{-\alpha}}{\sum\limits_{k \neq j} P_{W_n} h_k \left(D^t_{W_{s_n}^{b_n^k}}\right)^{-\alpha} + \sigma^2}$$

.

Then we define the average user rate when each vehicle user i crosses through these A record points as the payoff function π_i. For each vehicle user i , the payoff function can be expressed as:

$$\pi_i = \frac{1}{A+1}\sum_{t=0}^{A} B_i(t)\log_2[1+\frac{P_{W_n}h_j\left(D^t_{W_i^{b_n^j}}\right)^{-\alpha}}{\sum\limits_{k\neq j}P_{W_n}h_k\left(D^t_{W_i^{b_n^k}}\right)^{-\alpha}+\sigma^2}]. \tag{4}$$

The above equations (3) and (4) show that we define the payoff function, i.e. the user rate of vehicle users by combining the current locations and future expected locations of vehicle users (A+1 points in total), which reflects the communication demand of vehicle users more appropriately. Since it takes both the current locations and vehicle expected driving path into consideration.

C. Replicator Dynamics and ESS Formulation

To depict the dynamical behavior of users, we adopt the replicator dynamics in this section which can be expressed as follows:

$$\begin{aligned}\dot{x}_{s_n} &= \delta x_{s_n}(\pi_{s_n} - \bar{\pi}(\mathbf{x})) \\ &= \delta x_{s_n}(x_{s_n} - \sum_{s_n{}'\in\mathbb{S}} x_{s_n{}'}\pi_{s_n{}'}(\mathbf{x})), \forall n \in N. \end{aligned} \tag{5}$$

In the formula, $\delta > 0$ is the rate of strategy and $\bar{\pi}(\mathbf{x})$ is the average payoff of all populations. Based on the above replicator dynamics, the percentage growth rate of the population share of each strategy is proportional to the excess of the strategy's payoff over the population's average payoff [4]. It could be interpreted biologically as a model of natural selection, and economically as a model of imitation [3]. By replicator dynamics, we can get N first-order equations. Armed with these equations, all the vehicle users can find the fixed point, which is also the point of evolutionary equilibrium (EE). When the state of EE is established, there won't be any user would like to change his strategy. Next, we give the definition of ESS.

Definition 1: (ESS): We set $\mathbf{x}^*$ as an evolutionary stable strategy (ESS), if for any different population state $\mathbf{x} \neq \mathbf{x}^*$, we have

$$\bar{\pi}(\bar{\mathbf{x}}, (1-\varepsilon)\bar{\mathbf{x}} + \varepsilon\mathbf{x}) > \bar{\pi}(\mathbf{x}, (1-\varepsilon)\bar{\mathbf{x}} + \varepsilon\mathbf{x}), \tag{6}$$

where $\bar{\pi}(\bar{\mathbf{x}}, (1-\varepsilon)\bar{\mathbf{x}} + \varepsilon\mathbf{x})$ and $\bar{\pi}(\mathbf{x}, (1-\varepsilon)\bar{\mathbf{x}} + \varepsilon\mathbf{x})$ respectively denote the expected payoff in state$(1-\varepsilon)\bar{\mathbf{x}}+\varepsilon\mathbf{x}$ under the population state $(1-\varepsilon)\bar{\mathbf{x}} + \varepsilon\mathbf{x}$ with ε being a small constant. From the definition of ESS, we also have the Theorem 1, which shows our strategy is an ESS.

Theorem 1: The equilibrium point $\mathbf{x}^*$ obtained from Algorithm 1 is also an ESS.

Proof: Based on the theorem of an evolutionary game, any strict nash equilibrium (NE) will correspond to an ESS [3]. Meanwhile, we can obviously see that the solution from Algorithm 1 is an equilibrium point since there is no vehicle users would change his own strategy for there will be no other strategies that can provide more profit than the current one. i.e. $\dot{x}_{s_n}$=0 for any $s \in \mathbb{S}$. Then we prove that equilibrium point $\mathbf{x}^*$ is a strict NE. We assume the payoff obtained by a vehicle user selecting strategy s is $\pi_s = E\left\{\frac{1}{A+1}\sum\limits_{t=0}^{A}\mathrm{B}_s(t)\log_2[1+\gamma_s(t)]\right\}$. Now, suppose some vehicle users deviate from the strategy, then the population state becomes:

$$\mathbf{x}' = (x_1^*, \cdots, x_s^* - \xi, \cdots, x_l^* + \xi, \cdots, x_{|S|}^*), \tag{7}$$

where ξ is determined by the number of users. And $\xi > 0$. Then the payoff of vehicle users becomes:

$$\pi_l = E\left\{\frac{1}{A+1}\sum_{t=0}^{A}\mathrm{B}_l(t)\log_2[1+\gamma_l(t)]\right\}. \tag{8}$$

In equation (7), $\gamma_l(t)$ is the SNR influenced by the location of base station and the user, which will be not changed by the strategy selection. It is also the constant of record length. Because more users deviate to strategy l, so we have $\mathrm{B}_l(t)|_{x=x_l^*+\xi} < \mathrm{B}_l(t)|_{x=x_l^*}$, and $E[\cdot]$ just stands for the average value of each vehicle user. Then we can obtain that $\pi_l(\mathbf{x}^*) > \pi_l(\mathbf{x}')$, which shows that the deviating from the equilibrium state will lower the payoff of the vehicles. Now, the proof is completed. ■

In what follows, we show the algorithm of Multi-WSP spectrum allocation method.

Algorithm 1 Multi-WSP Spectrum Allocation Method

Initialization Each vehicle user first subscribes to a WSP randomly, and accesses the WSP's base station which is closest to him. And $t = 0$.
loop
Each user calculates the payoff π_i in the current access state by using (4), then he uploads the result to the alliance node G.
Alliance node G receives the user rate from all the vehicle users, and calculate the average payoff $\bar{\pi}(\mathbf{x})$, broadcast the results to all vehicle users.
if For vehicle user i , $\pi_i < \bar{\pi}(\mathbf{x})$ **then**
Vehicle user i change his strategy, subscribes to WSP m, where $m = \arg\max(\pi_{s_m})$ for each user i.
End if
Vehicle upload the new strategies to G, G update the data.
$t = t + 1$
End loop

In Algorithm 1, the alliance node acts as the information interactor in this region, and overall allocates the spectrum resources of multiple WSPs in this area. Because of the characteristics of the evolutionary game method, our spectrum allocation scheme can have a fast convergence speed. Besides, in our scheme, the alliance node only needs to calculate the average user rate of all the vehicle users in this area. The user rate will be calculated distributedly by each vehicle user. So our scheme can avoid numerous complicated calculations in the alliance node, which is equivalent to sharing the computing burden to each vehicle user.

IV. Numerical Results

In the blockchain based multi-WSP evolutionary game method, we illustrate the dynamic behaviors of the vehicle

TABLE I
PARAMETERS AND VALUES

Parameter	Value
Number of services N	3
Available bandwidth for each WSP	10 MHz
AWGN power density	-174 dBm/Hz
Path-loss exponent	4
Transmission power of base station P_{W_n}	46 dBm
Length of record points A	3

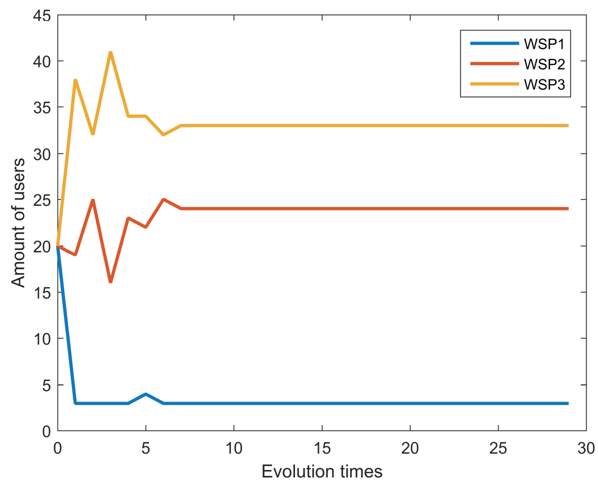

Fig. 3. The dynamics of the population share in the vehicle users of WSP1, WPS2 and WSP3 with $(\lambda_{W_1}, \lambda_{W_2}, \lambda_{W_3}) = (3, 3, 6)$ and $\lambda_u = 60$.

users. We consider the region where there are 3 WSPs and many vehicle users. The region is a 200 m $\times$ 200 m square area, and the base stations of different WSPs are randomly distributed in this area at a density of $\lambda_{W_1}, \lambda_{W_2}$ and λ_{W_3}. The vehicle users are distributed randomly in a randomly distributed over a crossroads area with the density λ_u. Some main parameters and values are shown in Table.1. Each of the vehicle users has an expected driving path. During the initialization of the simulation, users in each population would randomly subscribe to a WSP, select the closest base station of the WSP. Then the evolutionary game will start, each vehicle user will adopt the strategy that he can benefit most.

The dynamics of population state and the mean user rate are shown in Fig. 3, Fig. 4 and Fig. 5. In Fig. 3 and Fig. 4, we set $(\lambda_{W_1}, \lambda_{W_2}, \lambda_{W_3}) = (3, 3, 6)$ and $\lambda_u = 60$, while $(\lambda_{W_1}, \lambda_{W_2}, \lambda_{W_3}) = (4, 3, 6)$ and $\lambda_u = 300$ in Fig. 5. From these three figures, we can see that the evolutionary equilibrium of the evolutionary game can be achieved less than 8 iterations. Meanwhile, the mean user rate is also can be achieved quickly. Fast convergence speed ensures that vehicle users can still obtain spectrum allocation results while driving.

Then we compare the mean user rate between our blockchain-based multi-WSP spectrum allocation scheme and fixed WSP allocation scheme. In our blockchain-based multi-WSP spectrum allocation scheme, each vehicle user can select the best base station among all WSPs (i.e. WSP1, WSP2

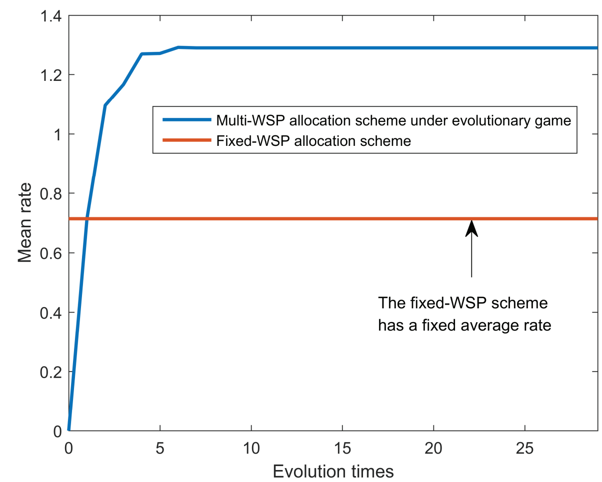

Fig. 4. The mean user rate of all vehicle users with $(\lambda_{W_1}, \lambda_{W_2}, \lambda_{W_3}) = (3, 3, 6)$ and $\lambda_u = 60$.

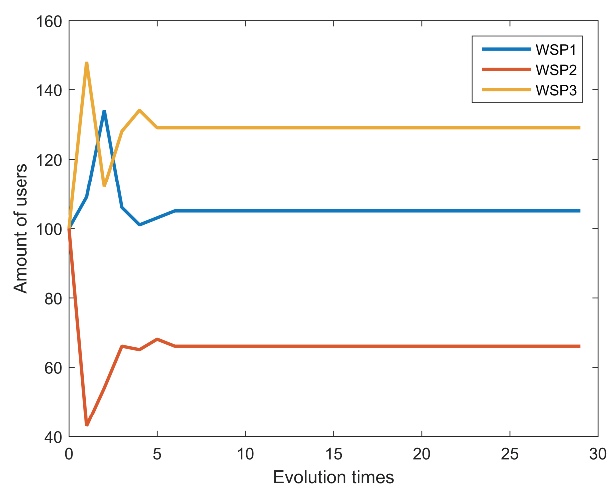

Fig. 5. The dynamics of the population share in the vehicle users of WSP1, WPS2 and WSP3 with $(\lambda_{W_1}, \lambda_{W_2}, \lambda_{W_3}) = (4, 3, 6)$ and $\lambda_u = 300$.

and WSP3) because of the assistance of blockchain. These WSPs can cooperate in a reliable way. And the vehicle users can use the spectrum resource more effectively. In a fixed WSP allocation scheme, vehicle users only can select the base station from the WSP they originally subscribe to, which is also consistent with traditional spectrum usage scenarios. Without the assistance of blockchain, it is difficult for WSPs to trust their rivals. Fig. 6 shows the mean rate of our proposed scheme and the fixed WSP allocation scheme under different amounts of vehicle users. We can see that our blockchain-based multi-WSP spectrum allocation scheme has a better mean rate than the fixed WSP allocation scheme. It is because, under the blockchain-based system, vehicle users can choose a

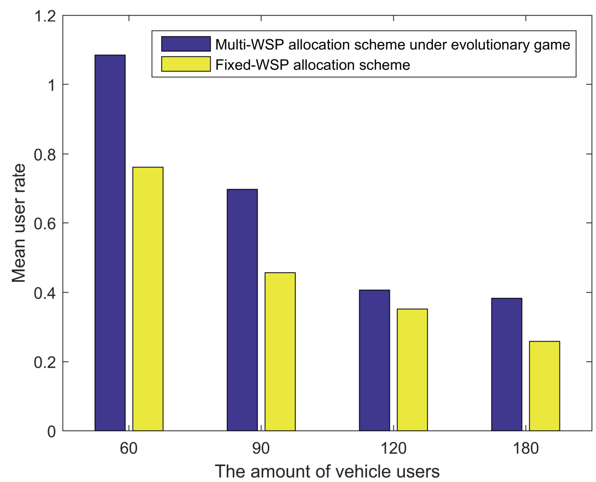

Fig. 6. The mean rate of our proposed scheme and the fixed WSP allocation scheme under different amounts of vehicle users.

TABLE II
PERFORMANCE IN OUR BLOCKCHIAN NETWORK

Command	Success rate(%)	Average latency(s)	Throughput(TPS)
data query	100%	0.11s	100.6
data storage	94%	3.52s	10.6

better strategy and select the best base stations from all WSPs, which help them make use of the spectrum more efficiently.

In addition, in order to investigate the implementability of the blockchain framework in our network model by using the hyperledger FABRIC and the hyperledger CALIPER tool, we simply analyze the performance of a 2-alliance node framework by the CALIPER. We show the data we obtain in table II. We perform simulation and testing in a personal computer (lenovo legion y7000,intel i7 8-th gen) environment by using CALIPER. In the fabric network, we simulate a 2-alliance node environment blockchain network and test the success rate and throughput of data storage and data query, and the result is listed in Table II. From Table II, we show that the network has a high success rate of these commands and in the future we will simulate a more complex network to confirm the effectiveness.

V. CONCLUSION

In this paper, we have proposed an evolutionary game-enabled multi-WSP evolutionary game spectrum allocation scheme. Moreover, when defining the payoff function of the vehicle users, we also take the vehicle mobility into consideration to reflect the vehicle users' communication demand more appropriately. In our system, each vehicle user will choose the strategy that allows him to get the maximum user rate. Armed with evolutionary game theory and blockchain framework, WSPs in our scenario can cooperate with each other and allocate their spectrum in a more reasonable way. The simulation results have shown that our proposed approach can outperform the fixed WSP allocation scheme. For future work, we will consider the details in the blockchain data verification and block generation.

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