Game Theoretical Approach of Blockchain-based Spectrum Sharing for 5G-enabled IoTs in Dense Networks

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***Abstract*—The demand for frequency is continuously increasing owing to the growth of wireless communication devices and the development of network technology. To share frequency effectively in a limited frequency resource environment, studies to develop spectrum-sharing technology should be conducted. In this study, a blockchain-based spectrum-sharing system, in which various types of users can efficiently share spectrum in dense networks, is proposed. Furthermore, a method to apply game theory to obtain cooperation from users who do not participate in the spectrum-sharing system is studied. When the simulation was conducted based on game theory, the proposed blockchain-based spectrum-sharing technique was simulated by using the tit-for-tat (TFT) strategy, in which the system cooperates with the users if the users collaborate and the system does not cooperate with the users if the users do not collaborate. Simulations show that there are more than a certain percentage of users who use the TFT strategy, and if users are encouraged to change their sharing strategy on a regular basis, they can provide more efficient spectrum sharing than traditional centralized methods. It was confirmed that this technique can improve spectrum sharing by 55.1% or more through optimization.**

Keywords—blockchain, cognitive radio, dense network, game theory, spectrum sharing

I. INTRODUCTION

With the development of wireless services and network technologies, various services based on mobile communication devices have been provided, and the Internet of things (IoT) and Internet of everything (IoE), in which various devices are connected to the Internet, have been developed [1]. As billions of IoT devices are expected to be connected to the Internet by 2020, the demand for frequency will increase continuously [2]. As the frequency resources are limited and an ultra-dense network environment will be developed soon, relevant studies should be conducted and appropriate policy should be established.

Owing to the 5G wireless network anticipated in the near future, securing frequency is becoming a core task for a hyper-connected society in the country in the future, and studies have been conducted to secure new frequency resources and improve frequency efficiency. Among these studies, technological solutions to utilize frequencies efficiently using cognitive radio technology, which can change the frequency allocation according to the needs of users or networks, have been studied as well [3]. Although many technical and policy measures have been applied nationwide in order to use the frequency efficiently, most of them attempt to share the frequency bands of TV broadcasts, public organizations, or mobile communication companies. However, sharing the frequencies provided by such companies and public organizations will not satisfy the rapidly increasing frequency demands. If the frequencies not used by government agencies, companies, ordinary citizens, and IoT devices are shared through a blockchain-based platform, more frequencies can be shared compared with those in the traditional centralized method. Furthermore, they will be able to trade and lease frequencies autonomously without the need for a third party. If a spectrum-trading platform is created to enable the participation of various users, the cost of sharing frequency will be reduced and the frequency will be more efficiently managed. Therefore, this paper proposes a model that can share the frequency in a decentralized manner by using blockchain and smart contract, rather than being operated via a centralized method through the government. The blockchain-based spectrum-sharing model can share frequencies that are not used by government agencies, companies, and the general public with other users, and can use smart contracts to trade frequencies quickly and efficiently without a third party.

The remainder of the paper is organized as follows. In Section 2, the research on spectrum sharing is introduced, and in Section 3, a blockchain-based frequency-sharing platform is proposed. In Section 4, a method to apply game theory is studied to activate frequency sharing and utilize the frequency resources effectively. In Section 5, conclusions are presented.

II. RELATED WORK

Cognitive radio network (CRN) has been studied in various ways to utilize frequency efficiently. The CRN consists of four steps: spectrum sensing, spectrum management, spectrum sharing, and spectral mobility, among which the spectral sharing step allows multiple cognitive users (CR users). Therefore, it can be categorized into centralization and decentralization depending on the management method. In [4], they were categorized into dynamic spectrum allocation (DSA) and dynamic spectrum selection (DSS) based on the network structure for dynamic frequency allocation and comparison. In this study, game theory was applied to analyze the DSA and DSS spectrum management strategies. Furthermore, only the future direction of research, and the necessity of business and economic models were

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discussed, and the technical solution of spectrum sharing was not included in this paper.

References [5, 6] applied dynamic frequency allocation using a centralized method. The authors solved the performance degradation problem caused by accessing the database and allocating spectrum sequentially. However, a technique to detect spectrum in real time or through a third party to manage deployment and sharing procedures was not discussed.

References [7-10] proposed an allocation policy or technique for distributed resources rather than a dynamic allocation of spectrum, and made it possible to share spectrum resources using game theory. Reference [11] claimed that, when distributed resources are dynamically allocated based on game theory, there would be no burden in the network, but the implementation would be complicated and the system would have low fairness in terms of spectrum sharing.

Having a centralized structure for dynamic allocation requires additional infrastructure for deployment. It also requires a third party to manage sharing, and there are many issues that need to be addressed in order to detect the spectrum in real time. In the case of a decentralized structure, additional infrastructure and spectrum allocation through a third party are unnecessary, but there are problems, such as complexity of the implementation, efficiency, and fairness [11]. Although the technology for managing and allocating spectrum is also important, studies on business models that can enhance sharing and dynamically evaluate and manage profit and cost are required [12]. The blockchain technology is a decentralized and distributed ledger that ensures integrity and reliability, and shares information transparently. Furthermore, once contents are recorded, they cannot be forged or altered; therefore, it is possible to conclude transactions by using smart contract without a third party. Using the blockchain technology for spectrum sharing will allow more users to participate and share more frequency resources than in existing systems. In addition, the blockchain technology will enable dynamic profit and cost to be evaluated and managed, and various business models can be designed.

III. BLOCKCHAIN-BASED SPECTRUM SHARING SYSTEM

A. System Model

Blockchain-based spectrum sharing (BSS) allows us to conclude transactions quickly and efficiently by using various spectrum sharers, spectrum users around us, blockchain, and smart contract. By using BSS, users in various types of IoT devices, individual users, companies, and public institutions can quickly share spectrum, and a reputation system for spectrum is used to improve frequency quality and maintain security. The reputation system of the BSS will evaluate spectrum quality, usage information, and security, and governments and regulation organizations can also efficiently manage frequencies based on the frequency resources and reputations recorded in the blockchain. Compensations for spectrum sharing can be in many forms, including monetary compensation, discounts on network communication costs, and other spectrum resources. As various types of compensations can be provided, the effects of market activation and sharing enhancement can be obtained. Fig. 1 illustrates the compensation for various types of spectrum sharing through the BSS.

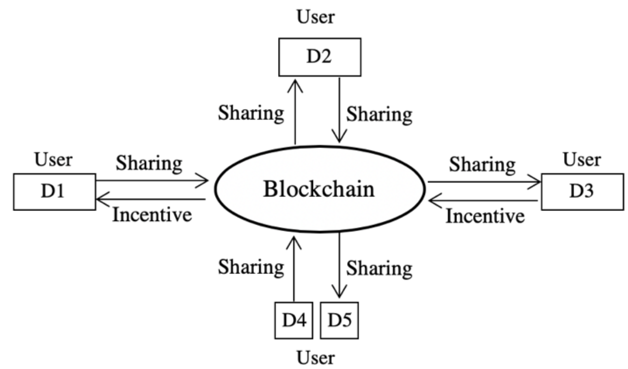

Fig. 1. Various compensation concepts for blockchain-based spectrum sharing

The BSS allows spectrum sharing through various devices. If the spectrum is shared based on a home wireless AP connected to a wired network, the sharer can set the conditions for the private mode and the share mode by using the smart contract. The time zone when a device is not used by a user can be configured to share the spectrum automatically, or conditions for long-range radio waves (sub 1 GHz band) and short-range radio waves (2.4 GHz and 5 GHz) can be set up separately. Not only the sharer but also the user can set trade conditions for the spectrum and time to connect the spectrum automatically that satisfies the condition. Fig. 2 illustrates the public mode, in which the spectrum is shared based on the conditions set by the smart contract, and the private mode, in which the owner can use the spectrum exclusively.

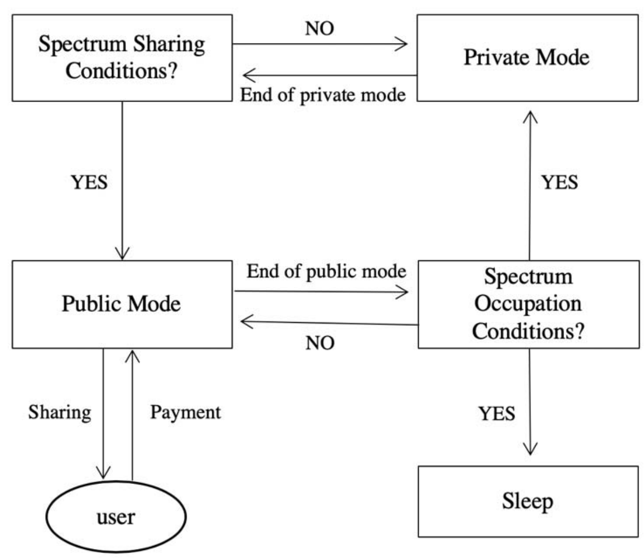

Fig. 2. Smart contract-based spectrum-sharing concept

In the BSS where various users can trade through various types of devices, the existence of users who share spectrum resources is essential. Although it is possible to induce sharing of spectrum resources through various compensations, as the spectrum resources are limited, it is expected that there would be more users in the BSS who want to receive shared spectrum than to share the spectrum. Therefore, maintaining a certain percentage of users who provide spectrum sharing in the BSS will be a key challenge.

B. *Application of Game Theory*

In this study, game theory will be applied to increase spectrum resources and induce spectrum sharing of users. Game theory is used to explain and predict the behavior of each player in situations where interests are conflicted and thus, players interact with other players. Game theory is divided into a cooperative game and a non-cooperative game depending on whether the players can make binding promises, and dynamic wireless networks can be expressed as non-cooperative games [13, 14]. If the sum of loss and gain earned by each player is zero, then it is a zero-sum game; if the sum of loss and gain earned by each player is not zero, then it is a non-zero-sum game. Spectrum sharing can be expressed as a non-zero-sum game because the sum of loss and gain of each player through spectral sharing is not equal to zero. Furthermore, as wireless communication occurs continuously, it is expressed as a repetitive game.

In such a game model, we intend to study a method to encourage general users, which are the devices that do not currently provide spectrum sharing, to share spectrum in the BSS. While incentive policies can be applied to improve spectrum sharing, compensation for spectrum sharing can be provided in many forms, including spectrum sharing at other devices at different times and monetary compensation. Therefore, the simulation through the game model was conducted without the payoff that can be obtained from incentive or spectrum sharing.

A political scholar, Robert Axelrod, described the most successful interaction strategy in repetitive games and non-cooperative games, and we applied this strategy to the BSS model [15]. The game model of Robert Axelrod assumes the following conditions. All users can recognize the partner that they interacted with and can remember their actions. Furthermore, they can confirm each other’s choices. In a network environment that requires frequency sharing, the partner’s terminal, which was networked based on the ID information assigned to the terminals, is recognized, and each other's actions and selections are stored and managed in a log file format. The most evident strategy (tit for tat, TFT) that can evolve cooperation in these games can be explained by four keywords, and they are Nice, Retaliatory, Forgiving, and Clear. They cooperate first, retaliate if their partners betray, and forgive if the partners cooperate again. Subsequently, they show these strategies clearly to their partners. In the BSS, we intend to set the user type based on the TFT strategy to create the evolution of such cooperation.

IV. EVALUATION AND ANALYSIS

A. *Simulation Method*

The BSS system was modeled based on the TFT strategy and game theory of the evolution of the cooperation. First, it was assumed that there are 10,000 players, and each player has one communication device. The player can choose whether to share the spectrum with other players or not. We have set up four spectrum-sharing types that determine the choice. The four types are: complete cooperators, conditional cooperators, non-cooperators, and random cooperators. Each type chooses cooperation or non-cooperation as follows.

- Complete cooperators always cooperate in all games.
- Conditional cooperators work conditionally and use the TFT strategy of the evolution of cooperation. Given that a total of 10 games are played, they will start with collaboration at first, and then follow the partner’s previous choice.
- Non-cooperators always choose non-cooperation in all games.
- Random collaborators randomly select cooperation and non-cooperation in all games.

When a game proceeds, it is assumed that the cooperation shares the spectrum with the partner in the public mode, and that the non-cooperation owns the spectrum in the private mode. If any one player shares the spectrum, the partner player gains 3 points. A player who shares a spectrum loses 1 point owing to the cost of sharing (battery, radio waves, power, etc.). Table 1 shows the scores for each player’s selection. For each round, players will play 10 games with all other players. Players choose to cooperate or not cooperate for each game and score based on the rewards table shown in Table 1. At the end of each round, the ranking is determined based on the score, and the type of the lower 5% user is changed to the type of the upper 5% user. If the user type of the lower 5% is changed, the score is initialized and the next round is executed.

To compare the spectrum sharing with a conventional method, 10,000 players were set in the conventional method as conducted in the simulation using the BSS model. It was assumed that each player has one communication device and the spectrum-sharing type was assigned to each player. Devices that provide spectrum sharing in the conventional centralized method are always cooperators, i.e., they always provide the spectrum without conditions. Furthermore, as conditional cooperators, non-cooperators, and random cooperators have spectrum-sharing function and most of them do not share spectrum in the BSS, they were set as the non-cooperator type in the comparative model. The players of the comparative model were set as cooperators (25%) and non-cooperators (75%). The comparative model also changes the type of the lower 5% to the type of the upper 5% when one round is over, and initializes the score and proceeds to the next round.

TABLE I. POINTS FOR A PLAYER’S CHOICE

Selection	**Public**	**Private**
Public	+2 , +2	+3 , -1
Private	-1 , +3	0 , 0

B. Simulation Results

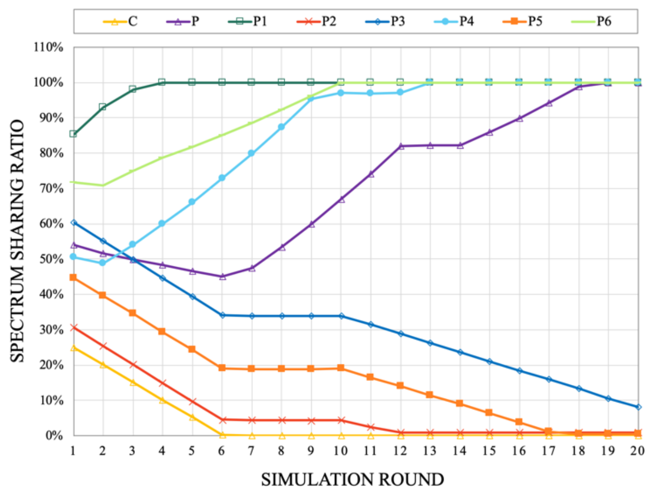

Fig. 3. Changes in the percentage of spectrum sharing according to the number of player types

Fig. 3 shows the changes in the percentage of spectral sharing of the conventional model, the proposed BSS model, the proposed model, and the proposed model with different player type ratios. The Y-axis is the percentage of players who selected the Public mode, or the percentage of spectrum sharing. If the spectrum sharing is 100%, it indicates that all users are cooperative, or they shared the spectrum. The X-axis represents the number of performed simulation rounds. A total of 20 rounds were performed in the first simulation. The percentage of spectrum sharing in the conventional model (C) was compared with that in the proposed model (P). Simultaneously, the player type ratio was changed and the percentage of spectrum sharing at each ratio was compared with the percentage at a different ratio. In this simulation, it was assumed that the conventional model (C) is a centralized dynamic frequency allocation model that maximizes the frequency efficiency of the TV White Space [5]. As complete cooperators always cooperate, the previous percentage (25%) was retained to increase spectrum sharing. Therefore, the models of P1–P6 changed the type ratio for the remaining 75% of the players except for the cooperator type. Table 2 shows the percentage of player types for each model.

As shown in Fig. 3, the proposed model (P) and the conventional model (C) reduce the percentage of spectrum sharing in the initial round. This is because the non-cooperator receives a high score and the complete cooperator receives the lowest score. During this process, the percentage of spectrum sharing in the conventional model and the proposed model will decrease. However, after all the complete cooperators who maintained the lowest score were changed to another type, the percentage of spectrum sharing in the proposed model was increased by 55.1%. It is because the non-cooperator cannot receive a score and thus, the type of the non-cooperator changes owing to the strategy of the conditional cooperator. As shown in Fig. 3, the proposed model shows an increasing percentage of spectral sharing after round 6, and 100% of the players share the spectrum after round 18. However, in the comparative model, only 0.1% of the devices share the spectrum after the type of cooperator is changed. Moreover, the comparative model does not share the spectrum from round 7. The P1, P3, and P6 models, in which the percentage of spectrum sharing increases continuously, have a low ratio of non-cooperative type users and a high ratio of conditional cooperator type users.

TABLE II. PERCENTAGES OF PLAYER TYPES FOR EACH SIMULATION MODEL

Model	Conditional Cooperator	Non-cooperator	Random
C	0	3	0
P	1	1	1
P1	10	1	1
P2	1	10	1
P3	1	1	10
P4	10	10	1
P5	1	10	10
P6	10	1	10

In the case of the conventional model (C), as the ratio of non-cooperators is the highest, the conventional cooperators cannot receive scores, and the percentage of spectrum sharing also decreases continuously. The P2 and P5 models, in which the percentage of spectral sharing continues to decrease rapidly, have a high ratio of non-cooperators. For the P3 model, the ratio of conditional cooperators to the non-cooperators is the same, but the ratio of random cooperators is high so that the non-cooperators steadily receive high scores. Therefore, the percentage of spectrum sharing decreased gradually owing to the increase in the number of non-cooperators.

Fig. 3 shows that the percentage of spectrum sharing increases when the ratio of conditional cooperators is high and the ratio of non-cooperators is low. The models in Fig. 4 also maintained the previous ratio (25%) to increase the spectrum sharing, as in the previous simulation. Fig. 4 shows the change in the percentage of spectrum sharing according to the change in the ratio of conditional cooperators. In the proposed model (P), when the conditional cooperators, non-cooperators, and random cooperators are 25% each, the P1a model through the P1e model were set to have 20% higher ratio of the conditional cooperators among the models. Table 3 shows the detailed percentages of the models by type.

Fig. 4 shows the change in the percentage of sharing based on the ratio of conditional cooperator users. For the P1a and P1b models, the percentage of spectrum sharing decreased. However, although the percentage of spectrum sharing decreased early for the P1c, P1d, and P1e models, the conditional cooperator assumes the advantage after the random cooperator and the complete cooperator with low scores are changed to the non-cooperator with high scores. Consequently, the percentage of spectrum sharing increased, and for the P1d and P1e models, all the players were changed to the conditional cooperators so that all the players can provide 100% spectrum sharing.

TABLE III. PERCENTAGE OF THE PLAYER TYPE FOR SIMULATING THE EFFECT OF THE CONDITIONAL COOPERATOR RATIO

Model	Conditional cooperator	Non-cooperator	Random
P	1	1	1
P1a	0.2	1.4	1.4
P1b	0.4	1.3	1.3
P1c	0.6	1.2	1.2
P1d	0.8	1.1	1.1
P1e	1.2	0.9	0.9

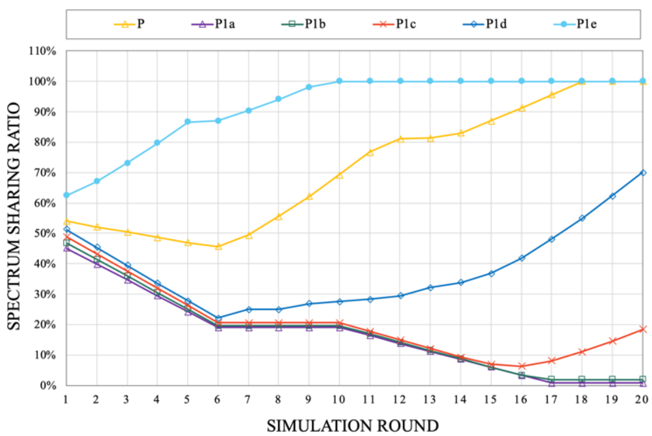

Fig. 4. Changes in the percentage of spectral sharing according to the ratio of conditional cooperators (Round 20)

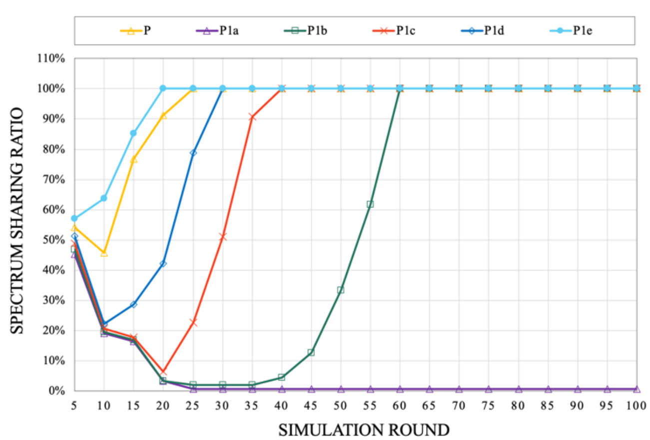

Fig. 5. Changes in the percentage of spectral sharing according to the ratio of conditional cooperators (Round 100)

Fig. 5 shows a total of 100 rounds conducted in the third simulation. As shown in Fig. 5, except for the P1a model, the percentage of spectrum sharing increased after a certain time within 100 rounds. In the initial setting, except for the P1e model, which had more conditional cooperators than non-cooperators, the cooperators and random cooperators did not receive the score in the early rounds and thus were changed to non-cooperators. Consequently, the percentage of spectrum sharing decreased. However, after a certain period of time, the percentage of spectrum sharing increased owing to the increase in the number of conditional cooperators. Furthermore, the higher the ratio of conditional cooperators, the more rapidly the percentage of spectrum sharing increased.

Non-cooperators cannot receive scores when they meet each other as partners in the game because they do not cooperate with each other. Therefore, when a non-cooperator meets a conditional cooperator, the non-cooperator receives scores only through the preemptive cooperation of the conditional cooperator, and the conditional cooperator loses scores through the preemptive cooperation. When a cooperator meets a conditional cooperator, the cooperator cooperates with the conditional cooperator for all the games to receive scores. Although it would depend on the rewards of the game, it can be observed that, if there is a certain percentage of cooperators, the cooperation will evolve even if non-cooperators do not cooperate.

Depending on the cooperative type ratio, it can affect the spectrum sharing, but the way of changing the type can be as effective as the initial setting to the spread of spectrum sharing. Fig. 6 shows the effects of the ratio and the method of type change on the percentage of spectrum sharing for the players with low scores at the end of the round.

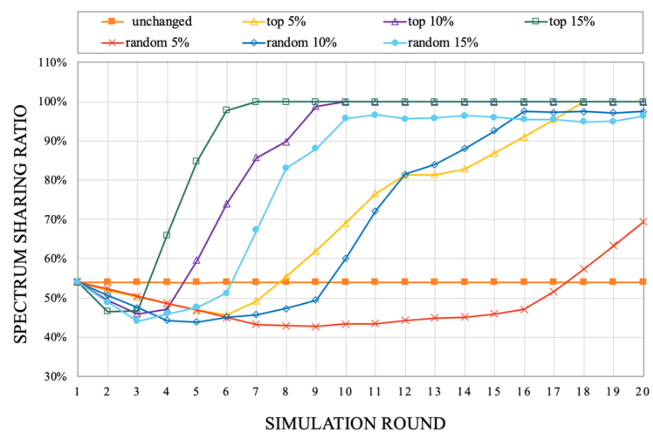

Fig. 6. Change in the percentage of spectrum sharing according to the method of change of the player type

In the fourth simulation, the models are divided according to the ratio and the method of change of player type. The methods of type change are divided into a case where a certain percentage of the players with lower scores are changed to a type with a high score (top), and a case where the type is randomly selected among the four conventional types. The type change ratios are categorized as 5%, 10%, and 15% of the low-score players. Fig. 6 shows the percentage of spectrum sharing of a total of seven models, including models that were divided by the ratio and the method of change of the type and unchanged models.

As shown in Fig. 6, when there is no change in the player type, a slight change occurs by random cooperators; however, it can be observed that spectrum sharing occurs steadily. Even when the types of users with the lower 5% scores were randomly changed, the percentage of spectrum sharing increased slowly. We observed in Fig. 6 that the maximum percentage of spectrum sharing was reached quicker when the types of users were changed at a higher rate and when they were changed to a higher type than when they were changed to random types.

V. Conclusions

In this paper, the BSS, which solves the frequency resource problem and allows various users to share the spectrum of various devices efficiently and quickly, was proposed. Furthermore, based on game theory, a TFT strategy that can lead to cooperation among users who do not share the spectrum in a repetitive interaction relationship was applied. Simulations were conducted to identify the conditions under which the TFT strategy could be used to enhance spectrum sharing further. Consequently, it was confirmed through simulations that in a game theoretic blockchain-based spectrum-sharing environment, if a TFT-strategy user exists, then cooperation can be drawn from users who do not share the spectrum, and that the spectrum sharing can be increased by more than 55.1% by using the TFT strategy.

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