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Cross-tier Coordination in Spectrum Sharing: A Blockchain Approach

1st Shuo Wang
Research & Development Center
Sony (China) Limited
Beijing, China
shuo.wang@sony.com

2nd Chen Sun
Research & Development Center
Sony (China) Limited
Beijing, China
chen.sun@sony.com

3rd Haojin Li
Research & Development Center
Sony (China) Limited
Beijing, China
haojin.li@sony.com

4th Tao Cui
Research & Development Center
Sony (China) Limited
Beijing, China
tao.cui@sony.com

***Abstract*—To solve the contradiction between the increasing spectrum demand of wireless services and the finite and underutilized spectrum resources, the concept of spectrum sharing was proposed to allow unlicensed secondary users to temporarily share unused spectrum of licensed primary users. Currently, approaches based on geolocation databases have been standardized and commercialized, such as TV white space, license shared access (LSA) and the citizen broadband radio services (CBRS). These are centralized schemes where all spectrum allocation decisions are made by a third party or a cloud-based spectrum manager. Recently, blockchain technology has drawn the attention of researchers for its characteristics, such as decentralization, transparency, privacy preservation, and immutability. In this paper, we propose a blockchain-based spectrum sharing scheme to enable the direct coordination of the interference budget between priority users and general access users in the CBRS network. Evaluation results show that our proposed approach can increase the total number of users that can access the shared spectrum.**

***Index Terms*—blockchain, Spectrum sharing, interference budget; CBRS**

I. Introduction

A. Background and Motivation

Due to the increasing number of wireless communication services and user equipments, the scarcity of spectrum resources poses a great challenge to wireless service providers. However, under the traditional spectrum licensing framework, some of the licensed spectrum is not fully utilized. Therefore, dynamic spectrum sharing technology was proposed to improve spectrum efficiency by opportunistically sharing the under-utilized spectrum of licensed primary systems [1]. Some successful examples include TV white space, license shared access (LSA) and the citizen broadband radio services (CBRS), where a centralized geolocation database calculates the available spectrum for secondary devices without causing harmful interference to the incumbent systems.

In 2018, the Commissioner of Federal Communications Commission (FCC) made a remark that smarter and more decentralized dynamic spectrum access techniques based on blockchain had the potential to reduce the administrative expense of dynamic access systems and increase spectral efficiency at a lower cost [2]. Subsequently, various studies on blockchain-based spectrum sharing were conducted to investigate the pros and cons of the combination of these two technologies [3] [4]. Despite the advantages of transparency, privacy preservation and immutability, blockchain technology can also enable more flexible spectrum coordination among wireless devices, both in the same tier and among different tiers.

B. Related Work

Some researchers have started investigating the application of blockchain technology in spectrum sharing. In [3], the authors proposed a blockchain-based media access protocol to verify spectrum sharing among mobile cognitive radio nodes. This method enables access to available licensed spectrum resources without the need for persistent spectrum sensing. The authors in [4] analyzed the benefits and limitations of blockchain solutions and their potential applications to four major types of spectrum sharing. In [5], the authors leveraged blockchain technology in the CBRS system to improve the spectrum management efficiency and quality-of-service of the secondary users. A blockchain-based decentralized spectrum access system was proposed in [6], which provided secure SAS services without relying on the trust of each individual SAS server for the overall system trustworthiness. In our previous study [7], we proposed blockchain-based spectrum trading in the same tier focusing on an interference-based consensus mechanism. The aggregated interference from all secondary users to incumbent users should be guaranteed below a certain threshold to protect the incumbent users. In this paper, we propose a cross-tier coordination approach where higher-tier users can sell their interference budget to lower-tier users, allowing more secondary user to have access to the shared spectrum.

The rest of this paper is organized as follows. We will firstly introduce the CBRS and blockchain technology in Section II, Secondly, a cross-tier spectrum coordination approach is proposed in Section III. Then, the simulation results are presented in Section IV Finally, Section V concludes the paper.

II. CBRS and Blockchain

A. CBRS

In 2015, the FCC established a three-tiered access and authorization framework to accommodate shared federal and non-federal use of the 3550-3700 MHz band (3.5 GHz band). The rules governing the sharing conditions are found in Part 96 of the FCC's rules [8]. The framework of spectrum sharing in the CBRS band is shown in Fig. 1. The first tier contains the incumbent users, which include authorized federal users, fixed satellite service (FSS) earth stations and grandfathered wireless broadband licensees. The second tier consists of priority access licenses (PALs) that will be licensed on a county-by-county basis through competitive bidding with up to seven PALs in any given county. Each PAL consists of a 10 MHz channel within the 3550-3650 MHz band. The lowest tier is called general authorized access (GAA), which enables flexible access to the band for the widest possible group of potential users. Incumbent users are protected from both PALs and GAA users, while PAL users are protected from GAA users. GAA users do not expect protection from either of the above tiers or other GAA users. The fixed stations that operate on a PAL or GAA basis in the CBRS band are also called CBRS devices (CBSDs).

The spectrum access system (SAS) is fully responsible for the rule enforcement of CBRS in a centralized manner, such as providing permissible channel and power to the CBSD, enforcing exclusion zones and protection zones, and resolving conflicting uses of the band while maintaining, as much as possible, a stable radio frequency environment.

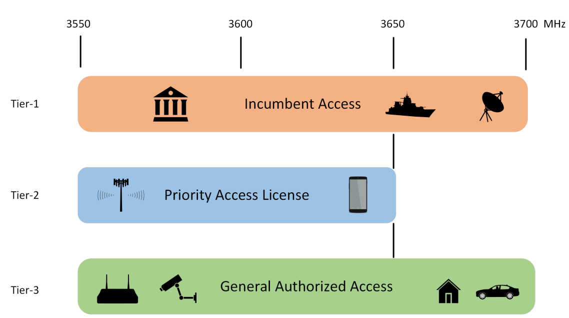

Fig. 1. The three-tier CBRS architecture.

B. Blockchain

Blockchain technology was adopted with other technologies, such as cryptography, to create modern cryptocurrencies (e.g. Bitcoin) in 2008 [9]. Blockchains are tamper-proof, decentralized digital ledgers that operate without a central authority. All participants of the network can independently verify the validity of all the transactions which are publicly recorded on the blockchain. Blockchain users utilize public and private keys to digitally sign the transactions to ensure security. A consensus mechanism is utilized to determine which user publishes the next block, , through which mutually distrusting users can work together.

Two basic categories of blockchain are permissionless and permissioned blockchains, based on who can maintain the blockchain. A blockchain is permissionless if anyone can participate and publish blocks. In contrast, only particular users can publish blocks in a permissioned blockchain, also known as a consortium blockchain. Various consensus models have been proposed for different use cases, such as proof of work (PoW), proof of stake (PoS), proof of authority (PoA), etc [10].

Despite the merits promoted by many publications [11], blockchain technology also has limitations. For example, permissionless blockchains can suffer from 51% attack and may consume a huge amount of resources. With the growth of the network, scalability becomes a major challenge for its application in spectrum sharing, we have proposed a multi-blockchain scheme to solve this issue in [12].

III. Cross-tier Spectrum Coordination Scheme

A. System Model

We consider a three-tier spectrum sharing scenario in the CBRS band based on the FCC Part 96 rules [8]. The incumbent user is an FSS earth station located in the center of a protection area with a 150 km radius. Multiple PAL users and GAA users are deployed in this area. Each PAL user has its own PAL protection area (PPA) where no harmful interference from other PALs or GAA users is allowed. The difference with the existing CBRS architecture is that a blockchain network is established among the CBSDs. The spectrum usage information of each CBSD (e.g., channel, bandwidth, transmit power, etc.) is recorded on the shared blockchain, which is immutable and transparent. Therefore, it gives an opportunity for the CBSDs to coordinate their spectrum usage behavior, both in the same tier and across tiers.

To protect the incumbent user from harmful interference, the aggregated interference to the incumbent user from all the PALs and GAA users within 150 km should not exceed the interference threshold, which is a median root mean square (RMS) value of -129 dBm/MHz for the FSS earth station. For a specific channel, the aggregated interference to a protection point is calculated by:

$$I_{Agg} = \sum_{n=1}^{N} I_n \tag{1}$$

Where I_{Agg} indicates the aggregated interference to the incumbent, I_n represents the interference caused by the CBSD$_n$ and is defined as:

$$I_n = P_n^t + G_t + G_r - P_L \tag{2}$$

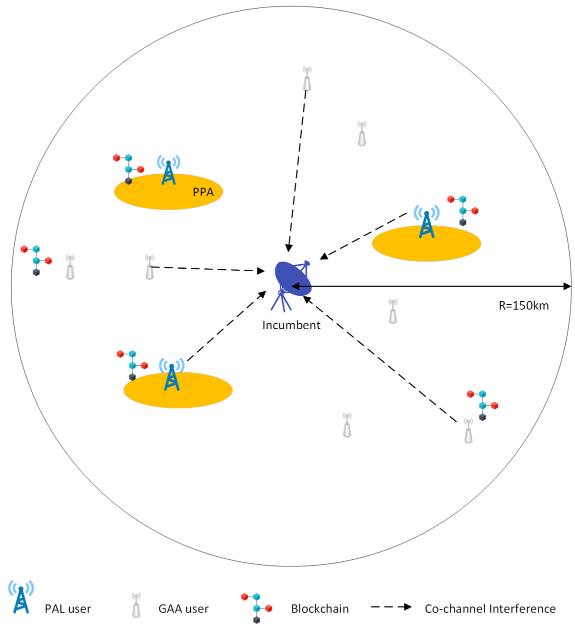

Fig. 2. System scenario.

where P_n^t is the transmit power of CBSD$_n$, G_t and G_r represent the transmitting antenna gain and receiving antenna gain respectively, P_L denotes the path loss from CBSD$_n$ to the incumbent according to the irregular terrain model (ITM) defined in the CBRS specification [13].

B. Procedures of cross-tier coordination for spectrum sharing

While in the current CBRS specifications, the SAS is responsible for all the interference calculation and spectrum management tasks, our proposed blockchain based solution allows GAA users directly coordinating with PAL users, which alleviates the burden on SAS and improves the flexibility of spectrum sharing. Our method includes the following main procedures, as shown in Fig. 3.

1) Coordination among GAA users: This procedure consists of steps 1 to 5 in Fig. 3. In our solution, When GAA-1 sends a spectrum request to the SAS, the SAS not only returns the available spectrum as in traditional method, but also returns a coordinating available spectrum. The available spectrum refers to idle channels and maximum allowed power that can be provided to the GAA requester by the SAS directly. The coordinating available spectrum is the channels in use by multiple CBSDs and can be provided after coordinating with other users. The first coordination process happens among GAA users willing to provide interference headroom to the new GAA spectrum requester by reducing transmit power. Two kinds of interference headroom are considered. One is the aggregated interference to the incumbent user from co-channel PAL and GAA users. The other is the aggregated interference to the PAL from all the co-channel GAA users.

After receiving the coordinating available spectrum, the GAA-1 sends a coordination request to other GAA users on the blockchain and then execute smart contract 1 to determine a GAA coordination scheme. When selecting the list of coordinating GAA user, a trust value determined by the credibility of its provided interference headroom according to history records will be considered. The GAA user with higher trust value will be selected in priority to improve the probability of successful coordination. The coordination scheme contains the list of coordinating GAAs, the interference headroom provided, the location and transmit power of each GAA user. The determined coordination scheme will then be broadcast to the PAL users on the blockchain.

2) Coordination among GAA and PAL users: In this coordination process, the PALs should consider the interference impact from two perspective. Firstly, the aggregated interference of all GAA users to the PPA should not exceed the PPA interference threshold. The PALs can also decide whether to adjust their interference threshold if they can tolerate more interference according to their operating status. Secondly, to ensure the aggregated interference from all GAAs and PALs to incumbent is below a threshold, the PALs can sell their interference budget to GAA users by reducing their transmit power, which will allow more GAA users having access to the spectrum. Then the PAL coordination scheme will be sent to GAA-1 which requested the spectrum. To encourage the participation of PAL users in coordination, a reimbursement will be paid by the GAA user that benefits from this coordination.

3) Grant process: When the spectrum requester GAA-1 receives response from other PALs and GAAs of their coordination schemes, it will decide whether to accept the coordination scheme and send a spectrum grant request containing detailed information on how to coordinate spectrum usage to the SAS in step 8. Then, the SAS will check the feasibility of this coordination request based on its calculation and send a response to GAA-1 in step 9.

4) Updating spectrum usage: If a success response is received in step 9, smart contract 2 will be executed on the blockchain to adjust the transmit power of each CBSD. A coordination factor η is defined to denote the contribution of interference headroom of CBSD$_i$:

$$\eta i = P_{red}^i/(P_{cur}^i - P_{min}) \tag{3}$$

where P_{red}^i is the reduced power of CBSD$_i$ in this coordination process, P_{cur}^i the transmit power of CBSD$_i$ before coordination and P_{min} is the minimum required power of CBSD$_i$ to ensure quality of service.

To monitor the behavior of GAA users, if PAL users detect harmful interference, they will report to the SAS. Then the SAS will determine which GAA user is transgressing the sharing rules and broadcast the non-compliant GAA users on the blockchain. Smart contract 3 will be executed to update the trust value of GAA as follows:

$$T_i^n = \begin{cases} \alpha \cdot T_i^{n-1} & \text{if not coordinating} \\ T_i^{n-1} + \triangle T_i & \text{if not transgressing} \\ \beta \cdot T_i^{n-1} & \text{if transgressing} \end{cases} \tag{4}$$

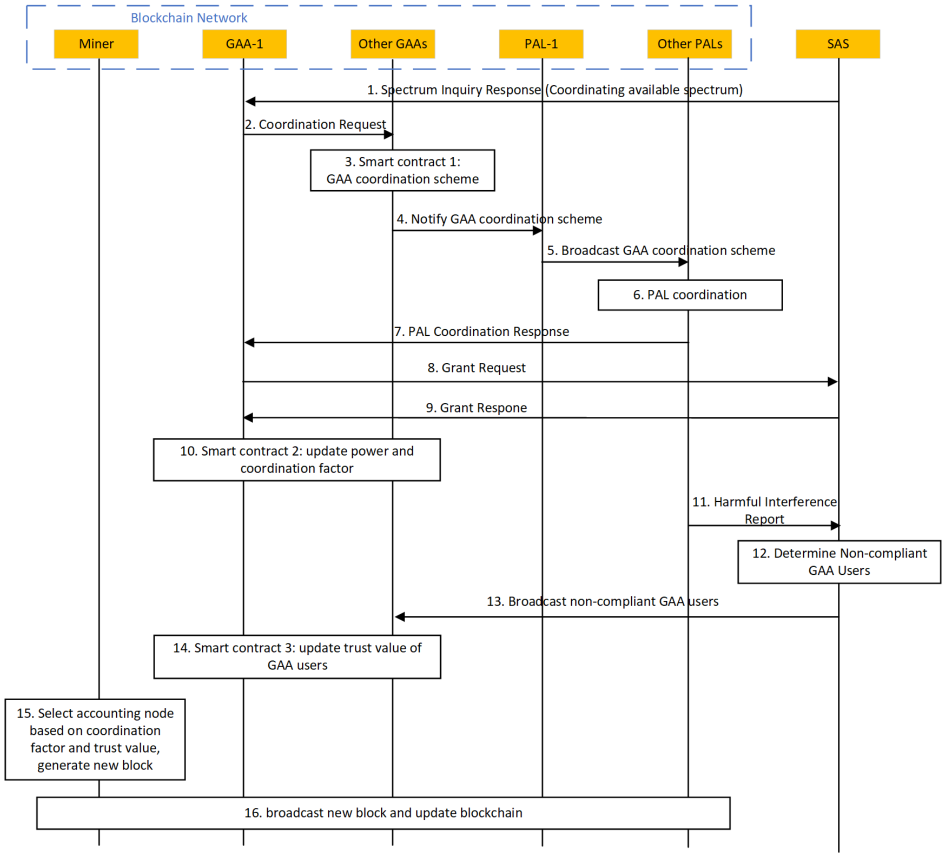

Fig. 3. Procedures of proposed solution.

where n is the times of a GAA user participating coordination, α is a declining factor which takes effect when GAA user does not coordinate, β is a declining factor when transgressing behavior of GAA user is detected and $\beta > \alpha$. $\triangle T_i$ is the increased trust value of GAA i if it successfully participating in the coordination and without transgressing behavior.

5) Consensus process: The consensus process is key to ensure the validity and synchronization of blockchain across decentralized nodes. In step 15, the accounting node responsible for generating new blocks will be determined firstly based on the coordination factor and trust value of each GAA user. Then the accounting node generates the new block containing latest transactions and updated coordination factor and trust values. After the new block is generated, it is broadcast to other nodes in the blockchain network. Each node will verify the block and append it to its local blockchain.

IV. Simulation Results

In this section, we will evaluate the performance of our proposed solution through Monte-Carlo simulation using MATLAB.

A. Simulation Setup

In the simulation setup as shown in Fig. 4, an incumbent user is located at the central coordinate of the simulation area. A total of 20 PALs and 150 GAAs are randomly distributed in a circular area with a radius of 80km with incumbent as the center. The simulation parameters are shown in Table I .

TABLE I
Simulation Parameters

Transmit power of PAL	47dBm/10MHz
Transmit power of GAA	23dBm/10MHz
Channel frequency range	3550-3560 MHz
Interference threshold of incumbents	-129 dBm/MHz
Propagation model	ITM model

B. Performance evaluation

We use the rules defined in Wireless Innovation Forum's specifications as the baseline scheme denoted as "WInnF Scheme" in Fig. 5. Then we compare it with two other schemes. The first one is that GAA can only request interference budget from its nearest PAL user, which is denoted as "Single PAL w/o coordination" in the figure. The other one is our proposed scheme where multiple PALs can coordinate through the blockchain to provide interference budget to GAA users. AS shown in Fig. 5, with the number of PAL CBSDs increasing, the number of licensed GAA user also increase for the schemes with cross-tier coordination (green and red line) while the number of licensed GAA user remains the same for the baseline scheme. This is because GAA users cannot utilize the interference budget of PALs. Furthermore, more

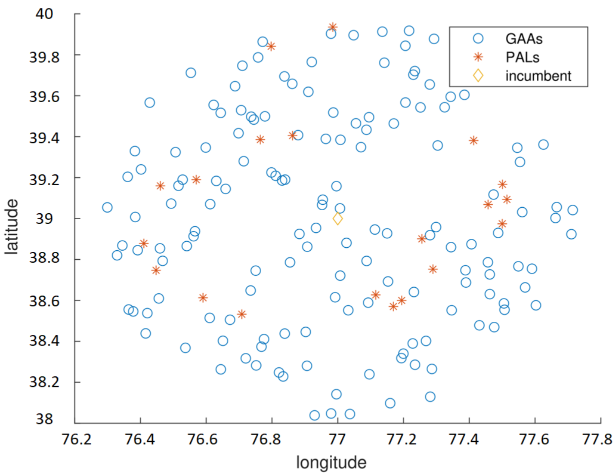

Fig. 4. Simulation setup.

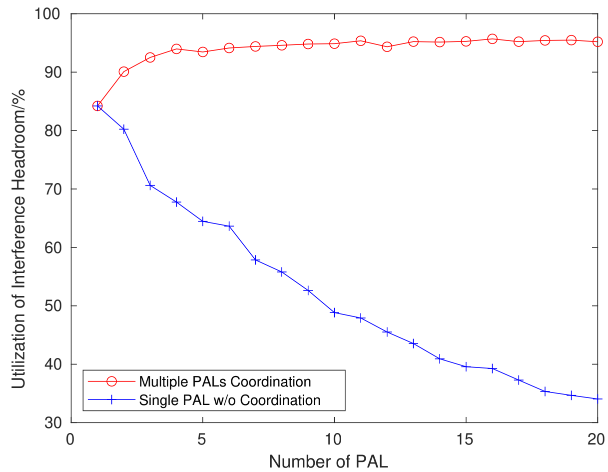

Fig. 6. Simulation setup.

licensed GAA users can be achieved when multiple PALs can coordinate their interference headroom. In Fig. 6, it can be observed that the scheme with multi-PAL coordination can have higher utilization ratio of the interference headroom of PAL users. This phenomenon becomes more obvious with the increase of the number of PALs, resulting a significant performance gap between the two schemes.

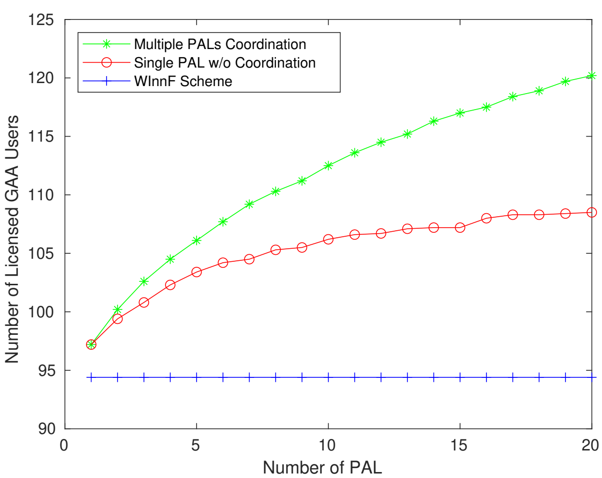

Fig. 5. Simulation setup.

V. Conclusion

In this paper, we designed an cross-tier coordination scheme based on blockchain for dynamic spectrum sharing. Our proposed solution enables the lower tier GAA users to utilize the interference headroom from upper tier PAL users to the incumbent through a secured blockchain network. The simulation results demonstrate that the proposed method improves the total number of GAA users that can have access to the shared spectrum and can fully utilize the unoccupied interference headroom to the incumbent. The application of blockchain technology in spectrum management presents a promising framework for a more flexible, transparent and secure utilization of the valuable electromagnetic spectrum resources.

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