Blockchain-Based Dynamic Spectrum Sharing for 5G and Beyond Wireless Communications

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Abstract. The blockchain technology written in smart contract has the advantages of the enabling intelligent settlement, value transfer and resource sharing, which provides a new secure and trusted platform for the dynamic spectrum sharing system. In this paper, we first summarize the application of blockchain technology in dynamic spectrum sharing considering the requirements of spectrum sharing. Then we discuss the key problems that need to be solved when applying blockchain to large-scale spectrum sharing system. After that, we analyze the key challenges in depth, and provide corresponding key technologies and possible solutions to the above problems.

Keywords: Dynamic spectrum sharing · Blockchain · Trusted spectrum ledger · Smart contract · Spectrum security

1 Introduction

With the wideband, ubiquitous, and syncretic development of wireless communications, the demand for spectrum resources keeps increasing explosively. However, the golden sub-6 GHz band that most suitable for wireless communications are almost exhausted, resulting in a serious structural supply-demand imbalance in spectrum resources. The shortage of available spectrum and low spectrum utilization caused by the static allocation mode forces us to adopt the dynamic spectrum sharing (DSS) technology. As a promising technology to improve the spectrum utilization, cognitive radio (CR) [1] technology has been developed almost 20 years, providing high levels of adaptivity to the communications environment with advanced spectrum sensing and sharing. However, the CR-based spectrum sharing still faces several problems that impede the implementation of DSS, such as lack of a spectrum sharing database that records the frequency information, lack of an effective incentive mechanism between primary and secondary users such that primary users cannot be compensated from sharing the idle spectrum, lack of a trusted platform that enables secure spectrum trading, and also severe security threats due to the open environment.

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Blockchain technology provides a good solution for the security and incentive problems in DSS. Through cryptography technology [2] and consensus mechanism, blockchain establishes a peer-to-peer [3] trust mechanism in the uncertain cyberspace. The blockchain-based distributed ledger technology (DLT) and smart contract [4] can also enable intelligent settlement, value transfer, and resource sharing, which naturally promotes the integration of blockchain and DSS. With DLT, the spectrum transactions can be recorded with transparency, immutability, and traceability guarantee, reflecting the status of every link in the circulation, and thus establishing a trusted relationship for the spectrum transaction. Based on the consensus mechanism, the spectrum resources rights can be confirmed, registered, and stored before the transaction, each node on the network can verify the validity of the rights, and thus providing a guarantee for maintaining spectrum sovereignty. In spectrum transactions, by establishing rules with smart contract, transactions can be realized automatically with guaranteed benefits for each participant. Thus, the blockchain-based DSS technology has also been regarded as one of the key technologies of 6G. The Federal Communications Commission (FCC) and French national spectrum management agency have started the research on spectrum blockchain. Moreover, the IMT-2030 Spectrum Group of Ministry of Industry and Information Technology of China is also promoting the research on the blockchain-based DSS.

1.1 State of the Art

Different from the cryptocurrency applications, the complex hierarchical relationship, highly dynamic scenarios, and users' random behaviors impede the direct application of blockchain to the DSS system. Considering the requirements of DSS system and the limitations of blockchain technology, a thorough understanding of the architecture of the complex dynamic system is required. To achieve spectrum sharing between spectrum providers and users, Kim et al. [5] designed a spectrum sharing system with blockchain, which is consisted of users, communication services, and blockchain network, and the communication services have mobile network operators (MNOs) and micro operators (MOs). A unified and shared database among all participating nodes is built with blockchain to enhance the clarity of the spectrum situation. Maksymyuk et al. [6] introduced a blockchain-based distributed mobile network infrastructure where smart contract automatically executes all transactions to eliminate the need for complex and expensive billing system. Zhou et al. [7] proposed a spectrum-sharing framework based on blockchain for human-to-human (H2H) and machine-to-machine (M2M) communications, which solves the two-sided matching problem between users and devices through a low-complexity stable matching method based on Gale-Shapley algorithm. Chen et al. [8] established a centralized private blockchain operating environment and a consortium blockchain operating environment in parallel with a full-spectrum blockchain as a service architecture. A unified interface for the two operating environments is developed to meet the needs of users' own operating environment.

To improve the spectrum utilization, it is necessary to provide double incentives for the owners and demanders of spectrum resources to promote efficient trading. A double-chain system combining public blockchain and consortium blockchain was developed in [9]. The operators in consortium blockchain can trade spectrum directly. Moreover, game theory is used for operators to share the spectrum between each other. In [10], to encourage authorized users to share their own spectrum, authors proposed a secure spectrum auction program based on blockchain, where spectrum monitoring obtains the information of idle bands. At the same time, the program improves the efficiency of spectrum auctions and ensures its effectiveness through two sealed bids. The program has the advantages of decentralization, accessibility, verification of user identity, and fraud prevention. In [11], an iterative double auction mechanism was proposed to maximize the benefits of both traders, which can encourage data demanders to submit bids and determine the number and price of transactions.

To deal with the security issues in CR, Kotobi and Bilén [12] proposed a blockchain verification protocol, which adopts a security algorithm that ensures the secure spectrum sharing in mobile CR network by authentication mechanism and preventing malicious nodes from accessing the spectrum without paying. [13] proposed a solution to the privacy problem of the consortium blockchain, preventing attackers from obtaining the private information recorded on the blockchain through data mining algorithms. [14] proposed a blockchain radio access network (B-RAN) architecture, and developed a distributed, secure, and efficient mechanism to manage network access and essentially untrusted authentication between network entities.

It is worth noting that even though some works have started to investigate blockchain-based DSS, a theoretical unified framework is still missing. In order to meet the requirements of response delay, throughput, computing and storage costs of large-scale spectrum sharing system, it is necessary to further study the key issues such as the architecture, the trusted spectrum ledger model, the incentive mechanism, and smart contract for spectrum trading.

1.2 Organization

We first investigate the application of blockchain technology in DSS, and propose the key challenges that need to be solved to achieve efficient dynamic spectrum sharing in Sect. 2. Then, we propose the architecture of blockchain-based DSS in Sect. 3, followed by key technologies to solve the above problems in Sect. 4. Conclusions are drawn in Sect. 5.

2 Challenges in Blockchain-Based DSS

To meet the requirements of DSS while guaranteeing the availability, credibility, security, and efficiency of the blockchain based spectrum sharing, the following key issues need to be solved.

2.1 The Blockchain Architecture for Large-Scale DSS System

Among the services supported by the radio spectrum, there are not only public mobile communications, broadcasting and television-oriented services for daily life, but also civil aviation, railway, and meteorological services related to life safety and public welfare, as well as military defense, disaster relief, and other services related to national security. Different services have different requirements for quality-of-service (QoS), security, and bandwidth, which greatly increase the complexity of spectrum sharing system. At the same time, considering the specific property of spectrum resources, the auction and utilization of spectrum cannot be separated from the regulatory and administrative intervention of the radio management department. Therefore, when designing the architecture of blockchain-based DSS system, both the administrative approval and monitoring of the national radio management department, and the decentralized characteristics of multi-party participation such as private network operation departments, mobile operators, radio and television operators, and other relevant special departments. In addition, some services have very high level of security requirements. To achieve the strict management and efficient spectrum sharing, a hierarchical and heterogeneous hybrid blockchain architecture that includes administrative supervision and free marketing competition is required to combine consortium blockchain and private blockchain. Considering the requirements of DSS, blockchain technology should be improved through the optimization of modules. For example, the data structure, storage and query, and consensus mechanism of blockchain should be redesigned and optimized.

2.2 The Spectrum Ledger

In order to achieve efficient secure sharing and strict management of spectrum resources, the transaction process and usage status of spectrum should be recorded into the spectrum ledger to form a distributed spectrum database. The wide-area and dynamic characteristics of spectrum sharing, the diverse types of data, and the dramatic changes in data bring great challenges to the construction of the spectrum ledger. Considering the requirements of spectrum asset ownership, account information query, and circulation process records, we need to establish an account-based model with the account as the asset and transaction object. Compared with traditional databases, the blockchain ledger does not allow delete and modify operations. However, with the increase of the amount of block data, the storage space of blockchain nodes will become larger and larger. To reduce the storage space requirements of nodes while ensuring the performance, efficient data storage mechanism is required. In addition, efficient consensus is needed to ensure that only one node can write data to the ledger at the same time. Blockchain solves the trust of distributed nodes through the consensus mechanism, and ensures the immutability of information by using digital signature and hash operation for distributed unified storage, but the consensus mechanism cannot solve the problem of data fraud. In order to perform data inspection and quality evaluation provided by sensing nodes and also identify malicious nodes, advanced smart contract based spectrum sensing deserves more research efforts.

2.3 The Incentive Mechanism for Spectrum Sharing

Double incentives for the owners and demanders of spectrum resources is a prerequisite for spectrum resources trading so that the effective spectrum sharing can be achieved. However, it will also cause problems such as malicious encroachment, transaction congestion, and transaction fairness during spectrum trading. To this end, we need to create a payment mechanism suitable for spectrum transactions, construct an incentive model, and establish a secure spectrum sharing and leasing mechanism to ensure efficient completion of transactions. However, how to design the spectrum trading incentive strategy and the multi-user cooperative spectrum sharing incentive model to maximize the revenues of both the owner and demander is still a challenging issue.

2.4 Smart Contract for Spectrum Management

In CR, there is no trust between primary and secondary users, thus it is easy to cause fraud and lose the fairness of spectrum transactions. Meanwhile, a large number of illegal behaviors in the wireless network not only causes interference to primary users, but also increases difficulty for radio monitoring and management. In order to solve the implementation laws and regulations in the process of mutual trust and supervision between each node in the blockchain based spectrum network, smart contract cooperative spectrum resource management should be introduced. Smart contract is a programmable language that automatically executes the terms of a contract. It can establish rights and obligations for both parties to an agreement, then a computer or computer network can automatically run the smart contract script code. To this end, we need to weight the fairness of "first shipment" and "first payment" from the perspective of transaction initialization, payment transaction, withdrawal transaction, refund transaction, etc. Meanwhile, to achieve "face-to-face" trading of spectrum resources in the true sense, we should study the fair payment agreement based on smart contract to ensure the fairness of transactions. Considering the identity of the executor of laws and regulations in the supervision and management process, the operation process of laws and regulations based on smart contract should be studied. Therefore, in the spectrum cooperative management, both the fairness of transactions and regulations should be considered, so as to achieve a credible, automated, and coordinated spectrum management system based on smart contract.

3 The Architecture of Blockchain-Based DSS

The blockchain architecture has evolved three phases up to now. Blockchain 1.0 [15] is the architecture of digital payment system represented by Satoshi Nakamoto's earliest application of Bitcoin technology; Blockchain 2.0 [16] is the architecture typically represented by Ethereum which first introduces smart contract into blockchain; Blockchain 3.0 does not yet have a recognized representative, but it will go beyond the financial field and become a system architecture for enterprise-level applications that provide services to all walks of life. Although the architecture at each stage differs in specific performance, the basic architecture is usually divided to six layers: data layer, network layer, consensus layer, incentive layer, contract layer, and application layer.

The blockchain-based DSS should be considered to meet the requirements of availability, effectiveness, and security, so that the value transfer of spectrum information and digital assets can be achieved. However, the spectrum sharing system covers a wide range, including not only centralized regulatory agencies such as the National Radio Monitoring Center (NRMC), but also multi-party participants such as mobile network operators, railways, airplanes, satellites, etc., as well as multiple types of users such as mobile users, internet, cars, etc. In addition, it cannot meet the requirement of response time for the real-time performance and processing speed of the smart contract mechanism on the fully decentralized public blockchain. A pure private blockchain is not fundamentally different from the current distributed architecture and cloud platform architecture, but only adds a constant and trusted data function, which is not suitable for the entire chain and applications of multi-party participants. Therefore, the application of blockchain technology in the construction of a blockchain-based spectrum system should establish a consortium blockchain with a government regulatory department as the core. Based on this, the overall blockchain-based DSS model is shown in Fig. 1. NRMC has the monitoring rights to all nodes in the blockchain-based DSS system. The spectrum transaction information and the available spectrum usage of all nodes are open and transparent to NRMC, but NRMC is independent of other nodes.

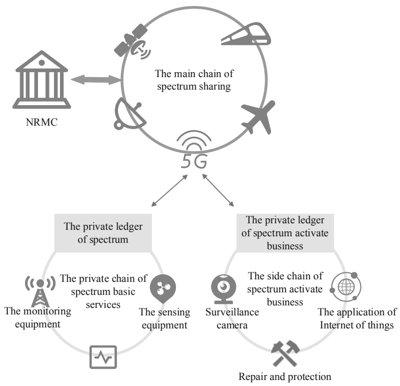

Fig. 1. The overall model of blockchain-based DSS.

Moreover, because the spectrum sharing system involves a large range and there may be cross-region transactions between different mobile network operators, it should be designed according to multi-level blockchains (main chain and side chain). Cross-region applications such as cross-region transactions are completed on the main chain, while intraregional applications are completed on the sidechain. In the local scope, the main services include distributed spectrum point-to-point [17] transactions, spectrum contracts, and spectrum data security. It is planned to consider deploying a sub chain in a local area, while the scenario of cross-region spectrum service plans to deploy the main chain of the blockchain-based DSS system. The main chain and the sub chain are side-chain relationships. The main chain mainly serves cross-region identity authentication, asset transfer, spectrum transaction, and data interaction, while the sub chain mainly serves blockchain application services in a single area. The sub chains between different regions realize flexible interconnection and disaggregation with the main chain according to channel conditions and functional requirements. There are different sub chains in multiple regions under a main chain of the complete blockchain-based DSS system. The sub chains do not directly exchange data with each other. All data interactions must be connected to the main chain through network security protection equipment (such as firewalls), and then the main chain completes the data interaction. Moreover, the operation security among the side chains, and that between the side chain and the main chain does not affect each other with flexible access and disassembly functions. In addition, the relationship between the spectrum blockchain and other activate business blockchains is the relationship between side chains.

The capacity of the public ledger will be increasing for the undeleted characteristic of blockchain. Thus, it's not necessary for each participating network node to maintain a complete ledger in practice, and the network node should be selectively classified according to the application scenario. Considering different requirements of the nodes on the main chain and the side chain, and the different authentication methods of the nodes participating in the blockchain, we divide the nodes into full nodes, relay nodes, and light nodes based on their functions. The full nodes are generally composed by the main and important participants in the blockchain, such as the telecommunications operators, which has the best communication resources and requires complete ledger records and consensus capabilities, completing data verification and synchronization functions. The relay nodes are generally composed by infrastructure in the network, e.g., communication base stations in local areas with data collection and forwarding capabilities. They can complete the data collection and allocation in the jurisdiction and provide this function for interactive information of other participants in the network. So the relay nodes own pretty good communication resources in the network. The light nodes are generally terminal equipment, such as mobile devices and civilian drones. They generally have the entry function for various applications and the ability to complete simplified authentication protocols, complete the collection and upload of raw data, and accept the interactive information of other participants in the network. But they do not have enough storage capacity of the entire blockchain data and only store neighboring node address information and block header information.

The blockchain-based DSS architecture is divided into system front-end and back-end. The front-end of the system is the user interface, including various user-oriented application interfaces, which can perform spectrum leasing and trading, asset transfers, etc. The back-end of the system is designed according to the basic framework of blockchain. The lowest-level includes the support system and the blockchain data layer. The distributed support system includes distributed computing, distributed storage, distributed network, and spectrum sensing. The data layer is responsible for encapsulating the underlying data blocks and related basic data and algorithms such as data encryption and time stamping. The core module includes four key functions: network layer, consensus layer, incentive layer, and contract layer. The network layer includes distributed networking mechanism, data transmission mechanism, and authentication mechanism. The consensus layer mainly encapsulates various consensus algorithms of network nodes such as Proof-of-Work (PoW), Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT) [18], etc. The incentive layer mainly considers the economic factors of the blockchain, including the spectrum coin issuance mechanism, allocation mechanism, and user reputation modelling and evaluation to inspire economic benefits. The contract layer encapsulates various programming languages, contract scripts and runtime environments to support the programmable characteristics of the blockchain. The top application layer encapsulates various application scenarios and use cases of the blockchain.

4 Key Technologies

In this section, we provide the key technologies in the blockchain based DSS system.

4.1 Trusted Spectrum Ledger

The distributed ledger provided by blockchain allows the spectrum transaction records to be open, transparent, immutable and traceable, which fully reflects the status of each link in the circulation, establishing a trusted relationship among various links in the circulation. It greatly promotes the implementation of spectrum sharing. Based on this, the blockchain-based DSS is essentially a distributed ledger which records spectrum information. Apart from the information such as spectrum auctions, spectrum transactions, and spectrum access, the spectrum ledger should also include sensing data from external spectrum sensing equipment. The information recorded in the spectrum ledger provides a basis for the efficient sharing of spectrum resources, fair transactions, and effective management and control, but it is also vulnerable to malicious node attacks. So, we should design and implement spectrum ledger data based on hash calculation to effectively solve the above problems. To this end, the spectrum ledger model is shown in Fig. 2. It should be noted that spectrum information usually has a large amount of data.

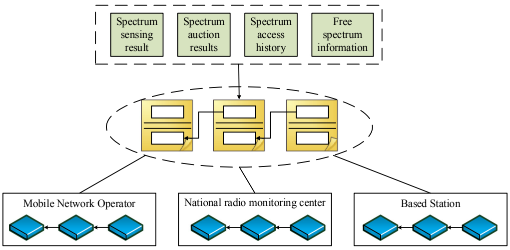

Fig. 2. The illustration of the spectrum ledger.

In order to ensure the storage in the block, on the one hand, data compression or pre-processing can be adopted. On the other hand, the original spectrum data can be uploaded to the edge storage server, and only the root hash value of the original data in the edge memory is stored in the blockchain. Figure 3 shows the architecture of the spectrum data block. The spectrum data generated in a certain period is hashed to generate a hash value. The hash value of each spectrum data is organized to form a Merkle tree, and thus any change in the spectrum data can be reflected on the root of Merkle tree.

At same time, the data in the wide-area with considerable values is helpful to understand the spectrum characteristics in the space. The monitoring and sensing network are established so as to obtain the spectrum sensing data [19]. Under the circumstance of limited sensing network resources, smart contract based spectrum sensing can be used, as shown in Fig. 4. First, the local spectrum management server deployed on the edge server or the cloud regularly releases spectrum sensing tasks, and proposes spectrum

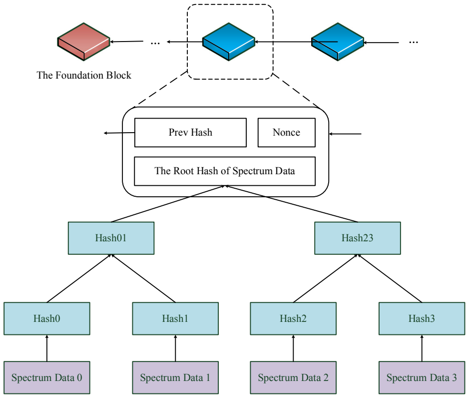

Fig. 3. The architecture of the spectrum block.

data collection task requirements including collection time, frequency band limits, and geographic area limitations. Spectrum data collection tasks are visible to all servers and nodes in the spectrum equipment network. When the spectrum management server issues a spectrum sensing task, it automatically generates and pre-stores the corresponding spectrum coin as a reward for the completion of the spectrum sensing task. Second, the sensing nodes decide whether to respond to the spectrum sensing task based on their own action plan, battery power, and geographic location. The nodes accepting the task complete registration on smart contract. Then smart contract completes the selection of nodes based on the location, price, and reputation. After that the smart contract informs the selected nodes. Finally, the sensing nodes complete the spectrum sensing task and upload the results. Smart contract completes the verification of the quality of the data, confirms whether it meets the contract requirements, and issues rewards according to the contract.

4.2 Smart Contract for DSS

By leveraging smart contract, spectrum trading can be completed automatically and securely by executing the contract terms without relying a trusted third party. In addition, the smart contract defined in the form of digital codes can be flexibly embedded in the spectrum management, asset transfer, and spectrum transaction information, which facilitates dynamic spectrum sharing. As shown in Fig. 5, the trigger conditions, response rules, and trusted data sources of the contract terms are preset in the codes of smart contract. The trigger conditions include specific trading time, data resources, and sharing institutions to ensure the orderliness of the system. Response rules include specific trading actions, legal agreements, etc., to ensure the legitimacy of transactions. Data sources mainly provide the information of spectrum data source that can be shared by both parties to a spectrum transaction. Secondly, smart contract is broadcasted to the nodes in the network along with the user-initiated transaction after mutual agreement and signatures by multiple parties. The miners verify them and stores them in the specific block after verification. The users can call the contracts by initiating a transaction after

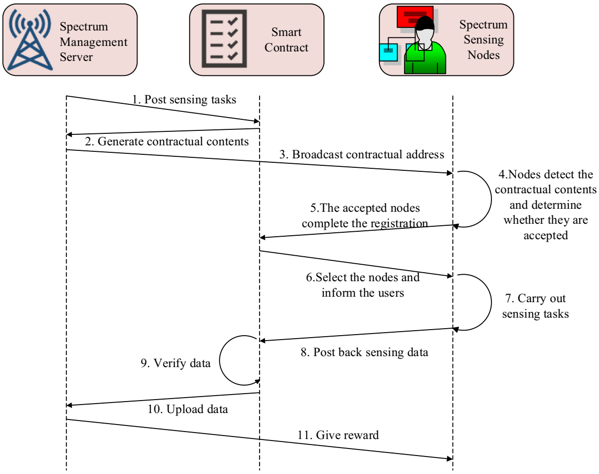

Fig. 4. The smart contract based spectrum sensing.

obtaining the returned contract address and contract interface. The miners are encouraged by the preset activating mechanism of the system, and provide their own storage and computing resources to verify the validity of the transaction. After receiving the contracts to create or call the transaction, the miners create contracts or execute the contract codes in the local sandbox execution environment. The codes automatically determine whether the current scene meets the contract trigger conditions based on trusted external data sources and inspection information to strictly enforce the response rules and update the world status. In the end, the trading verification is packaged and added to the new data block after being verified. The new block is authenticated by the consensus mechanism, and is linked to the main chain of the blockchain. All the updates take effect, and the miners get the block rewards.

4.3 The Spectrum Trading Mechanism

The status of each participants in the spectrum trading network is highly dynamic. Smart contract is added to each independent block to effectively separate the trading settlement of different participants. In [20], spectrum coin (SC) is used for spectrum trading settlement and mining rewards between UAV users and mobile operators. In [12], SC is used to pay for data transmission of cognitive radio networks, spectrum leasing between secondary users and primary users, and block rewards. SC is mainly used for spectrum transaction payment, transaction verification rewards and block rewards. In blockchain based DSS, SC can be used to facilitate the spectrum trading, including spectrum payment, trading verification rewards, and block generation rewards, etc. A possible spectrum trading scheme with SC is shown in Fig. 6. There are multiple spectrum authorized users forming part of blockchain. Primary spectrum users include spectrum authorization users and users who transfer spectrum resources, and secondary spectrum users include users who request or rent spectrum resources. The primary users and secondary users of the spectrum publish their spectrum resources and requirements to

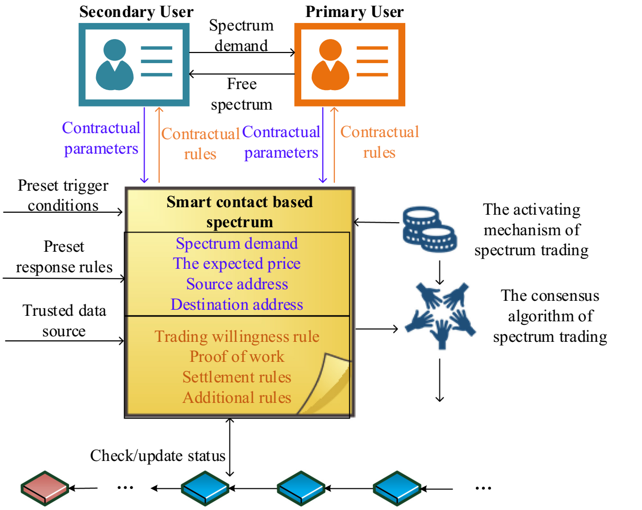

Fig. 5. The smart contract for DSS.

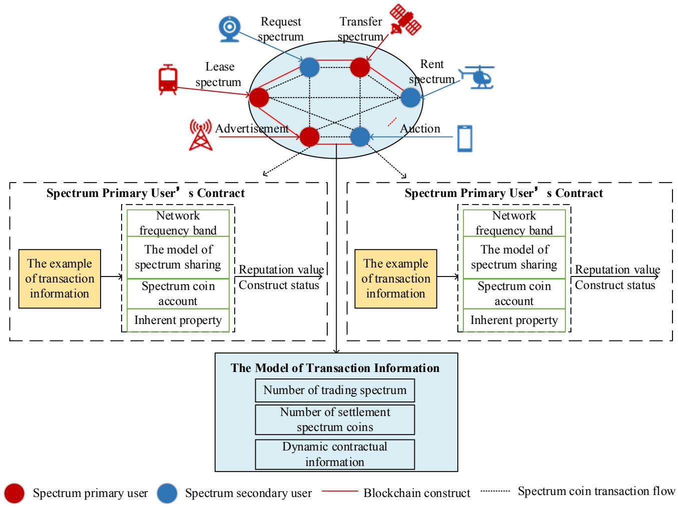

Fig. 6. The spectrum trading scheme based on SC.

all nodes in the network. Smart contract automatically communicates with users based on the request information, such as bidding, and frequency usage time. Once the information is matched, and the account balance meets the requirement. Then the agreement is automatically executed and the reputation value is updated. Smart contract determines whether to perform spectrum sharing trading based on the primary and secondary users' information matching results and reputation values. If the spectrum sharing trading is executed, smart contract establishes a transaction information model based on the number of spectrum trading, the number of settlement SCs, and dynamic contract information.

The spectrum trading information is eventually written into the spectrum ledger. After the trading is completed, the reputation value of the primary and secondary users is updated synchronously. With this spectrum trading method, the secondary users acquire the required spectrum usage rights by spending a certain amount of SCs, and the primary users obtain equivalent SCs by surrendering the spectrum usage rights.

5 Conclusion

In this paper, we have investigated the application of blockchain technology in dynamic spectrum sharing. Firstly, we have conducted a thorough literature review on the recent research on spectrum blockchains. Then, we have pointed out the key challenges in building the blockchain-based DSS. After that, we have discussed possible solutions. Although the combination of blockchain and DSS has attracted the extensive research attention, it is still in its infancy stage and has not yet formed completed standards. Even though the combination of blockchain and DSS is promising, the problems of blockchain on security, scalability, and algorithm performance, etc. are far from enough to be applied in DSS, which deserves more and more research efforts.

References

1. Mitola, J.: Cognitive radio. An integrated agent architecture for software defined radio (2002)
2. Katz, J., Lindell, Y.: Introduction to Modern Cryptography. CRC Press, Boca Raton (2014)
3. Milojicic, D.S., et al.: Peer-to-peer computing. Technical report HPL-2002-57, HP Labs (2002)
4. Buterin, V.: A Next-generation smart contract and decentralized application platform. White Paper **3** (2014)
5. Kim, J., Cha, H., Kim, S.-L.: Spectrum leasing for micro-operators using blockchain networks. In: Moerman, I., Marquez-Barja, J., Shahid, A., Liu, W., Giannoulis, S., Jiao, X. (eds.) CROWNCOM 2018. LNICST, vol. 261, pp. 66–77. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-05490-8_7
6. Maksymyuk, T., Gazda, J., Han, L., Jo, M.: Blockchain-based intelligent network management for 5G and beyond. In: 2019 3rd International Conference on Advanced Information and Communications Technologies (AICT), pp. 36–39. IEEE (2019)
7. Zhou, Z., Chen, X., Zhang, Y., Mumtaz, S.: Blockchain-empowered secure spectrum sharing for 5G heterogeneous networks. IEEE Netw. **34**, 24–31 (2020)
8. Chen, Y., Gu, J., Chen, S., Huang, S., Wang, X.S.: A full-spectrum blockchain-as-a-service for business collaboration. 2019 IEEE International Conference on Web Services (ICWS), pp. 219–223 (2019)
9. Han, S., Zhu, X.: Blockchain based spectrum sharing algorithm. In: 2019 IEEE 19th International Conference on Communication Technology (ICCT), pp. 936–940. IEEE (2019)
10. Liang, Y.-C.: Blockchain for dynamic spectrum management. In: Liang, Y.-C. (ed.) Dynamic Spectrum Management. SCT, pp. 121–146. Springer, Singapore (2020). https://doi.org/10.1007/978-981-15-0776-2_5
11. Chen, C., Wu, J., Lin, H., Chen, W., Zheng, Z.: A secure and efficient blockchain-based data trading approach for internet of vehicles. IEEE Trans. Veh. Technol. **68**, 9110–9121 (2019)
12. Kotobi, K., Bilen, S.G.: Secure blockchains for dynamic spectrum access: a decentralized database in moving cognitive radio networks enhances security and user access. IEEE Veh. Technol. Mag. **13**, 32–39 (2018)

13. Gai, K., Wu, Y., Zhu, L., Qiu, M., Shen, M.: Privacy-preserving energy trading using consortium blockchain in smart grid. IEEE Trans. Industr. Inf. **15**, 3548–3558 (2019)
14. Ling, X., Wang, J., Bouchoucha, T., Levy, B.C., Ding, Z.: Blockchain radio access network (B-RAN): towards decentralized secure radio access paradigm. IEEE Access **7**, 9714–9723 (2019)
15. Nakamoto, S.: Bitcoin: a peer-to-peer electronic cash system. Manubot (2019)
16. Wood, G.: Ethereum: a secure decentralised generalised transaction ledger. Ethereum Proj. Yellow Paper **151**, 1–32 (2014)
17. Simpson, W.: RFC1661: the point-to-point protocol (PPP). RFC Editor (1994)
18. Castro, M., Liskov, B.: Practical byzantine fault tolerance. In: OSDI, pp. 173–186 (1999)
19. Bayhan, S., Zubow, A., Gawłowicz, P., Wolisz, A.: Smart contracts for spectrum sensing as a service. IEEE Trans. Cogn. Commun. Netw. **5**, 648–660 (2019)
20. Qiu, J., Grace, D., Ding, G., Yao, J., Wu, Q.: Blockchain-based secure spectrum trading for unmanned aerial vehicle assisted cellular networks: an operator's perspective. IEEE Internet Things J. 1 (2019)