Research of the application of blockchain and smart contract technologies in spectrum management and trading in cognitive radio networks

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Abstract. The rapid growth of wireless communication technologies has led to an exponential increase in the demand for spectrum resources. Spectrum management, the process of allocation and control of limited radio frequency spectrum, is critical to the efficient and equitable distribution of this scarce resource. However, traditional methods of spectrum management face many problems, including inefficiency, lack of transparency and proneness to fraud. In recent years, blockchain technology has emerged as a potential solution to these problems. The emergence of smart contracts using blockchain technology has the potential to revolutionize spectrum trading and improve spectrum management practices. This paper explores the application of blockchain in spectrum management and discusses its potential to revolutionize the way spectrum resources are allocated and managed. Also, the concept of smart contracts and their application in spectrum trading are studied. It discusses the benefits of using smart contracts for transparent and efficient spectrum transactions, implementation challenges, and potential solutions. Through the use of smart contracts, a secure and decentralized market for spectrum resources can be created, facilitating dynamic and flexible allocation of spectrum.

1 Introduction

Wireless communication has become an integral part of our daily lives, enabling a wide range of applications such as mobile communications, Internet access, satellite communications, and IoT devices. Efficient management of the radio frequency spectrum is necessary to ensure interference-free and reliable wireless communication. Traditional approaches to spectrum management, such as command-and-control regulation and auctions, have limitations in terms

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of transparency, flexibility, and adaptability to dynamic spectrum requirements. Blockchain technology offers a decentralized and transparent platform that can revolutionize the spectrum management paradigm. Spectrum trading allows licensees to transfer or lease their allocated spectrum to other organizations, allowing for more efficient use of the spectrum. However, traditional spectrum trading processes are often complex, time-consuming and lack transparency. This paper introduces the concept of smart contracts and their potential to simplify spectrum trading by automating and enforcing contractual transactions. Traditional spectrum licensing models often fail to respond to the dynamic nature of wireless communications systems, resulting in underutilization of valuable spectrum resources. Short-term spectrum trading offers a promising solution by allowing licensees to rent or sell their allocated spectrum over a period of time.

Cognitive Radio Networks. Cognitive radio networks (CRNs) are a promising solution to the growing demand for wireless communication services. CRNs are designed to improve the use of radio frequency spectrum by allowing unlicensed users to use spectrum currently used by licensed users. This technology is based on the concept of cognitive radio, which allows radios to sense their environment and adapt transmission parameters to optimize spectrum use. The main idea behind CRN is to allow radios to dynamically access the spectrum without interfering with licensed users. This is achieved by using intelligent algorithms that allow the radios to sense the spectrum and determine which frequencies are usable. Once a frequency is detected, the radio can use it for communication. If the frequency is occupied by a licensed user, the radio will switch to another available frequency. CRNs are also designed to be self-organizing, meaning they can form ad hoc networks without requiring centralized management. This allows for greater flexibility and scalability, as well as increased reliability and durability. One of the main advantages of CRNs is their ability to improve spectrum utilization. In traditional wireless networks, most of the spectrum is allocated to licensed users, even if they don't use it all the time. This leads to underutilization of the spectrum and limits the number of users who can access it. On the other hand, CRN allows unlicensed users to access the spectrum when it is not being used by licensed users, thus improving overall spectrum utilization. Another advantage of CRN is its ability to improve network performance. By allowing radios to access the spectrum dynamically, CRN can reduce interference and improve signal quality, resulting in overall network performance. However, there are also problems with CRN. One of the main challenges is to ensure that unlicensed users do not interfere with licensed users. To overcome this problem, CRNs should be designed with strong noise mitigation techniques such as spectrum sensing and power management. Another challenge is ensuring that CRNs are secure and reliable. Because CRNs are self-organized, they can be vulnerable to attacks by malicious users. To solve this problem, CRNs should be designed with strong security mechanisms such as authentication and encryption [1-2].

Blockchain and Smart Contracts. Blockchain technology has revolutionized the way transactions are carried out, offering a decentralized and secure system that eliminates the need for intermediaries. Blockchain is a distributed ledger technology that allows multiple parties to maintain a shared database without the need for intermediaries. It ensures data integrity, transparency and immutability through cryptographic algorithms and consensus mechanisms. These features make blockchain an ideal solution for spectrum management, where trust, accountability and efficiency are paramount. The technology has been used in a variety of industries, including finance, healthcare and supply chain management. One of the most promising applications of blockchain technology is in the field of smart contracts.

Smart contracts are self-executing contracts that are programmed to automatically execute when certain conditions are met. They are designed to eliminate the need for intermediaries such as lawyers and brokers and reduce transaction costs. Smart contracts are stored on the blockchain, which provides a secure and transparent platform for their execution. The basic idea behind smart contracts is to create a digital agreement that automatically executes when

certain conditions are met. For example, a smart contract can be used to automate the process of buying and selling a house. The contract would be programmed to automatically execute when the buyer transfers payment to the seller. Once payment is received, the contract transfers ownership of the home to the buyer. One of the main advantages of smart contracts is their ability to reduce transaction costs. By eliminating intermediaries, smart contracts can significantly reduce transaction costs. This is especially useful for industries that rely on intermediaries, such as finance and real estate. Another advantage of smart contracts is the ability to increase transparency and security. Because smart contracts are stored on the blockchain, they are immutable and transparent. This means that once a smart contract is implemented, it cannot be changed or deleted. It provides a high level of security and transparency, which is especially important for networks that deal with sensitive data. However, there are also problems with smart contracts. One of the main challenges is to ensure that the code is error-free. Since smart contracts are executed automatically, any error in the code can have serious consequences. To solve this problem, smart contracts must be developed with robust testing and auditing processes. Another challenge is to ensure that the legal framework is in place to support smart contracts. Since smart contracts are relatively new, their legal status is still unclear. To solve this problem, governments and regulatory bodies must work together to create a legal framework that supports the use of smart contracts [3].

The integration of CRN and blockchain technology can provide a number of advantages, such as increased security, reliability and transparency. One of the main advantages of combining CRN and blockchain is the ability to provide secure and reliable communication. Because blockchain is a decentralized system, it eliminates the need for intermediaries and provides a transparent platform for secure communication. This can significantly improve the security and reliability of CRN. Another benefit of combining CRN and blockchain is the ability to improve spectrum utilization. By dynamically allocating spectrum resources based on user needs, CRN can significantly improve spectrum efficiency. Blockchain technology can further improve spectrum utilization by providing a transparent platform for spectrum trading. This allows users to sell unused spectrum resources, which can further improve spectrum utilization. However, there are also problems with the integration of CRN and blockchain technology. One of the main challenges is the need for efficient consensus algorithms. Because blockchain is a decentralized system, it requires consensus algorithms to ensure that all nodes in the network agree on the state of the blockchain. However, traditional consensus algorithms may not be suitable for CRNs due to their dynamic nature. Another challenge is the need for efficient resource allocation algorithms. Since CRN allocates spectrum resources dynamically, efficient resource allocation algorithms are essential to ensure that users get the spectrum resources they need. Blockchain technology can further complicate resource allocation by introducing additional constraints, such as the need for consensus [4-5].

In summary, the integration of CRN and blockchain technology has the potential to revolutionize the way spectrum resources are allocated and improve the security and reliability of CRN. However, there are challenges associated with integrating these two technologies, such as the need for efficient consensus and resource allocation algorithms. As research in this area continues, the integration of CRN and blockchain technology is expected to become an increasingly important part of the global communication infrastructure.

2 Methods

In CRN, the blockchain can be used to perform the following functions [6-7]:

Spectrum Allocation and Licensing. Blockchain can simplify the spectrum allocation process by providing a transparent and tamper-proof record of spectrum licenses. Smart contracts, self-executing software on the blockchain, can automate licensing, renewal and

cancellation based on predefined rules. This eliminates manual paperwork and reduces administrative overhead. In addition, blockchain-based identity management systems strengthen authentication and verification processes, preventing unauthorized access to spectrum resources.

Spectrum Exchange and Trading. Blockchain can facilitate dynamic spectrum sharing and trading, enabling efficient use of underutilized spectrum bands. Using blockchain-based decentralized markets, spectrum owners can rent or sell their unused spectrum to other users in real time. Smart contracts can automate payment calculations, ensuring fair and transparent transactions. This approach encourages efficient use of spectrum and reduces the need for exclusive ownership, leading to a more flexible and cost-effective spectrum management system.

Interference monitoring and control. Blockchain can strengthen interference monitoring and control mechanisms in spectrum management. By integrating blockchain with IoT devices, real-time spectrum monitoring can be achieved, enabling immediate detection and mitigation of interference events. Blockchain-based reputation systems can encourage users to comply with spectrum usage rules, as non-compliance can result in reputational penalties. This self-regulatory aspect of blockchain can significantly reduce the burden on regulators.

Security and Privacy Issues. Blockchain technology brings inherent security advantages such as data integrity and immutability. However, privacy issues arise when dealing with sensitive spectrum usage data. Solutions such as zero-knowledge proofs and privacy-preserving smart contracts can be used to ensure privacy while maintaining transparency in the spectrum management process. In addition, access control mechanisms based on cryptographic methods can protect confidential information from unauthorized access.

Blockchain is a type of DLT (Distributed Ledger Technology) that enables consensus and data recording without a central authority. It stores information in blocks that are linked together in a chain, with each block being verified and linked to the previous one. The use of blockchain in CRN offers benefits such as decentralization, transparency, immutability, availability, and security. However, integrating blockchain and CRN faces challenges such as efficient consensus and resource allocation algorithms. As research continues, the integration of these two technologies is expected to become increasingly important in global communication infrastructure. Figure 1 shows a conceptual diagram of using blockchain in spectrum management in CRN.

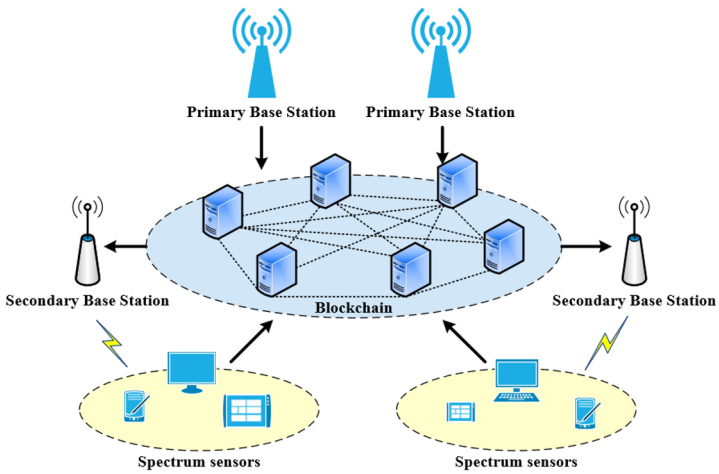

Fig. 1. The Concept of Blockchain-based Spectrum Management in CRNAuthorized

Blockchain network authorities can grant or withdraw various user access rights. The integration of blockchain and CRN offers several advantages, such as decentralization, transparency, immutability, availability, and security, which are particularly beneficial for spectrum management. These benefits are discussed in detail in reference:

One benefit of integrating blockchain and CRN for spectrum management is decentralization, which allows users to manage their data without requiring third-party verification. This eliminates the need for database administrators and provides users with more control over their information.

Another advantage of combining blockchain and CRN for spectrum management is increased transparency. With the ledger being accessible to multiple nodes, the history of transactions and blockchain algorithms can be easily reviewed, leading to better visibility and more effective enforcement of spectrum management regulations.

The third benefit of using blockchain for spectrum management is its immutability and high level of security, which makes it extremely challenging to alter any data on the blockchain. This attribute is valuable for ensuring accurate auditing, compliance, and enforcement of regulatory and contractual obligations.

The fourth advantage of utilizing blockchain technology for spectrum management is its increased availability due to the interlinking of ledgers between nodes. This enhances the reliability of the blockchain as a database for spectrum management, ultimately safeguarding the interests of current users.

The fifth benefit of employing blockchain technology for spectrum management is the heightened security it provides. The ledger entries are secured through cryptography, and transactions between nodes are digitally signed. Moreover, access to the blockchain is only possible through a private/public cryptographic key pair, which bolsters the security of the wireless network infrastructure against potential attacks.

In order to fully utilize the benefits of dynamic spectrum allocation in CRNs, it is necessary to have comprehensive regulation of spectrum usage, interference management, and security measures. This can be achieved through the use of dense spectrum sensing and the creation of a spectrum resource space for dynamic access decisions. Spectrum regulation is also crucial for detecting and preventing illegal transmissions. However, implementing full-spectrum applications in CRN network architectures poses significant challenges for spectrum regulation.

The implementation of dynamic spectrum allocation in CRNs requires thorough regulation of spectrum usage, interference management, and security measures. To overcome the challenges associated with full-spectrum applications, a blockchain-based spectrum management model can be established. This model enables comprehensive transaction tracking, deposit sensing, signal identification, and dispute arbitration through on-chain and off-chain coordination. The immutability features of blockchain technology facilitate the establishment of a fully traceable regulatory process that includes on-chain registration, spectrum trading, and spectrum regulation. The spectrum management model involves wireless network operators, a blockchain network, and an off-chain monitoring system.

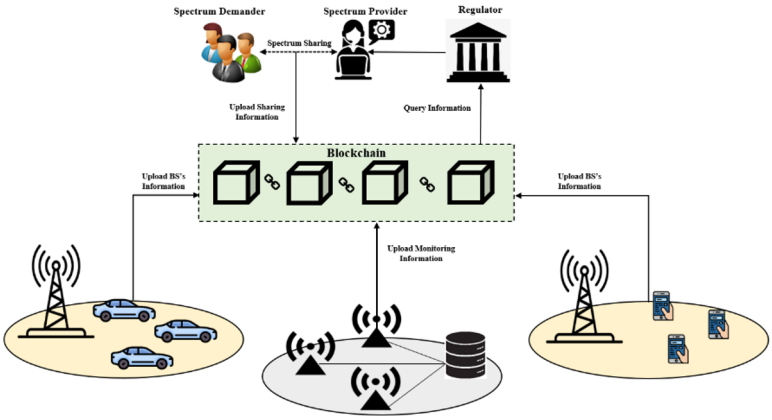

Fig. 2. Blockchain based Spectrum Management ModelAccording to this model, the process of spectrum management in CRN can be explained as follows [8-9]

- Each BTS associated operator registers their open/secret keys and certificates on the blockchain network to obtain them. The registration data includes location, antenna or radiation types, pre-defined modulation type, and maximum transmission power. The registered data cannot be tampered with and can be monitored by querying the distributed ledger. Additionally, monitoring devices also record their identifiers, locations, and operational parameters on the blockchain network;
- Each operator can function as a spectrum demander or provider in an adaptive manner and participate in spectrum trading or auctions with other operators. The transactions between operators are recorded on a chain of operations;
- Under a spectrum sensing system based on blockchain technology, the area in question is constantly monitored by devices across a specific range of frequencies. The data collected from this monitoring is either recorded in its original form or summarized and then added to the blockchain to ensure that the data is accurate and has not been tampered with;
- Each operator has the ability to file a complaint regarding interference, which would include information such as the location, frequency, and duration of the interference;
- After an operator file a complaint about interference, the controller will review the details provided such as the location, frequency, and duration of the interference. The controller will then analyze sensor data using algorithms to identify and locate the source of the interference, including its transmission power and modulation. Additionally, the regulator will monitor transaction records on the chain to aid in making decisions based on the analyzed data;
- The results are recorded in the chain for further processing.

3 Results and Discussion

3.1 Implementation of Blockchain based Spectrum Trading in CRN

When an interference complaint is filed by an operator, the controller will carefully examine the details provided, such as the location, frequency, and duration of the interference. They will then use algorithms to analyze sensor data and identify the source of the interference, including its transmission power and modulation. The regulator will also monitor transaction records on the chain to aid in making decisions based on the analyzed data.

In a CRN, allowing secondary users to share radio frequency spectrum with the primary network can pose a security risk if users are malicious. Malicious behavior during the spectrum auction process can also cause confusion in sharing the spectrum of the primary user. The

main challenge in establishing a secure spectrum sharing mechanism in wireless communication systems is how to deal with a malicious user's access to the primary user's spectrum. Blockchain technology's inherent security attributes can be utilized to create a secure architecture for spectrum sharing in wireless communication systems.

A blockchain-based architecture for spectrum trading is proposed in Figure 3, which includes an authorization center, spectrum provider, spectrum requester, virtual coin, and base station. The authorization center sets the initial standards and rules for the blockchain, but does not participate in the trading process. Edge nodes, acting as base stations, complete mining calculations, verify commercial users, and conduct spectrum trading. The system uses a virtual currency called a spectrum coin for transactions, which is stored on edge nodes. Transaction records are stored on each edge node to ensure transparency and communication security. Secondary users act as spectrum demanders and must pay a virtual coin through border nodes to use the main network's spectrum. This mechanism has several important features [10]:

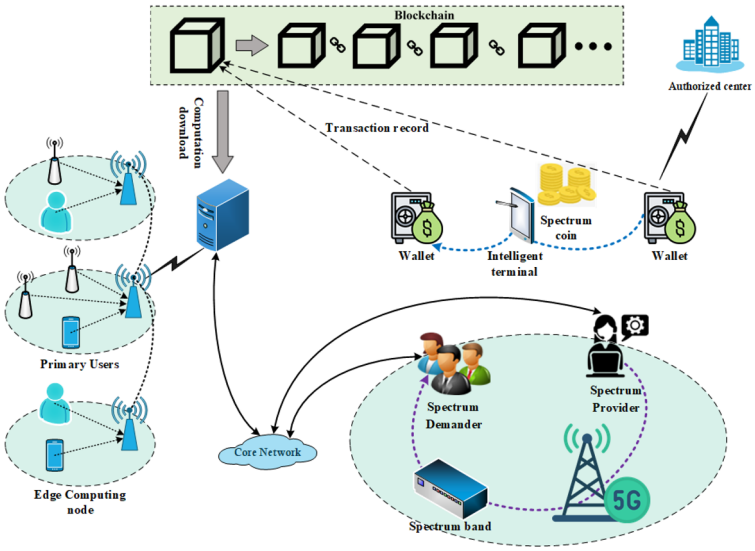

Fig. 3. Implementation Architecture of Blockchain-based Spectrum Tradingto address the issue of computing power in blockchain creation, a restricted number of nodes are implemented.

In Figure 2, the secondary network's distributed scenario is emphasized, and a central node or base station is chosen as the intermediary to communicate with primary network base stations. This intermediary has adequate computing power and energy reserves to carry out crucial block creation and processing tasks;

- a process is put in place to select a minimum number of nodes based on the trustworthiness of border nodes. This is done to prevent any malicious or underpowered nodes from entering the main network. A table is created for each potential access node, which contains all registration, transaction, and other relevant data. This information is distributed to authorized nodes for verification. The table must be regularly updated and maintained to ensure that any illegitimate nodes are blocked in a timely manner and access to malicious nodes is prevented;
- The process involves selecting trustworthy border nodes to prevent malicious or weak nodes from entering the main network. Each potential access node is evaluated based on registration, transaction, and other relevant data, which is then verified by authorized nodes. The table containing this information must be regularly updated to block any illegitimate nodes and prevent access to malicious ones. Additionally, the transaction between a secondary user and the main system is facilitated using a virtual spectrum coin, which is stored on a specific edge node. Border nodes that successfully access the blockchain through mining also

receive a spectrum coin incentive, which helps determine the difficulty coefficient of Mahbul min and maintains system balance.

Blockchain-based spectrum trading in CRN brings the following advantages:

Transparency and trust. Smart contracts provide transparent and tamper-proof records of all transactions on the blockchain, ensuring trust between parties involved in spectrum trading. All participants have the same information, reducing the risk of fraud or manipulation.

Efficiency and automation. By automating the execution of contractual agreements, smart contracts eliminate manual processes, reduce administrative costs and reduce human error. This automation enables near-real-time trading that allows for dynamic and flexible spectrum allocation.

Improve market access. Smart contracts enable the creation of a decentralized market for spectrum resources, providing equal opportunities for all stakeholders to participate in spectrum trading. Increased access to this market encourages competition and efficient allocation of spectrum.

3.2 Challenges and Solutions in Implementing Spectrum Trading using Blockchain

Regulatory frameworks. The implementation of smart contracts for spectrum trading requires the development of supporting regulatory frameworks that recognize and accommodate the unique characteristics of blockchain technology. Regulators must address legal and policy issues related to smart contracts, including contract enforcement and dispute resolution mechanisms.

Regulators, industry stakeholders, and blockchain experts should work together to develop regulatory frameworks that address the legal and policy issues surrounding smart contracts in spectrum trading. This cooperation should focus on contract enforcement, establishing dispute resolution mechanisms, and establishing accountability frameworks.

Compatibility. Interoperability between different blockchain networks is essential for seamless spectrum trading across multiple platforms. Standardization efforts are required to ensure compatibility and interoperability between different smart contract implementations.

Standardization bodies and industry consortia should work to develop compatible performance standards for smart contracts in spectrum trading. These standards should ensure seamless integration and communication between different blockchain networks, which should facilitate cross-platform spectrum trading.

Scalability. Blockchain networks like Ethereum currently face scalability limitations in terms of transaction processing speed and capacity. Overcoming these limitations is necessary to support the high volume of transactions associated with spectrum trading.

Technological advances such as layer 2 scaling solutions (e.g., sidechains and state channels) can increase the scalability of blockchain networks. Research and development should focus on implementing these solutions to support the high transaction volumes required for efficient spectrum trading.

4 Conclusion

Despite its potential, the use of blockchain in spectrum management faces a number of challenges. These include scalability issues, regulatory barriers, interoperability and standardization requirements. Future research should address these issues to realize the full potential of blockchain in spectrum management. In addition, interdisciplinary collaboration between blockchain experts, wireless researchers, policymakers, and industry stakeholders is needed to develop practical blockchain-based solutions.

Blockchain technology has the potential to revolutionize spectrum management by providing transparent, efficient and secure solutions for the allocation, sharing and implementation of spectrum resources. By leveraging blockchain's decentralization and immutability, the wireless industry can overcome the limitations of traditional spectrum management methods and pave the way for more equitable and efficient use of radio spectrum.

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