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Interference-Based Consensus and Transaction Validation Mechanisms for Blockchain-Based Spectrum Management

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ABSTRACT The convergence of dynamic spectrum access (DSA) and blockchain has been regarded as the new paradigm of spectrum management. Because of the inherent properties of blockchain, such as decentralization and tamper-resistance, the deployment of blockchain in future networks has advantages to address problems exposed in traditional centralized spectrum management systems, such as high security risk and low allocation efficiency. In this article, we first compare blockchain-based spectrum management with the traditional centralized approach and then present a reference architecture for blockchain-based spectrum management. In particular, we propose an interference-based consensus mechanism, which can be employed to improve transaction efficiency and reduce system overhead while promoting spectrum sharing. The proposed consensus mechanism is based on the comparison of aggregated interference experienced by each node, such that the node that suffers the most aggregated interference will obtain the accounting right as a compensation. Furthermore, to avoid harmful interference caused by spectrum traders, an interference-based transaction validation mechanism is designed to validate the spectrum transactions stored in the blocks. Different from existing transaction validation mechanisms in which every transaction needs to be validated by all nodes, a ''transaction validation area'' is determined for each spectrum transaction, and only the nodes located in the validation area need to validate the transaction. The simulation results show that the system fairness and nodes' signal-to-interference-and-noise power ratio (SINR) can be improved by adopting the proposed mechanisms while reducing the system overhead.

INDEX TERMS Blockchain, consensus mechanism, spectrum management, transaction validation.

I. INTRODUCTION

With the commercialization of fifth-generation (5G) mobile communications, increasing numbers of wireless services are emerging. In the 5G era, there are three major application scenarios: enhanced mobile broadband communications (eMBB), massive machine type communications (mMTC) and ultra-reliable and low-latency communications (URLLC). With the dramatically increasing number of new applications such as virtual/augmented reality (VR/AR), autonomous driving, and Internet of Things (IoT), as well as numerous future applications, the demand on radio spectrum continues to increase significantly [1], [2]. However, the radio spectrum is still limited. The traditional centralized spectrum management approach can no longer satisfy the requirements of higher data rates and lower latency for the next generation of mobile communication, namely, 6G [1]. The United States President's Council of Advisors on Science and Technology (PCAST) report [3] emphasized the need for creative thinking to address the overarching spectrum crisis in spectrum allocation, utilization and management. How to satisfy the ever-increasing demand for spectrum and improve the spectrum management efficiency for future dense heterogeneous networks has become a major research issue for 6G. Apart from the problems of low spectrum utilization and low spectrum allocation efficiency, there are other problems

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in centralized spectrum management systems, such as high security risk regarding users' data, high maintenance costs and a lack of incentive mechanisms [4].

Over the past twenty years, dynamic spectrum access (DSA) has been investigated extensively to improve spectrum utilization [4], [5]. DSA is a spectrum sharing method; i.e., when the primary users (PUs) do not use the channel, the secondary users (SUs) can access the channel dynamically. However, the SUs must evacuate the occupied channel when the PU occupies the channel again [5], [6]. DSA can be employed to improve the efficiency of spectrum utilization. Distributed spectrum management is becoming the trend in research to meet the highly dynamic spectrum demand in 6G scenarios. The distributed method can improve spectrum allocation efficiency, relieve the processing pressure of the centralized spectrum management systems, and reduce the security risk caused by malicious attack to the centralized database [7]. At the *Mobile World Congress Americas* held in September 2018, Ms. Jessica Rosenworcel, commissioner of the Federal Communications Commission (FCC), said that the FCC should use blockchain to manage the wireless spectrum [8]. The convergence of DSA and blockchain has become a hot research topic for 6G.

Blockchain is an integrated application of distributed data storage, point-to-point transmission, consensus mechanism, encryption and other technologies [9], [10]. It allows transactions to be finished without any central entity. In recent years, the architecture of blockchain has been thoroughly studied, and the throughput of blockchain has been greatly improved [11]. Furthermore, blockchain has been applied to many fields, such as crowd sensing [12], industrial IoT [13], smart contracts [14] and data verification [15]. Due to its inherent characteristics, blockchain has been considered the key enabler for 6G telecommunication systems. Spectrum transactions can be executed without central authorization, and the transaction information recorded in blockchain is immutable, which makes it more efficient and safer for spectrum sharing. As a consequence, telecom operators, research institutions and spectrum regulators around the world have begun to explore the potential applications of blockchain. Blockchain was first discussed at the IEEE DSA network group meeting in March 2017; France's spectrum regulator (ANFR) had experimented with the use of blockchain technology to manage 2.4 GHz, 5 GHz and other frequency bands in 2018. Blockchain has significant advantages to solve the problems exposed in centralized spectrum management systems [16], as summarized in Table 1. First, users' data are difficult to recover when the centralized database suffers from a malicious attack. However, this problem can be simply avoided by using blockchain to encrypt the users' data and store these data in a distributed manner. Second, the lack of incentive mechanisms in centralized spectrum management systems to encourage PUs to share their spectrum [4] poses a problem. In blockchain systems, there are various methods to award users, such as virtual currency [9], [10], and spectrum owners can lend their spectrum and be rewarded by automatic

TABLE 1. Comparison between centralized spectrum management and blockchain-based spectrum management.

Problems of centralized spectrum management	Advantages of blockchain-based spectrum management
High security risk	Distributed storage and encryption techniques are employed to ensure the security of the users' data
Lack of incentive mechanisms for spectrum sharing	Various incentive methods (such as virtual currency) can be employed to award the nodes for spectrum sharing
Vulnerable to malicious attack	Validation mechanisms are used to validate the transactions
Low spectrum allocation efficiency	Distributed spectrum management can effectively improve the allocation efficiency
High maintenance cost	Low maintenance cost as there is no centralized database to be maintained

execution of the smart contract. Moreover, the spectrum allocation efficiency will be decreased with the increasing number of nodes in centralized systems, especially in IoT scenarios. Decentralization schemes of blockchain can be used to solve that problem [16]. Other problems, such as vulnerability to malicious attack and high maintenance cost, can also be solved with blockchain.

Recently, significant research progress has been made in blockchain-based spectrum management. The potential use cases of blockchain in the Citizens Broadband Radio Service (CBRS) band are discussed in [17]. Four use cases are summarized, namely, lightweight transactions, provenance tracking, interorganizational recordkeeping and multiparty integration. In recent blockchain-based spectrum management studies, blockchain is commonly used as a trusted database for transaction information, spectrum sensing data and auction results. In [18], a blockchain verification protocol is proposed for enabling and securing spectrum sharing. The blockchain is used as a decentralized database to verify spectrum sharing between cognitive radio networks. This method can be used to access available licensed spectrum without the need for constant spectrum sensing. However, harmful interference caused by buyer nodes to other nodes is not considered.

Access authentication is one of the key applications of blockchain-based management approaches. A blockchain-based distributed scheme is proposed to improve the security of the systems and users' QoS in [19]. The blockchain-based scheme in wireless virtualization can ensure the security in the transactions between Primary Wireless Resource Owners (PWROs) and Mobile Virtual Network Operators (MVNOs) and can also prevent PWROs from overcommitting their resources by stopping double-spending attacks, which eventually helps MVNOs to meet the QoS requirements of their users. However, mathematical analysis and extensive evaluation of the framework are still needed. A multi-operator spectrum sharing smart contract is designed in [20]. Spectrum trading is implemented based on a permissioned blockchain without the need of a trustless spectrum broker. Additionally, blockchain is applied in spectrum trading for unmanned aerial vehicle (UAV)-assisted cellular networks in [21]. However, design of consensus and transaction validation mechanisms suitable for spectrum sharing scenarios are not considered in these works.

The consensus mechanism (also known as the accounting right determination mechanism in blockchain) is applied in a distributed system to ensure an unambiguous order of transactions, thereby ensuring the consistency of the system [22]. The performance of the blockchain system, such as latency and transaction throughput, is largely determined by its adopted consensus mechanism. Currently, the different consensus mechanisms adopted by blockchain systems can be divided into proof-based consensus (such as proof of work (PoW) [23], proof of stake (PoS) [24] and proof of honesty [25]) and voting-based consensus (such as practical byzantine fault tolerance (PBFT) and Raft [26]). However, none of these mechanisms is specially designed for spectrum sharing scenarios and cannot be applied directly in blockchain-based spectrum management systems. For example, PoW has long been criticized for its waste of resources (such as power resources). Moreover, the long transaction validation time makes it relatively unsuitable for the commercial application of lightweight spectrum transactions. PoS may lead to centralization and unfairness. The characteristics of spectrum sharing (such as potential harmful interference avoidance) are not considered in the existing blockchain mechanisms. Therefore, a fair and efficient consensus mechanism specially tailored for spectrum sharing scenarios remains to be developed. In this paper, we propose an interference-based consensus mechanism and a spectrum transaction validation mechanism. To the best of our knowledge, we are the first to take harmful interference mitigation into consideration when designing consensus mechanisms. Our main contributions are as follows.

- We compare blockchain-based spectrum management and the traditional centralized approach. We then present a reference architecture for blockchain-based spectrum management.
- We propose an interference-based consensus mechanism for spectrum trading. Consensus is reached by evaluating the interference caused by spectrum transactions. The spectrum transaction efficiency of blockchain-based spectrum management systems can be improved by adopting the proposed consensus mechanism.
- We propose a transaction validation mechanism to avoid harmful interference to other coexisting nodes. The transaction validation area is proposed. Each transaction has to be validated by the nodes located in the validation area before it is accepted.

The rest of this paper is organized as follows. In Section II, we compare blockchain-based spectrum management and the traditional centralized approach and present a reference architecture for blockchain-based spectrum management. In Section III, we propose the interference-based consensus and transaction validation mechanisms. In Section IV, simulation results are presented and discussed. Section V concludes this paper.

II. COMPARISON BETWEEN CENTRALIZED SPECTRUM MANAGEMENT AND BLOCKCHAIN-BASED SPECTRUM MANAGEMENT

In this section, we review the major problems associated with traditional centralized spectrum management. Then, we elaborate the advantages of blockchain-based spectrum management and present a reference architecture of blockchain-based spectrum management.

A. MAJOR PROBLEMS OF TRADITIONAL CENTRALIZED SPECTRUM MANAGEMENT

Spectrum management systems can be classified into centralized systems and distributed systems. Centralized systems can perform overall planning for the entire network and implement the optimal spectrum allocation scheme to improve the system performance. Moreover, the centralized approach seems easier to develop and maintain [27]. However, with upcoming new wireless services, various demanding QoS requirements need to be satisfied dynamically. Additionally, the number of radio devices will increase explosively with the widespread applications of the IoT, resulting in an extremely high density of radio connections, e.g., greater than 1 million/km^2. Centralized spectrum management has the following major problems:

1) SECURITY RISK OF USERS' DATA

Currently, users' data are stored in centralized databases maintained by service providers such as telecom operators. Although the anti-attack capability of a centralized database is good enough to prevent the most malicious attacks, incidents such as credit card data leakage or theft cannot be entirely avoided. Moreover, users' data may pose a threat to privacy or integrity if access and use of the information is not appropriately secured [8]. For example, the use of a centralized spectrum database in DSA systems offers a pragmatic approach for enabling spectrum sharing between PUs and SUs. PUs are usually government or military users, while SUs are typically commercial users. Therefore, the system incurs a number of security and privacy concerns by unintentionally facilitating the collection and aggregation of sensitive information by SUs.

2) LACK OF INCENTIVE MECHANISMS

As the demand for spectrum continues to increase, it will become increasingly difficult to meet the demand through the legacy spectrum policy based on assignment. Moreover, it has become difficult for centralized systems to satisfy the demand for spectrum and system requirements of all users. DSA has been regarded as the key technology to address the spectrum scarcity problem. However, the PUs might be unwilling to share their spectrum with other SUs while considering security risks and lack of financial rewards. Therefore, appropriate incentive mechanisms need to be designed to encourage PUs to share their spectrum [4].

3) LOW SPECTRUM ALLOCATION EFFICIENCY

The end-to-end latency requirement in 6G could be much less than 1 *ms* in order to satisfy the requirements of vehicle-to-everything (V2X) communication scenarios. This means that the centralized systems need to have the capability to realize efficient spectrum allocation with extremely low latency, which tends to be a challenging task for centralized systems. With the number of radio devices increasing exponentially, it is challenging for centralized spectrum management systems to allocate spectrum efficiently for all types of users in a timely manner.

B. ADVANTAGES OF BLOCKCHAIN-BASED SPECTRUM MANAGEMENT

Blockchains are distributed databases that can be securely and iteratively updated. The working mechanism of blockchain is introduced in [9]. The core characteristic of blockchain is decentralization, in which there is no centralized entity. Moreover, encryption technology and timestamps are used to prevent users' data from being maliciously tampered with. Other technologies (such as consensus mechanisms, smart contracts and P2P transmission) are also used in blockchain. The advantages of blockchain-based spectrum management are described in detail as follows:

1) SECURITY OF USERS' DATA CAN BE ENSURED

Blockchain has advantages to ensure the security of users' data. First, the distributed data storage method and the use of encryption technology make it easier to recover the users' data regardless of which node has been maliciously attacked. At the same time, the risk of manipulation of users' data by a central management entity can be entirely avoided. Finally, the use of a consensus mechanism makes it almost impossible to tamper with the blockchain records because malicious attackers need to manipulate the most users, which is almost impossible.

2) VARIOUS INCENTIVE METHODS ENCOURAGE PUS TO SHARE THEIR SPECTRUM

In the blockchain, digital currency, such as bitcoin (BTC) or ether coin (ETH), can be issued to award the nodes that have the accounting right. The BTC/ETH-based incentive mechanism can be used to encourage more participants to join the network and compete for the accounting right. Similar mechanisms can be applied in blockchain-based spectrum management systems. For example, a digital currency reward (such as spectrum coin) can be applied to encourage PUs to share their spectrum with other users. Spectrum trading rules (such as the price of the spectrum) can be determined in advance in the smart contract. Spectrum transactions can be executed automatically through smart contracts, and spectrum owners can share their spectrum and be rewarded automatically.

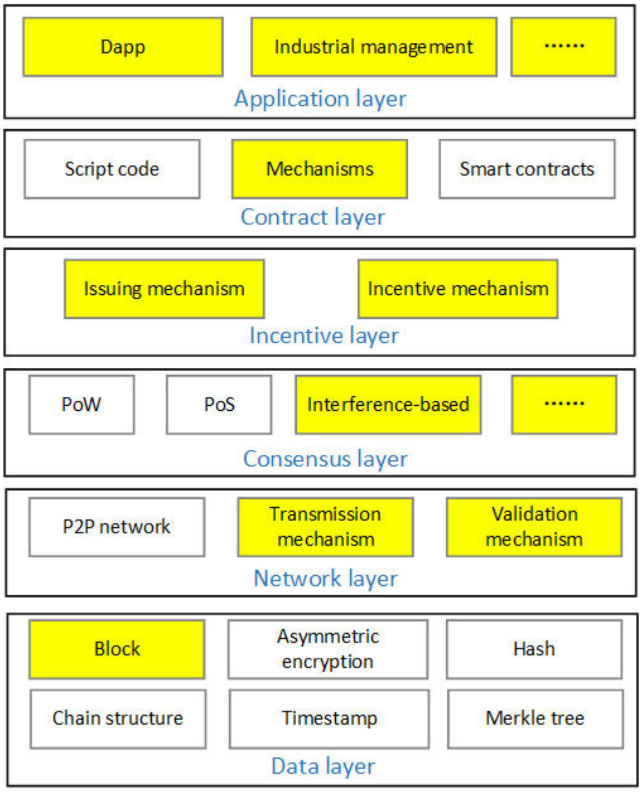

FIGURE 1. Architecture of blockchain-based spectrum management. Note: The yellow blocks are the modules that can be innovated when integrating spectrum management functionality into blockchain.

3) DISTRIBUTED MANAGEMENT IMPROVES THE SPECTRUM ALLOCATION EFFICIENCY

In centralized systems, all the spectrum management procedures are executed by central entities, which leads to high processing delay. Blockchain-based spectrum management methods eliminate the central authority and replace it with a distributed ledger to realize spectrum transactions. Therefore, the processing pressure can be relieved significantly. As a consequence, the allocation efficiency is improved [22]. Blockchain-based systems make it possible to satisfy the extremely low latency (1 *ms* or less) requirement in 6G networks.

C. BLOCKCHAIN-BASED SPECTRUM MANAGEMENT ARCHITECTURE

As shown in Fig. 1, the blockchain-based spectrum management reference architecture is composed of a data layer, network layer, consensus layer, incentive layer, contract layer and application layer. In this figure, yellow blocks are the modules that can be innovated when integrating spectrum management functionality into blockchain. The functions of these layers are discussed as follows:

- *Data Layer:* The data layer encapsulates the underlying data blocks and related data encryption and timestamp technologies. The block size, chain structure, encryption method and composition of transaction information are determined in this layer. In the data layer, transaction records are organized according to a specific structure in order to ensure that the transactions in blockchain systems are immutable. For example, the bitcoin system uses a Merkle tree to store the hash value of each transaction in the blocks [9]. Blocks are chained together by the hash pointer in chronological order. To improve the transaction speed and system scalability, block-less data structures have been adopted in recent blockchain networks. In IOTA [28], transactions are structured as a directed acyclic graph (DAG). Despite the organization structure of transaction data, asymmetric encryption mechanisms are adopted to prevent tampering of the transaction data. When integrating spectrum management functionality into blockchain, the block size, block generation interval and other parameters can be optimized to adapt to the actual spectrum sharing scenarios.

- *Network Layer:* Transaction information transmission and transaction validation mechanisms are determined in this layer. Transaction information is transmitted via a P2P network or telecommunication network, and the blocks are connected to the blockchain after being validated by using validation mechanisms. In existing blockchain-based systems, a transaction is validated when the buyers have enough balance in their account. In spectrum sharing scenarios, spectrum trading must consider spectrum access rules, primary user protection and harmful interference mitigation. In this paper, an interference-based transaction validation mechanism is proposed, and spectrum transactions will be validated only when the spectrum trading action does not cause harmful interference to coexisting nodes.
- *Consensus Layer:* Consensus mechanisms are adopted to maintain the consistency of blockchain-based systems. Various consensus mechanisms that can be used to realize the decentralization of the systems are contained in this layer, such as PoW, PoS and delegated proof of stake (DPoS). These mechanisms can be divided into proof-based consensus and voting-based consensus. In proof-based consensus mechanisms, nodes are required to solve a mathematical puzzle or to show that they are more eligible than other nodes to win the accounting right. In voting-based mechanisms, consensus is reached by the communications of each node. However, existing consensus mechanisms do not fit well in spectrum sharing scenarios. In this paper, an interference-based consensus mechanism is proposed. Nodes that suffered most aggregated interference in the last round are given the accounting right in the next round.
- *Incentive Layer:* An incentive layer is applied for promoting spectrum sharing among spectrum users. More PUs will be encouraged to share their spectrum by adopting appropriate pricing and incentive mechanisms together with digital coin issuance mechanisms. In recent studies, different spectrum sharing incentive methods are proposed, and spectrum coin is proposed to promote spectrum sharing [29]–[31].
- *Contract Layer:* The contract layer mainly includes various scripts, algorithms and smart contracts for spectrum trading, which is the basis of the programmable feature of blockchain. Spectrum owners, infrastructure providers and network slice brokers can be integrated into the blockchain platform, and spectrum transactions can be executed automatically based on the smart contract.
- *Application Layer:* The characteristics of blockchain enable it to serve spectrum management. The application layer provides various application scenarios and use cases of blockchain in spectrum management, including spectrum trading, industrial management in IoT use cases, etc. In each scenario, smart contracts can be customized according to specific needs.

III. MECHANISM DESIGN FOR BLOCKCHAIN-BASED SPECTRUM MANAGEMENT

In this section, an interference-based consensus mechanism is designed to improve the spectrum transaction efficiency of blockchain-based spectrum management systems. Furthermore, the transaction validation mechanism is designed to avoid harmful interference with other coexisting nodes.

A. INTERFERENCE-BASED CONSENSUS MECHANISM

Fig. 2 shows the system scenario, in which the nodes represent spectrum traders in spectrum management system, such as eNBs from different micro-operators or some other secondary spectrum users. Additionaly, N blocks have been connected to the blockchain. The accounting right of Block-($N + 1$) needs to be determined, and only one node will be selected. All the transactions stored in Block-N have been completed, and the buyer of each transaction may cause harmful interference to the other nodes. As illustrated in Fig. 2, there are N_{trs} transactions stored in Block-N. Taking the first 3 transactions as an example, the buyers are Node-1, Node-3 and Node-5. Other coexistent nodes may suffer from interference caused by those 3 buyers. Other coexistent nodes can calculate the aggregated interference according to the information of those 3 transactions in Block-N. Considering that interference decreases with distance, it is reasonable to neglect the interference from far-away nodes. Accordingly, the concept of "protection area" is proposed to reduce the system overhead. Each node will determine its protection area, and the interference emitted from the buyer nodes outside of the protection area will be ignored. The radius of the protection area for Node-i can be calculated by

$$R_i = \frac{\lambda}{4\pi} \cdot \sqrt[\alpha]{\frac{P_{max} \cdot G_{Tx} \cdot G_{Rx}}{I_{th}^i}}, \tag{1}$$

where λ is the wavelength of the carrier frequency; α is the pathloss coefficient between the interfering node and the victim receiving node; G_{Tx} and G_{Rx} are the transmitter

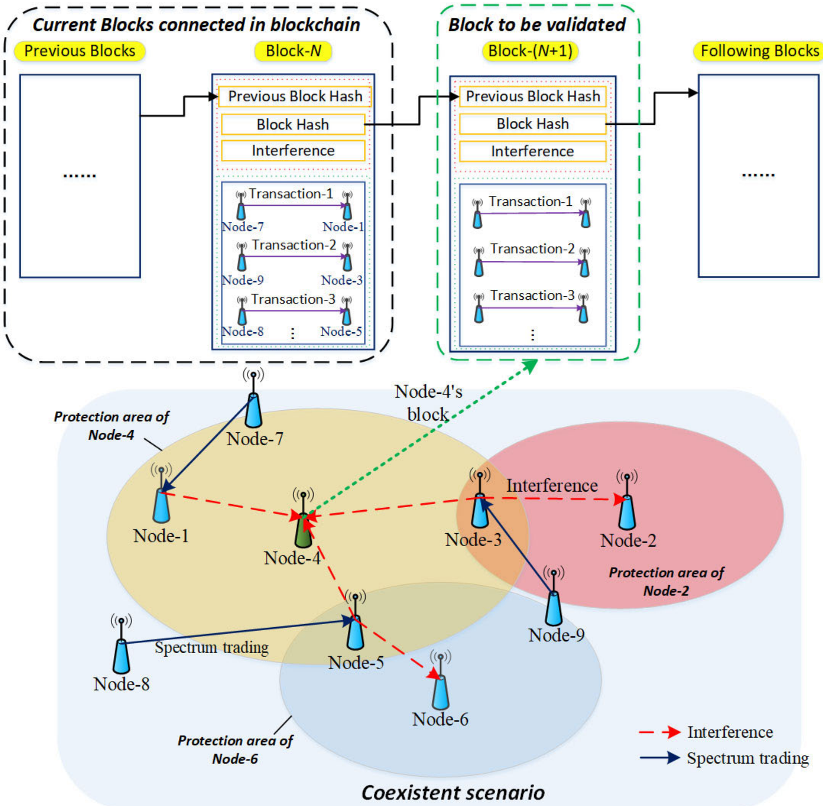

FIGURE 2. Illustration of the interference-based consensus mechanism.

antenna gain and the receiver antenna gain, respectively; P_{max} is the maximum transmit power of all nodes; and I_{th}^{i} is the interference threshold of the i-th node.

To improve the system fairness, only the nodes with the competition right can compete for the accounting right of Block-($N + 1$). The competition right factor (CRF) of each node can be determined according to the available spectrum and spectrum coins held by each node. The more spectrum and spectrum coins held by the node, the higher CRF that node obtains. Only the nodes with a CRF value higher than the CRF threshold (CRF_{th}) have the right to compete for accounting rights. The accounting right determination mechanism can be presented briefly as follows: for the nodes that have the competition right, compare their experienced aggregated interference suffered from the buyer nodes of the transactions stored in Block-N and then select the node that suffers from the largest aggregated interference to receive the accounting right of Block-($N + 1$).

For example, assuming that Node-4 in Fig. 2 suffers the largest aggregated interference from the buyer nodes of the transactions stored in Block-N, Node-4 will be selected to have the accounting right of Block-($N + 1$). Node-4's block will be connected to the blockchain after being validated by the other coexisting nodes, and Node-4 will receive spectrum coins as a reward.

The procedures of the interference-based consensus mechanism are detailed in **Algorithm 1**.

B. TRANSACTION VALIDATION MECHANISM

Block-($N + 1$) cannot be immediately connected to the blockchain even though the ownership of the accounting right has been determined. Furthermore, the transactions stored in that block will not be completed immediately. The system scenario is shown in Fig. 3. Assuming that Node-p has the accounting right of Block-($N + 1$), transactions stored in Node-p's block need to be validated because some spectrum transactions may be invalid. For example, transaction information may have been maliciously tampered or the balance in the buyer's wallet may be not enough to pay for the spectrum transaction. More importantly, the buyers (i.e., Node-2, Node-4) of the spectrum transactions may cause harmful interference to the neighboring nodes. Therefore, the problem is how to identify harmful interference and design an appropriate transaction validation mechanism.

Since there is no central node to conduct interference validation, the traders of each transaction need to provide necessary information, such as the traders' position and transmit power, to the other nodes for interference calculation. As the interference generally decreases with distance, interference can be ignored when the interfering nodes are far away from the receiving node. Different from the existing transaction validation mechanisms in which each transaction needs to be validated by all nodes in the blockchain, in the proposed interference-based transaction validation mechanism, a transaction validation area is determined for each transaction, and

Algorithm 1 Procedures of the Interference-Based Consensus Mechanism for Blockchain-Based Spectrum Management

Input: Transaction information contained in Block-N
Output: Accounting right determination of Block-$(N+1)$

Assume block-N has been connected to the blockchain and the accounting right of Block-$(N+1)$ needs to be determined;
Assume Node-k has the accounting right of Block-N;
for Node-$i \in$ whole node set of the blockchain **do**
  if $CRF_i > CRF_{th}$ **then**
    Create Node-i's own block containing spectrum transactions;
    Calculate the radius of the protection area R_i;
    Calculate the aggregated interference caused by transactions in Block-N for Node-i;
    Submit the aggregated interference information to Node-k;
  end if
end for
Compare the aggregated interference experienced by different nodes;
if Node-p suffers the largest aggregated interference **then**
  Node-p gains the accounting right of Block-$(N+1)$;
  Broadcast the accounting right determination result to all coexistent nodes;
end if

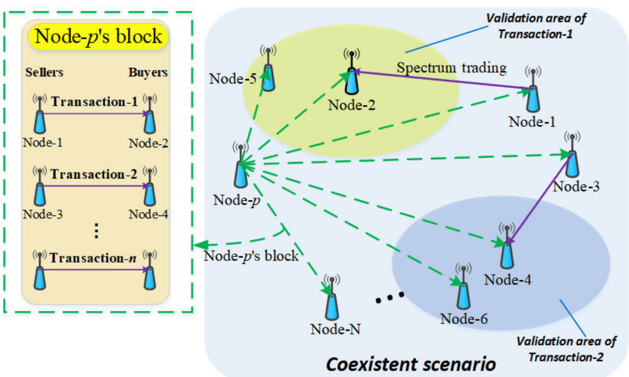

FIGURE 3. Illustration of the interference-based transaction validation mechanism.

only the nodes located in the validation area need to validate the transaction. In this way, the system overhead is reduced significantly.

The validation mechanism can be summarized as follows: for each transaction, every node (e.g., Node-i) located in the transaction validation area calculates its signal-to-interference-plus-noise ratio (SINR). Then, Node-i compares its SINR with the SINR threshold ($SINR_{th}$). If SINR $> SINR_{th}$, Node-i judges that the transaction is valid after verifying the relevant transaction information (e.g. account balance); otherwise, SINR $< SINR_{th}$, which indicates that

Algorithm 2 Procedures of the Interference-Based Transaction Validation Mechanism for Blockchain-Based Spectrum Management

for Transaction $i \in$ Node-p's block **do**
  Calculate the radius of the validation area of transaction i;
  Store the transactions information and validation area information into Node-p's block;
end for
Send Node-p's block to the other coexistent nodes;
for Transaction $i \in$ Node-p's block **do**
  for Node-j in the validation area of transaction i **do**
    if $SINR > SINR_{th}$ **then**
      if Information of transaction i is valid **then**
        Node-j confirms transaction i;
      else
        Node-j rejects transaction i;
      end if
    else
      Node-j rejects transaction i;
    end if
  end for
  Calculate the passing rate (Pr_i) of transaction i;
  if $Pr_i > Pr_{th}$ **then**
    Transaction i is validated;
  else
    Transaction i is rejected;
  end if
end for
if $\forall$ transaction $i \in$ Node-p's block is validated **then**
  Node-p's block is validated;
else
  Node-p's block is rejected;
end if

this transaction results in harmful interference to Node-i. In this case, Node-i judges that the transaction is invalid. Finally, the transaction is determined to be valid only if the passing rate is higher than the predefined passing rate threshold (Pr_{th}). Note that the passing rate is defined as the ratio between the number of nodes that judge that the transaction is valid and the total number of nodes in the validation area of that transaction.

The procedures of the interference-based transaction validation mechanism are detailed in **Algorithm 2**.

IV. SIMULATION ANALYSIS

In this section, we evaluate the performance of the interference-based consensus and transaction mechanisms via simulation.

A. PERFORMANCE COMPARISON: FAIRNESS AND USER SATISFACTION

In the simulation scenario, there are 100 nodes distributed randomly. Each node owns different amount of spectrum.

When the spectrum it owns cannot meet the demand, it needs to purchase spectrum from other nodes. The total number of transactions stored in Block-N varies from 50 to 80. The number of buyers is the same as the number of transactions. The transmit power of each node is either 10 dBm or 20 dBm. The pathloss coefficient is 2.5. The CRF of each node depends on how much available spectrum and spectrum coins it holds. The CRF threshold is set as 0.4, which indicates that the nodes with a CRF lower than 0.4 cannot compete for the accounting right. The node with the accounting right will receive the spectrum coins reward issued by the spectrum management system. The spectrum coins can be used to trade with other nodes to obtain spectrum. Fig. 4 shows the number of spectrum coins and the difference in the satisfaction factor of each node after 100 blocks are connected to the blockchain. The satisfaction factor of the i-th node is defined as

$$\delta_i = N_{sp}^i / D_{sp}^i, \tag{2}$$

where N_{sp}^i is the total spectrum held by the i-th node, and D_{sp}^i is the total spectrum demand of the i-th node.

As seen from Fig. 4, the spectrum coins are concentrated at a few nodes when the PoS mechanism is used. On the other hand, the distribution of spectrum coins of each node is relatively average when using the proposed mechanism, and the standard deviation of the distribution of spectrum coins also indicates that point. When the PoS mechanism is used, the standard deviation of the distribution of spectrum coins is 374, and when the proposed mechanism is used, the standard deviation is 67. Therefore, it can be concluded that the system fairness can be improved by using the proposed accounting right determination mechanism. The difference in the satisfaction factor of each node is shown in Figure 4 (the brown curve) and is defined by the difference between the satisfaction factor when using the proposed mechanism and that of the same node while using the PoS mechanism. As shown in Fig. 4, the satisfaction factor of most nodes increases by using the proposed mechanism.

The PoS mechanism is based on the stake of each node. As a result, the node with higher stake has higher probability to obtain the accounting right. By contrast, all nodes have the same probability to obtain the accounting right when using the proposed mechanism. Therefore, the system fairness and satisfaction factor can be improved by using the interference-based consensus mechanism.

B. PERFORMANCE GAIN IN TERMS OF SINR IMPROVEMENT AND SYSTEM OVERHEAD REDUCTION

In the simulation scenario, the total number of nodes varies from 200 to 4000, and the active nodes ratio is 40%; i.e., 40% of the nodes in the scenario are trading at the same time. The transmit power of each node is either 10 dBm or 20 dBm. The pathloss coefficient is set as 2.5. The interference threshold (I_{th}) is set as −96 dBm when calculating the radius of the "validation area". The SINR threshold is 20 dB. The SINR of each node and system overhead are compared.

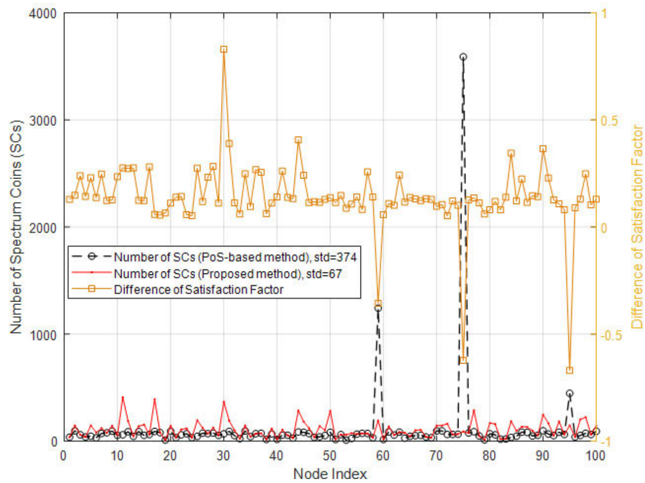

FIGURE 4. **Comparison between the interference-based consensus mechanism and PoS mechanism in terms of the distribution of spectrum coins and the difference in the satisfaction factor.**

As seen from Fig. 5, the SINR of each node can be improved significantly by using the proposed mechanism. When the number of nodes increases, the SINR difference further increases. When the total number of coexistent nodes reaches 3000, the difference in user SINR reaches 10 dB. The reason is that the transactions that will cause harmful interference to other nodes are invalid and will not be executed. Therefore, we can conclude that the proposed transaction validation mechanism can improve the SINR of each node and can also work well in dense network scenarios.

The system overhead is compared in Fig. 6. In this simulation, the system overhead is represented by how many times the validation procedure is executed. The total number of nodes in the simulated scenario is N_{node}, and the number of transactions is N_{trs}. Without using the interference-based transaction validation mechanism, the total number of transaction validation is as large as $N_{tr} = N_{node} \cdot N_{trs}$ since each transaction needs to be validated by all the nodes. However, the number of nodes that need to validate each transaction (N_{per-tr}) is significantly less than N_{node} when using the proposed mechanism. Therefore, the total number of validations will be significantly reduced by using the interference-based transaction validation mechanism. Note that in Fig. 6, the system overhead reduction ratio is defined as

$$\eta = N_{tr}^* / N_{tr}, \tag{3}$$

where N_{tr}^* is the total number of validations when adopting the proposed mechanism (in which each transaction needs to be validated by those nodes inside the validation area only), and N_{tr} is the total number of validations when adopting the traditional mechanism (in which each transaction needs to be validated by all nodes). There are several factors that can affect the system's computational complexity, such as interference threshold and the ratio of active nodes. As shown in Fig. 6, the total system overhead increases with the ratio of active nodes while decreasing with the interference threshold.

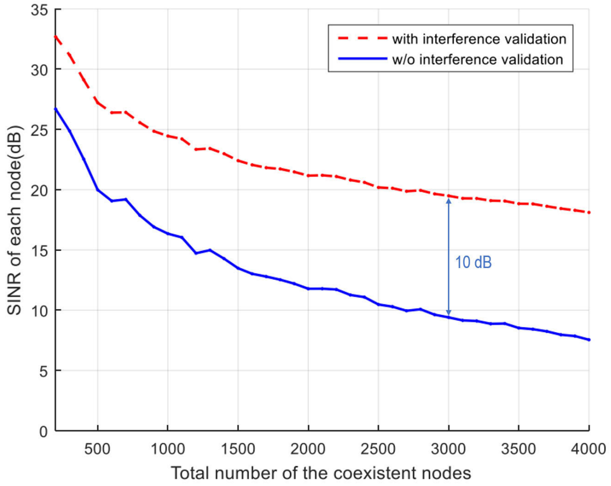

FIGURE 5. Comparison of nodes' SINR.

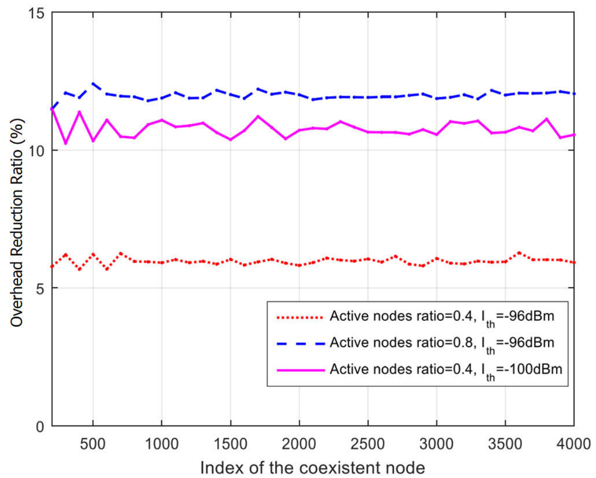

FIGURE 6. Comparison of system overhead.

And the system overhead is greatly reduced while adopting the proposed transaction validation mechanism, because fewer nodes participate in the transaction verification process.

V. CONCLUDING REMARKS

In this paper, we compare blockchain-based spectrum management with the traditional centralized approach and present a reference architecture of blockchain-based spectrum management, which can be employed in the next generation of mobile communications, namely, 6G. In particular, interference-based consensus and transaction validation mechanisms are proposed based on the reference architecture. The simulation results show that the system performance (such as system fairness, nodes' satisfaction factor, and nodes' SINR) can be improved significantly while reducing the system overhead.

It should also be noted that there are still many open issues to be addressed. A series of mechanisms needs to be developed to support the proposed blockchain-based spectrum management architecture, which includes a block generation mechanism, incentive mechanism, and pricing mechanism, among many other mechanisms. Moreover, a blockchain-based DSA test platform needs to be built to test the proposed mechanisms and evaluate the system performance in various 5G and/or 6G mobile communication scenarios. Finally, a blockchain-based spectrum management system that can be employed by various practical wireless networks or vertical applications could be the direction of future research and development.

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