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Special Topic: Spectrum, Coverage, and Enabling Technologies for Intelligent 6G

SpectrumChain: a disruptive dynamic spectrum-sharing framework for 6G

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Abstract The sixth-generation (6G) wireless network will support ubiquitous connectivity and diversified scenarios to satisfy the requirements of various emerging applications. Full spectrum is a key enabler for 6G to achieve the ambitious goal of a Tbps-scale data rate. In this paper, we first review the scenario and potential spectrum plan for 6G and then focus on SpectrumChain, a blockchain-based dynamic spectrum-sharing (DSS) framework for 6G. The unique characteristics of blockchain for DSS are presented along with key technologies. Finally, the conclusion and future development trends are discussed.

Keywords dynamic spectrum sharing, blockchain, 6G

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1 Introduction

With the commercialization of the fifth-generation (5G) wireless networks, research on the sixth-generation (6G) wireless network has started in academia and industry, aiming to support ubiquitous connectivity and the Internet of intelligence. It is anticipated that 6G will evolve toward full spectrum, full coverage, and full applications, supporting immersive extended reality (XR), holographic communication, digital twins, etc. [1–3]. Therefore, 6G network services are expected to present new development trends, such as digitization, intelligence, and personalization. To support such diversified services with unique service requirements, evolutionary and revolutionary technologies in architecture and key enablers will be adopted in 6G [4]. On the one hand, the 6G network will integrate different network segments ranging from conventional terrestrial networks to aerial and spatial networks, forming a space-air-ground (SAG) integrated networking framework. On the other hand, new enhanced air interfaces and emerging techniques will be adopted in physical layers and network layers.

Compared with their 5G counterparts, 6G networks are expected to achieve extreme connectivity performance with a Tbps-scale data rate, which requires hundreds of MHz to tens of GHz of spectrum resources to cater to capacity-hungry applications [5, 6]. As shown in Figure 1, spectrum resources from the sub-6 GHz band to millimeter wave (mmWave), terahertz (THz), and visible light communications (VLCs) are applied to provide enhanced connectivity in different network segments.

Although the SAG integration brings special strength in coverage, it confronts challenges in spectrum resource management and service orchestration. The integration of satellites and aerial moving platforms makes the network topology highly dynamic, and the interference pattern becomes more complex than that of a single terrestrial network. As the terrestrial networks began to use high-frequency bands,

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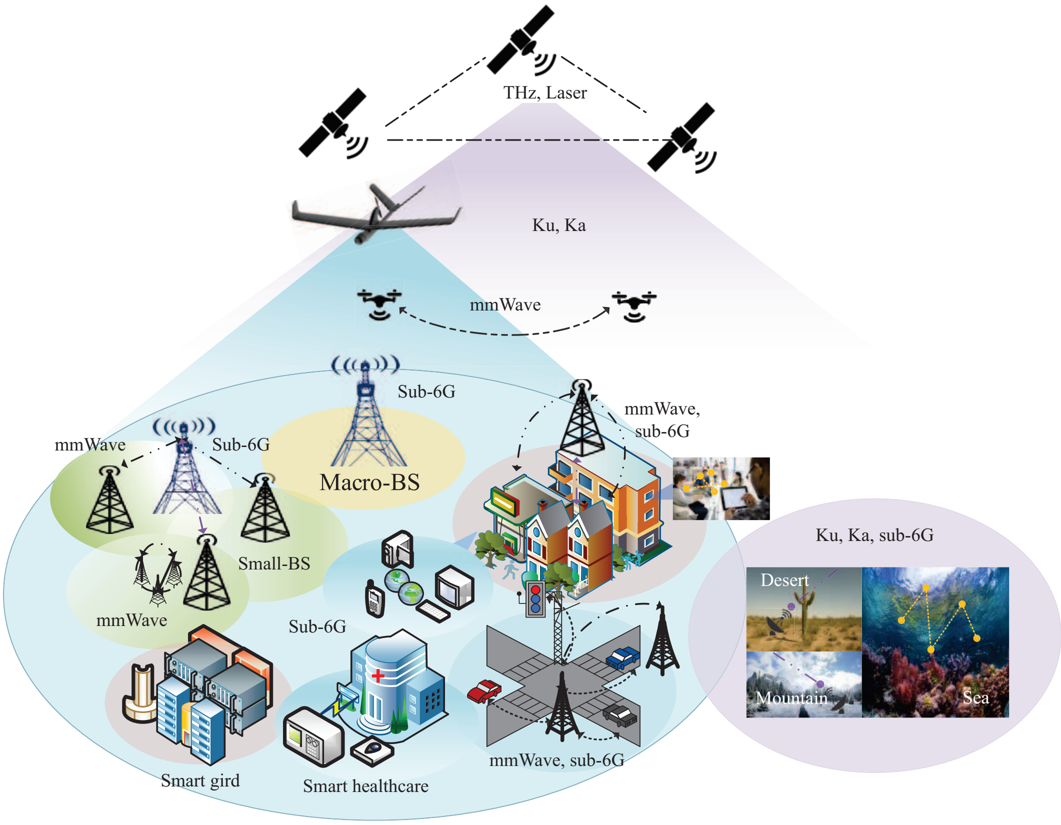

Figure 1 (Color online) 6G scenario and spectrum usage.

such as the C-band and Ka-band, spectrum overlapping was more likely to occur, resulting in severe mutual interference that rarely existed before. To avoid interference, spectrum resources are usually exclusively allocated to different mobile network operators (MNOs) and vertical industries. Such coarse resource management, however, further exacerbates the supply/demand imbalance for spectrum resources. Therefore, one critical bottleneck for 6G is to realize secure, efficient, and fine-grained spectrum resource management.

As a distributed ledger technology, blockchain establishes a distributed peer-to-peer trusted network with cryptography and a consensus mechanism, and thus secure spectrum sensing, spectrum resource auctioning/trading, and spectrum access and regulation can be conducted without a trusted third party [7, 8]. Combining crowd sensing with blockchain technology, efficient and cost-effective spectrum sensing can be realized using the capability of sporadic sensing devices, forming an accurate and large-scale spectrum situation for further spectrum use. With the consensus mechanism, the spectrum rights of each owner can be confirmed and stored in the block before transactions, and thus the revenues of participants can be guaranteed. Particularly, the consensus process can be combined with a spectrum allocation strategy to avoid unnecessary computing [9]. With a smart contract deployed on the chain, spectrum trading/sharing transactions can be automatically executed with predefined rules, which greatly facilitates efficiency and justice. Moreover, with blockchain, each step during spectrum sharing can be permanently recorded, and thus any violations can be traced back with on-chain transaction records. Thus, blockchain technology naturally facilitates dynamic spectrum sharing (DSS), and blockchain-based DSS technology is also considered a key enabler for 6G [10–15].

To advance the 6G vision, unified planning and scheduling of spectrum resources should be promoted. In this paper, we first review the scenario and potential spectrum usage for 6G and then focus on a blockchain-based DSS framework and related key techniques. The remainder of this paper is organized as follows. In Section 2, we present the spectrum vision and requirement for 6G and briefly review the current DSS architecture. Then, in Section 3, we introduce blockchain-enabled DSS, including the unique advantages of blockchain for DSS and a hierarchical SpectrumChain architecture. In Section 4, blockchain-empowered key technologies for DSS are presented. Section 5 concludes this paper.

2 6G spectrum requirement and vision

To realize the full experience of 6G, ultrahigh data rates up to Tbps are expected. According to [16], a data rate of 1 Tbps could be achieved with 25 GHz bandwidth ideally, under the multiple input multiple output (MIMO) rank-4 configuration with 1024 quadrature amplitude modulation, while the required bandwidth may increase to 33.3 GHz assuming 25% overhead. In 5G, although sub-6G and mmWave bands were initially explored, their maximum available bandwidths are rather limited [17] and thus far from meeting the demands of 6G. Therefore, the development and use of new frequency bands toward higher frequencies at the THz and visible light (VL) bands and facilitating DSS are essential solutions for 6G. In this section, we elaborate on 6G spectrum vision from these three aspects and then discuss DSS in detail.

2.1 6G spectrum vision

The ambitious vision in 6G brings a formidable challenge that is substantially greater than evolved 5G [18]. In terms of the spectrum, exploring new spectrum bands and reusing existing spectrum resources are required to continuously serve billions of citizens and massive Internet of Things devices everywhere.

2.1.1 *6G new spectrum*

For 6G spectrum usage, several critical factors should be considered, such as coverage, throughput, and quality of service (QoS). Here, we first summarize the properties of different frequency bands.

- **Low band:** Frequency band below 1 GHz. This band can provide broad area coverage and deep indoor penetration because of its excellent propagation characteristics.
- **Mid band:** Frequency range from 1 to 24 GHz. This band can provide relatively large contiguous bandwidth (up to hundreds of MHz) to balance coverage and capacity. However, the bandwidth remains insufficient for supporting throughput-hungry environments in the 6G era.
- **High band:** Frequency range from 24 to 300 GHz. This band comprises the mmWave band (24–92 GHz) and the sub-THz band (92–300 GHz). The mmWave band can provide high-capacity services and has been used in 5G, whereas the sub-THz band remains under exploration for ultrahigh capacity and ultralow latency services in 6G, such as hologram and XR.
- **THz band:** Frequency range from 100 to 10 THz. Although this band can provide ultra-large transmission capacity, it suffers from severe attenuation during transmission in the atmosphere because of its high-frequency characteristics and molecular absorption characteristics. Therefore, THz is mainly applied to satellite communications and short-range ground communication, including microscale communication scenarios.
- **VL band:** Frequency range from 380 to 750 THz. The optical wireless communication system over the VL band can provide a centimeter-level precision positioning service and realize fine motion capture. Note that, as VLC does not generate electromagnetic radiation and is not susceptible to external electromagnetic interference, it is thus suitable in certain scenarios sensitive to electromagnetic interference [19].

In the early stage of 6G, a candidate spectrum has been intensively discussed in academia and industry. Even without confirmed standards, 6G will inevitably use all of the above frequencies to support various scenarios, including wide coverage with low or high capacity and low coverage with high capacity and low latency.

2.1.2 *Enhanced DSS*

Although vast spectrum resources in low, mid, and high bands can be used for 6G, they are still insufficient to meet all of the 6G capacity demands, particularly under wide coverage constraints. Meanwhile, network traffic demands are not evenly distributed in many aspects because of the uneven spatial and temporal traffic patterns, imbalance in uplink and downlink, user variances among different operators, etc. The variant network traffic loads cause a strong imbalance in spectrum demands, where the static spectrum management diagram alone cannot meet the dynamic spectrum requests of different operators considering spatial and temporal variance. DSS on top of cognitive radio is in urgent demand to improve the spectrum use and promote high levels of adaptivity of different operators under guaranteed QoS and priority.

As predecessors, licensed shared access (LSA) [20] and citizens broadband radio service (CBRS) [21,22] have been developed in Europe and the US, respectively. For LSA, incumbent license holders can share their owned spectrum resources with secondary users (e.g., mobile operators) in a controlled way to improve spectrum use in the 2.3 GHz band. In contrast, CBRS supports three-tier dynamic access with a spectrum access system (SAS) in the 3.5 GHz band [23], where the top tier includes incumbents with the highest protection, the second tier is the prioritized access license holders, who pay for the spectrum usage rights of the incumbents when they are free of use, and the lowest tier is general authorized access, which is free to use without any protection.

Note that LSA and CBRS rely on either a centralized database or centralized management authority, which may become a bottleneck for large-scale applications and may also suffer severe malicious attacks. In addition, the QoS of secondary users cannot be well guaranteed without comprehensive regulations, and any spectrum violation may not be traced, which substantially impedes the practical implementation of DSS. In the 6G era, enhanced DSS will be developed by the above driving force and promoted by emerging technologies, such as integrated sensing and communication, artificial intelligence (AI), and blockchain [14, 24, 25].

2.1.3 *Spectrum regulation*

Spectrum regulation will play a pivotal role before full DSS can be applied in the 6G era. As spectrum security affects not only the communication itself but also the carried services, spectrum regulation is always a key concern in front of DSS. At the moment, passive regulation is dominant with less active intervention. With the employment of various spectrum resources in 6G, the regulation requirement will be more stringent than ever before. On the one hand, the regulators need to evaluate the usage or occupancy of a shared spectrum for further policy making. On the other hand, potential intended/unintended interference or jamming should be identified to manage the spectrum order in an open and highly dynamic environment. In this case, blockchain provides a complete solution for spectrum security regulation, which has never been achieved before. Particularly, the spectrum-sharing transactions and transmission parameters of each source can be recorded on the chain in a tamper-proof manner, and the off-chain spectrum sensing data can be recorded on the chain for data integrity verification. Then, interference or jamming forensics and arbitration can be achieved by coordinating on-chain transaction traceability and off-chain signal identification, which has never been achieved without the assistance of blockchain.

2.2 DSS architecture

Considering the strong desire for DSS, in this subsection, we overview the system architecture and workflow of existing DSS, including centralized and decentralized solutions.

2.2.1 *Centralized DSS architecture*

For the centralized solution, advanced management nodes (AMNs) are introduced to minimize the mutual interference among operators, managing and allocating spectrum resources shared among operators in a unified manner.

As shown in Figure 2, each operator has one operation administration and maintenance (OAM) server and multiple base stations (BSs), where the OAM server is responsible for spectrum assignment and management of the assigned BSs. During DSS, each BS first sends the spectrum demand request to its OAM server, and then OAM determines the spectrum demand and submits the demands to the AMN to obtain spectrum resources. The AMN makes spectrum allocation decisions and returns the results to OAM servers, after which each BS can dynamically change the operating frequency under the control of the OAM server.

For the centralized DSS architecture, spectrum resource management can be conducted at either the operator level or the BS level, which are detailed as follows.

- **Operator level:** The AMN manages spectrum resources at the operator level and does not participate in the spectrum allocation of BSs within each operator. The OAM server forecasts and aggregates spectrum demand within each operator and sends it to the AMN. The AMN allocates spectrum resources to each OAM server, where spectrum allocation among different operators is conducted by the OAM server rather than the AMN.

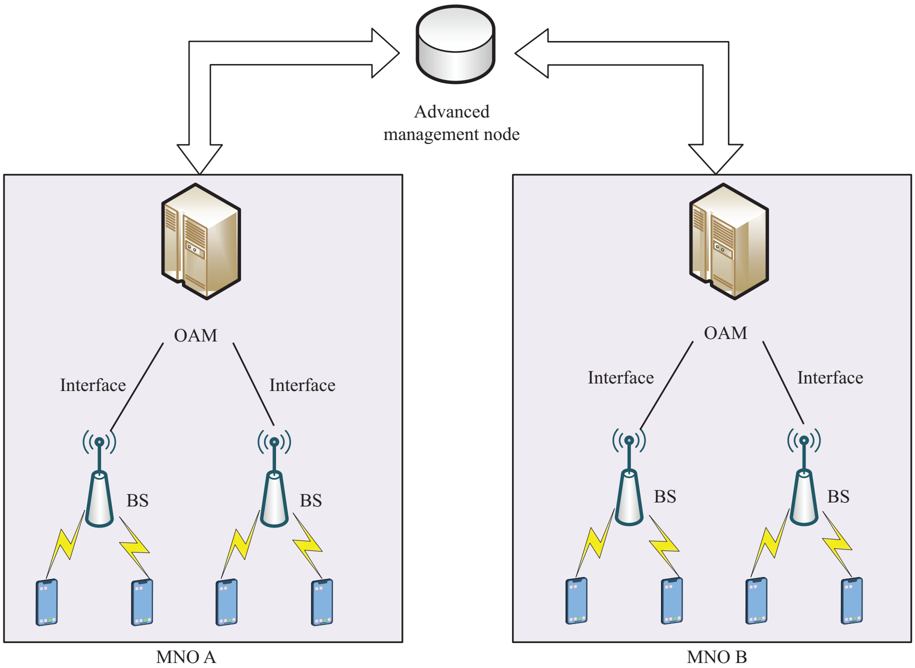

Figure 2 (Color online) Centralized DSS architecture.

- **BS level:** In this case, the AMN manages the spectrum resource allocation of each BS under its administration. Each BS forecasts and aggregates spectrum demand and related parameters and sends this information to the OAM server. Then, the OAM server performs strategic filtering to obtain accurate spectrum requirements and sends requests to the AMN. Finally, the AMN executes the spectrum allocation decision of each BS.

2.2.2 *Decentralized DSS architecture*

In the centralized cross-operator spectrum-sharing architecture, operators cannot directly communicate with each other but must collect and process transactions through a central AMN. As shown in Figure 3, for the decentralized architecture, there is no AMN, and each MNO is configured with a spectrum controller that is an independent physical entity or a functional module for spectrum-sharing decisions. The spectrum controller is integrated into a physical entity, such as an OAM server, and can interact with other spectrum controllers through predefined communication interfaces. With the interaction between different spectrum controllers, multiple operators can exchange information and negotiate spectrum-sharing rules. The corresponding DSS workflow is given as follows.

- Each BS reports spectrum requests to the spectrum controller, where the request information includes the traffic load and service requirements.
- The spectrum controller calculates spectrum demand for each BS according to the collected information.
- The spectrum controllers interact with each other to share the spectrum demand information (e.g., the available channel and power).
- The spectrum controller updates available spectrum resources based on the shared information from other spectrum controllers.
- The spectrum controller allocates available channels to every BS.
- Each BS configures available channels to the associated users.

Note that even though centralized and distributed DSS have been proposed, they have not been well-adopted in practice because of the lack of proper incentive mechanisms, QoS guarantees, and security and privacy concerns. To facilitate flexible and efficient spectrum management, innovative new technologies such as AI and blockchain are required in 6G.

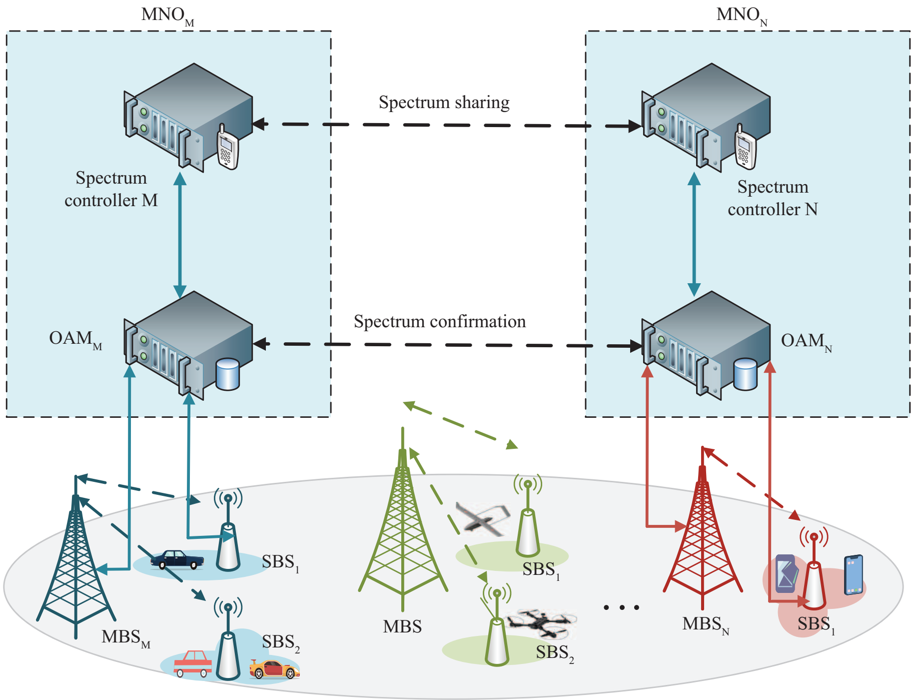

Figure 3 (Color online) Decentralized DSS architecture.

3 Blockchain-enabled DSS for 6G

As an enabling technology with the important characteristics of decentralization, transparency, and traceability, blockchain opens up new opportunities for DSS, and it is considered a promising solution and key enabler for DSS in future 6G wireless networks [10–12, 26–28]. For example, with blockchain, a decentralized DSS framework is constructed to facilitate trusted spectrum sharing between spectrum providers and spectrum requestors without a third proxy, and the consensus mechanism provides a feasible way to solve the channel contention problem where multiple users compete for unlicensed bands.

In this section, we first summarize the unique features and advantages that blockchain can bring for DSS and then present a multilayer hierarchical blockchain-enabled DSS framework.

3.1 Unique advantages of blockchain for DSS

In this subsection, we elaborate on the specific potentials and benefits of blockchain for DSS that cannot be achieved using conventional technology.

• **Incentive mechanism:** To motivate users or operators who have idle spectrum resources for DSS, proper incentive rewards should be guaranteed. In conventional DSS systems, the reward for DSS is usually handled by the central authority; thus, the revenue of the participants may not be ensured because of the inequality between the two parties. With blockchain, the obligation and responsibility can be clearly defined as an agreement in a smart contract, and thus the expected rewards can be ensured [29].

• **Immutability:** The unique data structure of blockchain makes it almost impossible to modify previous data, which guarantees data integrity. In this way, blockchain can be integrated with the spectrum monitoring and spectrum transaction system, where the sensing data (or data abstract) and transaction details can be directly recorded in blockchain with a tamper-proof nature and traceability and thus can provide proof-of-existence for spectrum regulation arbitration.

• **Consensus:** Consensus is the core for guaranteeing the consistency of the distributed blockchain system, e.g., the proof-of-work (PoW) consensus in bitcoin relies on a complex mathematical problem, costing much computing and energy resources. However, the spectrum resource allocation problem in wireless communications is nonconvex in general and thus requires intensive computing resources to obtain the optimal solution. This attribute naturally caters to the PoW mechanism. By combining PoW and conventional spectrum allocation algorithms, the heavy meaningless of computation can be used to calculate the spectrum allocation solutions, as in [30]. Moreover, the consensus mechanism can also help the users to reach an agreement for spectrum access competition, such as the consensus-before-talk mechanism [31], and dynamic spectrum access [32].

• **Smart contract:** A smart contract is a chaincode programmed with a certain logic and is automatically executed once the predefined conditions are satisfied [33]. In this way, transactions can be automatically implemented with a smart contract, which greatly improves efficiency.

• **Security and privacy:** During spectrum trading and auctioning, the identity of relevant users may be revealed, which brings severe privacy concerns to participants. In addition, the spectrum usage information may somehow disclose the behavior or patterns of relevant users; for example, the spectrum sensing data may contain location information. By introducing blockchain, participants can anonymously achieve secure transactions, which greatly promotes DSS in the 6G era.

Some studies have considered blockchain in DSS, such as [9, 12, 22, 34–38]. The authors of [34] divided the SAS structure based on blockchain into two levels of chains for different service objects, i.e., a global chain and a local chain. The global chain serves servers and regulators of cross-international businesses, while the local chain serves users who use spectrum resources in local areas. The authors of [35] used blockchain technology to design a secure and reliable trading platform for spectrum sharing between primary users and secondary users, in which each user node anonymously uploads its own information using ring signature technology. Because of its strong anonymity, ring signature technology has been studied in many articles to design privacy protection mechanisms with high security. For example, the authors in [9] used ring signature technology to prevent the personal data exposure of users participating in DSS on the blockchain. The authors of [38] combined blockchain and auction theory to design a reverse auction mechanism to support many wireless access requirements and dynamic user service requests under the background of beyond 5G.

However, because of the massive spectrum users, ultra-large spectrum data, and very stringent delay requirements in a time-varying environment, the popular public blockchain may not be suitable for large-scale DSS. Compared with a public blockchain, a consortium blockchain has the merit of flexible node control and management and caters to the efficiency and scalability requirements of large-scale DSS[1)]. Given these attributes, consortium blockchain will be the most suitable choice for DSS. In [39], considering the different communication requirements in 5G networks, a consortium blockchain-based spectrum planning framework was designed to improve spectrum efficiency. In Subsection 3.2, we focus on consortium blockchain and present a hierarchical DSS architecture for efficiency and scalability requirements.

3.2 Blockchain-based hierarchical DSS framework

To enable secure large-scale spectrum sharing with guaranteed performance, such as up to thousands of TPS efficiency, system scalability with different sharing granularity, and up to the second or less confirmation delay, we propose a blockchain-based hierarchical DSS framework, i.e., SpectrumChain.

As shown in Figure 4, a hierarchical blockchain framework is developed, comprising one main chain and multiple subchains. The main chain runs state/nation-level spectrum resource trading and regulation publishing services, whereas each subchain runs local spectrum sharing. The main chain comprises possibly multiple MNOs, a regulator, and multiple SAS servers, where MNOs can sell/buy spectrum resources with each other for their own demand, and the regulator can publish regulative information for security and fair spectrum sharing. A subchain is curated by a local committee comprising an SAS server and multiple spectrum controllers, where spectrum controllers can rent spectrum resources to meet BSs' spectrum demand. The SAS server may update the data of the subchain to the main chain at a certain frequency. Compared with the existing SAS architecture, the hierarchical SpectrumChain architecture can achieve a consensus-based fault-tolerant decision process at the global level (for regulation) and the local level (for local spectrum sharing) [34]. This capability not only facilitates the DSS processing efficiency but also guarantees certain isolation between different services with flexible scalability. We elaborate on the functionalities of SpectrumChain as follows.

3.2.1 *Main chain*

The main chain is a consortium blockchain, including service provider nodes, a regulator node, and SAS servers, and it mainly focuses on global-level spectrum sharing, spectrum regulation, and information

1) It is reported that up to several tens of thousands of transactions per second (TPS) of a single chain can be achieved under the consortium blockchain framework.

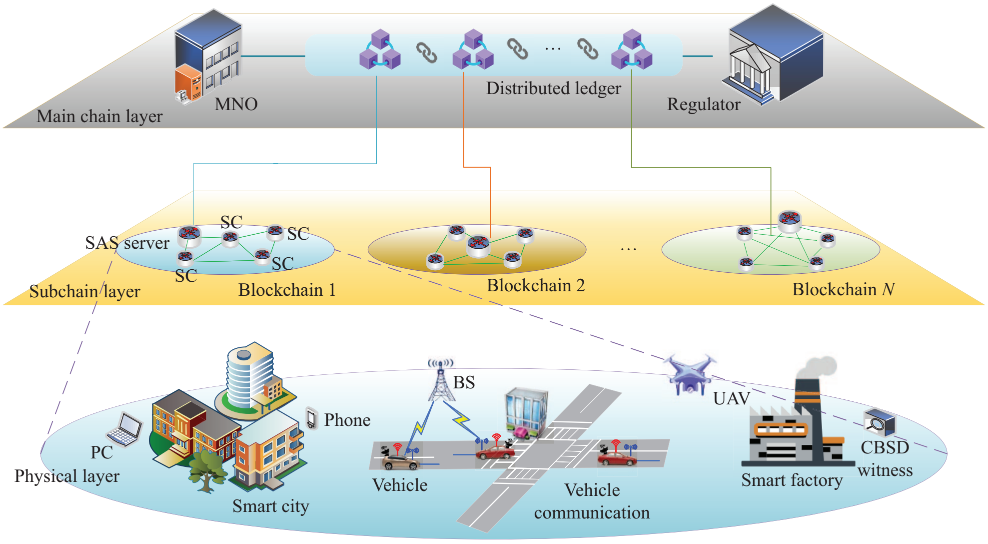

Figure 4 (Color online) Hierarchical DSS framework.

synchronization. The main functionalities are described as follows.

- **Spectrum sharing:** Global-level spectrum sharing is realized on the main chain to achieve large-scale coarse resource sharing among different services or vertical industries, which greatly facilitates the development of various 6G scenarios.
- **Regulation publication:** To facilitate secure and efficient DSS on the chain, regulator nodes integrate regulation policies into a smart contract, which is deployed as chaincodes on the blockchain. The regulation rules may be updated regularly to facilitate dynamic management.
- **Information synchronization:** Each SAS server node on the main chain can synchronize the data of the distributed spectrum ledger with the SAS server nodes on the subchain and delivers the rules published on the main chain to each subchain.

The main chain is mainly responsible for global information synchronization and service level spectrum resource sharing within a large area. Since the transaction throughput and frequency are not very large, the throughput and delay performance requirements for the main chain are not very stringent.

3.2.2 *Subchain*

The subchain is designed for spectrum sharing within each local DSS zone. Participants on each subchain comprise the SAS servers and spectrum controllers of MNOs. The user terminals of MNOs are connected to the corresponding nearby BSs for wireless services, and the BSs monitor and analyze the spectrum usage and spectrum demand within the region at a relatively small time scale, e.g., a several hours or days level. Then, the BSs send the spectrum request to the corresponding spectrum controller. According to the request information collected from the BSs, each spectrum controller can determine the spectrum demand during a period and choose to act as a spectrum buyer or seller. The spectrum-sharing transactions among spectrum controllers are recorded on the chain and synchronized to the main chain at a certain frequency. The two types of transactions on the subchain are given as follows.

- **Channel update transaction:** A SAS server issues a channel update transaction, which means a change in available channels when the server receives a regulation update from the main chain.
- **Spectrum-sharing transaction:** A spectrum controller issues spectrum-sharing requests in the local spectrum zone. Each spectrum controller on the subchain can adaptively act as a spectrum provider or spectrum requestor based on its demand.

Since the subchain controls DSS at a relatively fine-grained level compared with the main chain, the requirements on transaction throughput and transaction or consensus delay for the blockchain system performance will be much more stringent. Advanced lightweight architecture, efficient consensus, and channel isolation techniques may be adopted at each subchain to improve performance.

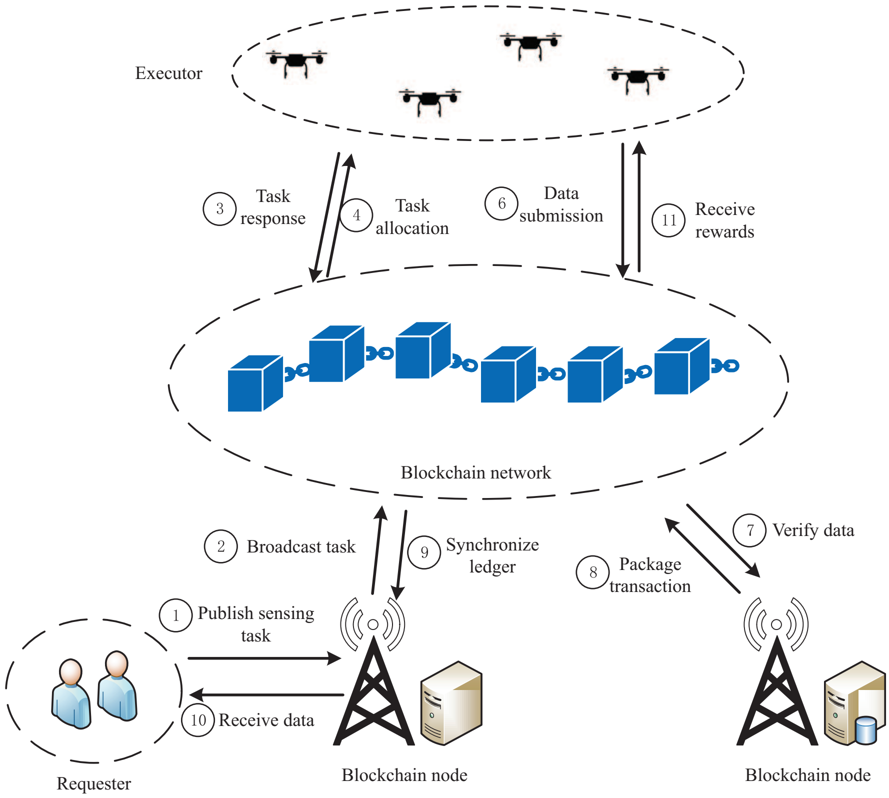

Figure 5 (Color online) Blockchain-based crowd spectrum sensing model.

4 Blockchain-enabled technologies for DSS in 6G

In the previous section, we presented the SpectrumChain architecture to build an ideal framework for future DSS. In this section, we further elaborate on several key enablers under this architecture and then identify the particular advantages of blockchain for these technologies.

4.1 Blockchain-based crowd spectrum sensing

Crowd sensing is an emerging data aggregation paradigm with high mobility and scalability [40], and it can greatly reduce the operation and maintenance costs of a sensing network [41]. Combining crowd sensing and spectrum sensing can build efficient large-scale and high-precision spectrum data acquisition and facilitate spectrum situational awareness. However, traditional crowd sensing is vulnerable to malicious attacks because of its centralized architecture [42, 43]. The process of sensing tasks will consume power, computing, and storage resources, which need to be compensated for with reasonable rewards. Otherwise, rational users may refuse to participate in crowd-sensing tasks [44]. More importantly, the spectrum sensing data submitted by participants may contain their time and location information, through which their behaviors can be inferred, and thus their private information is disclosed. Therefore, to facilitate crowd sensing, a fully distributed, secure, and efficient platform with privacy-preserving and guaranteed incentives for participants should be built.

Considering the unique properties of blockchain as described in the previous section and the requirements for crowd sensing, crowd sensing integrated with blockchain has become a fascinating solution for spectrum sensing in future 6G systems. As shown in Figure 5, blockchain-based crowd sensing mainly comprises a task requester, task executor, and blockchain network, whose roles are described as follows.

- **Task requester:** The requester represents the organization that has spectrum sensing tasks and wants to acquire spectrum sensing data. The requester recruits possible task executors to work for them by publishing sensing tasks and pays them according to the obtained sensing data.
- **Task executor:** Task executors are those who respond to the task request and can conduct sensing tasks with their own devices. They execute sensing tasks and provide sensing data to obtain the reward from the requester.

• **Blockchain network:** The blockchain network is the basis of the system. The transactions between the requester and executor are recorded on the chain. By leveraging blockchain, no central server is required; thus, the blockchain network can resist malicious attacks and improve stability and reliability. Moreover, since the transaction is recorded on the blockchain in a tamper-proof manner, fraud or falsification can be avoided.

The detailed procedure of blockchain-enabled crowd sensing is described as follows.

• **Task publishing stage:** The task requester first publishes sensing tasks by deploying a specific smart contract on the blockchain, wherein the requester can set task requirements, rewards, etc. Then, the blockchain node broadcasts the task in the network, and task executors can query the published tasks on the blockchain.

• **Task performing stage:** Candidate task executors decide whether to participate in the task based on the task information and their own capability. If the task can be completed, a candidate may send a task response to the blockchain. Then, the pre-deployed smart contract will select candidates and allocate tasks. Upon receiving the notification, the selected candidates become task executors to perform the spectrum sensing tasks.

• **Task-ending stage:** Each task executor submits the collected sensing data to the blockchain node, which will be verified by the blockchain nodes with certain algorithms. Then, the blockchain node will package the transaction into a new block for consensus and update the ledger once an agreement is reached. Finally, the task publisher will obtain the collected sensing data, and then the smart contract will automatically distribute the reward to task executors.

On the basis of the above description, the unique advantages of blockchain for crowd sensing are summarized as follows.

• Blockchain provides a secure and trusted platform without a centralized trusted authority, resulting in improved system reliability and stability.

• The rewards for the participants can be guaranteed with blockchain and a smart contract. Thus, cheating, such as free-riding and false reporting, can be avoided.

• The original sensing data or data abstract can be permanently recorded on the blockchain, and thus data falsification can be prevented, which ensures the reliability of the sensing process.

• The private information of the participants can be well preserved with anonymous identity on the chain. Therefore, more potential participants can be encouraged to participate in crowd sensing.

Regarding these advantages, some studies on blockchain-based crowd-sensing have appeared in the literature. In [45], the authors proposed a decentralized crowd-sourcing framework on the basis of blockchain, named CrowdBC. They used a smart contract to perform crowd-sourcing tasks and verified the feasibility of the proposed scheme through software prototypes and real datasets on Ethereum. The authors of [46] illustrated a blockchain-enabled service architecture for the intelligent perception of SAG-integrated vehicular crowd sensing and constructed a unified representation model. Then, they proposed a tensor computing-based incentive mechanism to encourage vehicles to participate in completing tasks, ensure the safety of the entire process, and maximize social welfare. A blockchain-based mobile crowd-sensing system was developed to overcome the shortcomings of traditional MCS systems in [41]. It used miners to verify sensing data, designed a dynamic reward ranking incentive mechanism, and developed a sensing data quality detection scheme. The authors of [41] also built a prototype on Ethereum and conducted extensive experiments in real factory studios.

4.2 Blockchain-enabled spectrum trading

At present, the spectrum allocation mode mainly includes an administrative examination and approval approach and an auction-based marketing approach. An administrative approach is still the most typical method for spectrum allocation but suffers from high administrative and maintenance costs. Conversely, spectrum trading or auctioning may facilitate DSS efficiently [47]. In contrast to the centralized database-based approach, the multi-party maintained and distributed ledgers of blockchain combined with cryptography and a consensus mechanism can achieve secure and effective spectrum management without a proxy [48]. With a smart contract, DSS can be automatically executed. Thus, blockchain-enabled DSS has recently been intensively investigated. Kotobi et al. [49] introduced a virtual currency (i.e., spec-coins) to stimulate dynamic spectrum access, where the spec-coins can be used to pay for spectrum access. A blockchain-based secure spectrum auction was considered in [50], which obtains idle frequency

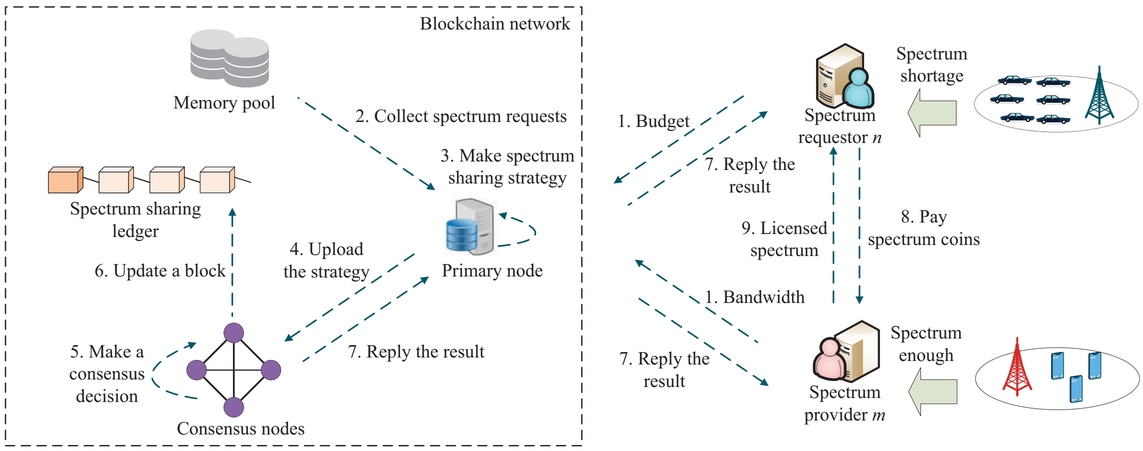

Figure 6 (Color online) Blockchain-enabled DSS workflow.

bands with spectrum monitoring to encourage authorized users to share a spectrum. The workflow of a typical blockchain-based DSS is shown below.

Although blockchain provides a trusted platform for spectrum trading and auctioning, the corresponding trading and auctioning algorithms should be designed to satisfy different objectives. As shown in Figure 6, spectrum requestor m submits the spectrum requesting message $\mathrm{MSG_{req}}$ with its digital signature to the memory pool through its local client, i.e., $\mathrm{MSG_{req}} = \{\mathrm{id}_m, \mathrm{sig}_m, Q_m, \mathrm{loc}_m, \mathrm{dep}_m, \mathrm{slot_{no}}\}$, where id_m and sig_m are the digital identity (ID) and signature of m, respectively. Q_m and loc_m are its total budget and location information, respectively. dep_m is its deposit for spectrum sharing, and $\mathrm{slot_{no}}$ is the slot number. On the spectrum provider side, spectrum provider n sends the spectrum providing message $\mathrm{MSG_{pro}} = \{\mathrm{id}_n, \mathrm{sig}_n, \mathrm{loc}_n, B_n, C_n, \mathrm{dep}_n, \mathrm{slot_{no}}\}$ with its digital signature to the memory pool, where C_n is the cost per unit bandwidth of n.

On the consortium blockchain, a primary node is selected to collect spectrum requesting and supplying messages at the beginning of each slot. Next, it executes the DSS smart contract to obtain the spectrum-sharing strategy, which is then submitted to consensus nodes as a proposal. Consensus nodes include endorsers and orderers, which validate and sort the proposal, respectively. After that, the proposals are packaged into a new block, and each node on the chain updates the ledger by adding the block. Spectrum requestors pay the providers after obtaining the spectrum usage rights according to the trading results in the ledger. If any participant violates the spectrum-sharing rule, the deposits will be confiscated.

Although the consortium blockchain has higher TPS performance than the public blockchain, further improvements in performance in DSS scenarios with highly dynamic environments should be sought, particularly the consensus delay performance.

4.3 Blockchain-enabled spectrum regulation

To fully reap the benefits of DSS in 6G, comprehensive and in-depth spectrum regulation is required by evaluating the spectrum usage, managing the interference and jamming, and maintaining the security operation. On the one hand, crowd sensing provides large-scale and high-precision spectrum sensing capability so that the global spectrum security situation can be obtained. To provide dynamic spectrum access decisions for different services, a spectrum resource pool should be constructed. The spectrum situation also allows the spectrum usage of each MNO to be evaluated. On the other hand, spectrum regulation guarantees normal operation and identifies illegal transmissions, such as black radio, malicious jamming with high transmission power, and unintended signal transmission. However, the full spectrum applications in 6G and SAG integrated networking architecture make spectrum regulation a very challenging issue.

By leveraging blockchain, complete transaction tracing, sensing deposit, signal identification, and dispute arbitration solutions can be achieved with on-chain and off-chain coordination. A completely traceable full-process supervision mechanism can be established based on its tamper-proof characteristics, including on-chain registration, spectrum trading, and spectrum regulation. As shown in Figure 7, the regulation model comprises MNOs (including spectrum requestors and spectrum providers), a blockchain network, and an off-chain monitoring system. The entire regulation procedure is described as follows.

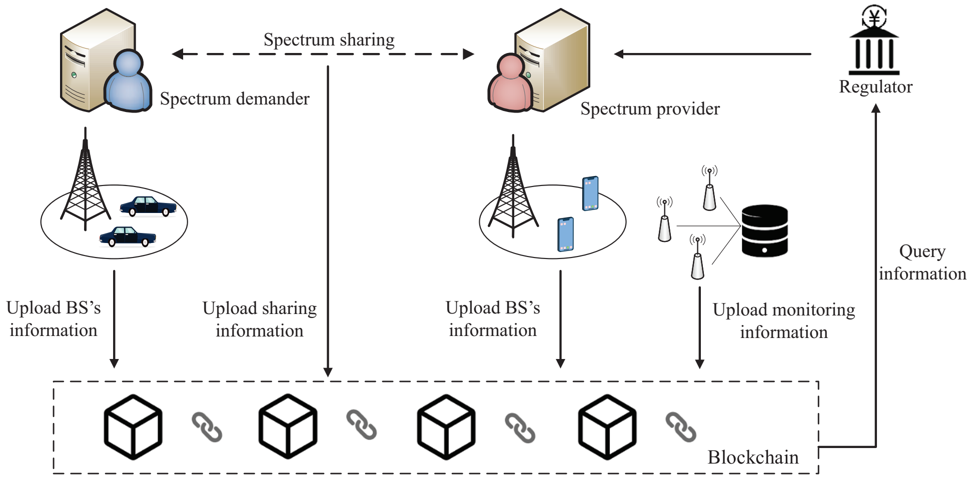

Figure 7 (Color online) Spectrum regulation model.

- The BSs belonging to each MNO register on the blockchain network to obtain their public/private keys and certificates. The registration information includes the locations, antenna or radiation patterns, predefined modulation type, and maximum transmission power. The registered information cannot be falsified and can be traced by querying the distributed ledger. Meanwhile, the monitoring devices also register their ID, locations, and operating parameters on the chain.
- Each MNO can adaptively act as a spectrum demander or provider and performs spectrum trading or auctioning with other MNOs. The sharing transactions among MNOs are recorded on the chain.
- The monitoring devices continuously monitor the considered area at a predefined spectrum band under the blockchain-enabled crow sensing framework. The original sensed data or data abstract is recorded on the chain for data integrity verification.
- Each MNO can launch an interference complaint, including the interfering area, frequency, and time.
- The regulator receives the complaint and then traces the original sensing data with the parameters in the complaint. With sensing data analysis, signal identification and localization algorithms can be used to identify the position, modulation, and transmission power of the jamming signal. With the analyzed information, the regulator also traces the on-chain transaction recordings for comparison to make an adjudgement.
- The arbitration results are recorded on the chain for further processing.

5 Conclusion

In this paper, we provide an overview of the vision and requirements for 6G in terms of spectrum usage. Then, we introduce a blockchain-enabled DSS framework by identifying the unique advantages of blockchain for DSS. The hierarchical SpectrumChain DSS architecture with consortium blockchain is presented in detail. Moreover, we also present blockchain-enabled technologies for 6G DSS, including crowd spectrum sensing, spectrum trading, and spectrum regulation. However, applying blockchain for 6G DSS remains incipient, and more research efforts covering DSS-related techniques and the fundamental blockchain revolutions should be required with global cooperation. We hope that this paper can provide a fundamental basis and guidance for researchers to pursue more advanced solutions to soon realize 6G DSS.

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References

1 You X H, Wang C-X, Huang J, et al. Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts. Sci China Inf Sci, 2021, 64: 110301
2 Tataria H, Shafi M, Molisch A F, et al. 6G wireless systems: vision, requirements, challenges, insights, and opportunities. Proc IEEE, 2021, 109: 1166–1199

3 Wang Z Q, Du Y, Wei K J, et al. Vision, application scenarios, and key technology trends for 6G mobile communications. Sci China Inf Sci, 2022, 65: 151301
4 Yuan Y F, Zhao Y J, Zong B Q, et al. Potential key technologies for 6G mobile communications. Sci China Inf Sci, 2020, 63: 183301
5 You X H, Huang Y, Liu S, et al. Toward 6G TKμ extreme connectivity: architecture, key technologies and experiments. 2022. ArXiv:2208.01190
6 Zhuang W, Ye Q, Lyu F, et al. SDN/NFV-empowered future IoV with enhanced communication, computing, and caching. Proc IEEE, 2019, 108: 274–291
7 Chen W, Wang W, Li Z, et al. Joint pricing and task allocation for blockchain empowered crowd spectrum sensing. Peer-to-Peer Netw Appl, 2022, 15: 783–792
8 Li Z, Wang W, Wu Q, et al. Multi-operator dynamic spectrum sharing for wireless communications: a consortium blockchain enabled framework. IEEE Trans Cogn Commun Netw, 2022. doi: 10.1109/TCCN.2022.3212369
9 Zhang H, Leng S, Chai H. A blockchain enhanced dynamic spectrum sharing model based on proof-of-strategy. In: Proceedings of 2020 IEEE International Conference on Communications (ICC), Dublin, 2020. 1–6
10 Wang J, Ling X, Le Y, et al. Blockchain-enabled wireless communications: a new paradigm towards 6G. Natl Sci Rev, 2021, 8: nwab069
11 Khan A H, Hassan N U, Yuen C, et al. Blockchain and 6G: the future of secure and ubiquitous communication. IEEE Wireless Commun, 2021, 29: 194–201
12 Maksymyuk T, Gazda J, Volosin M, et al. Blockchain-empowered framework for decentralized network management in 6G. IEEE Commun Mag, 2020, 58: 86–92
13 Wu W, Zhou C, Li M, et al. AI-native network slicing for 6G Networks. IEEE Wireless Commun, 2022, 29: 96–103
14 Li Z, Wang W, Guo J, et al. Blockchain-empowered dynamic spectrum management for space-air-ground integrated network. Chin J Electron, 2022, 31: 456–466
15 Yin Z, Jia M, Cheng N, et al. UAV-assisted physical layer security in multi-beam satellite-enabled vehicle communications. IEEE Trans Intell Transp Syst, 2021, 23: 2739–2751
16 Samsung. 6G spectrum expanding the frontier. May 2022. https://cdn.codeground.org/nsr/downloads/researchareas/2022May 6G Spectrum.pdf
17 Nan L, Chunxia G, Dapeng W. Considerations on 6 GHz spectrum for 5G-advanced and 6G. IEEE Comm Stand Mag, 2021, 5: 5–7
18 Taleb T, Aguiar R L, Yahia I G B, et al. White paper on 6G networking. University of Oulu, 2020. http://hdl.handle.net/1854/LU-8668820
19 Chi N, Jia J. 6G-oriented visible light communication. ZTE Technol J, 2020
20 Mueck M D, Frascolla V, Badic B. Licensed shared access-state-of-the-art and current challenges. In: Proceedings of the 1st International Workshop on Cognitive Cellular Systems (CCS), Duisburg, 2014. 1–5
21 Ying X, Buddhikot M M, Roy S. SAS-assisted coexistence-aware dynamic channel assignment in CBRS band. IEEE Trans Wireless Commun, 2018, 17: 6307–6320
22 Li Z, Wang W, Guo J, et al. Blockchain-assisted dynamic spectrum sharing in the CBRS band. In: Proceedings of 2021 IEEE/CIC International Conference on Communications in China (ICCC), Xiamen, 2021. 864–869
23 Xin C, Song M. Analysis of the on-demand spectrum access architecture for CBRS cognitive radio networks. IEEE Trans Wireless Commun, 2020, 19: 970–978
24 Xu W, Yang Z, Ng D W K, et al. Edge learning for B5G networks with distributed signal processing: semantic communication, edge computing, and wireless sensing. 2022. ArXiv:2206.00422
25 Ye Q, Zhuang W, Zhang S, et al. Dynamic radio resource slicing for a two-tier heterogeneous wireless network. IEEE Trans Veh Technol, 2018, 67: 9896–9910
26 Federal Communications Commission (FCC). Remarks of commissioner Jessica rosenworcel at mobile world congress Americas, Los Angeles, California, September 13, 2018. https://docs.fcc.gov/public/attachments/ DOC-354091A1.pdf
27 Sun Z, Liang W, Qi F, et al. Blockchain-based dynamic spectrum sharing for 6G UIoT networks. IEEE Network, 2021, 35: 143–149
28 Zhang H, Leng S, Wu F, et al. A DAG blockchain-enhanced user-autonomy spectrum sharing framework for 6G-enabled IoT. IEEE Internet Things J, 2022, 9: 8012–8023
29 Wang Y, Su Z, Zhang N. BSIS: blockchain-based secure incentive scheme for energy delivery in vehicular energy network. IEEE Trans Ind Inf, 2019, 15: 3620–3631
30 Zheng X, Zhang Y, Yang F, et al. Resource allocation on blockchain enabled mobile edge computing system. Electronics, 2022, 11: 1869
31 Seo H, Park J, Bennis M, et al. Consensus-before-talk: distributed dynamic spectrum access via distributed spectrum ledger technology. In: Proceedings of 2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), Seoul, 2018. 1–7
32 Fernando P, Dadallage K, Gamage T, et al. Proof of sense: a novel consensus mechanism for spectrum misuse detection. IEEE Trans Ind Inf, 2022, 18: 9206–9216
33 Bayhan S, Zubow A, Gawlowicz P, et al. Smart contracts for spectrum sensing as a service. IEEE Trans Cogn Commun Netw, 2019, 5: 648–660
34 Xiao Y, Shi S, Lou W, et al. Decentralized spectrum access system: vision, challenges, and a blockchain solution. IEEE Wireless Commun, 2022, 29: 220–228
35 Ye J, Kang X, Liang Y C, et al. A trust-centric privacy-preserving blockchain for dynamic spectrum management in IoT networks. IEEE Internet Things J, 2022, 9: 13263–13278
36 Zhu R, Liu H, Liu L, et al. A blockchain-based two-stage secure spectrum intelligent sensing and sharing auction mechanism. IEEE Trans Ind Inf, 2022, 18: 2773–2783
37 Khanna A, Rani P, Sheikh T H, et al. Blockchain-based security enhancement and spectrum sensing in cognitive radio network. Wireless Pers Commun, 2022, 127: 1899–1921
38 Wilhelmi F, Giupponi L. On the performance of blockchain-enabled RAN-as-a-service in beyond 5G networks. In: Proceedings of IEEE Global Communications Conference (GLOBECOM), Madrid, 2021
39 Zhou Z, Chen X, Zhang Y, et al. Blockchain-empowered secure spectrum sharing for 5G heterogeneous networks. IEEE Network, 2020, 34: 24–31
40 Ma H, Zhao D, Yuan P. Opportunities in mobile crowd sensing. IEEE Commun Mag, 2014, 52: 29–35

41 Huang J, Kong L, Dai H N, et al. Blockchain-based mobile crowd sensing in industrial systems. IEEE Trans Ind Inf, 2020, 16: 6553–6563
42 Wei L, Wu J, Long C, et al. The convergence of IoE and blockchain: security challenges. IT Prof, 2019, 21: 26–32
43 Wei L, Wu J, Long C. A blockchain-based hybrid incentive model for crowdsensing. Electronics, 2020, 9: 215
44 Liu J, Huang S, Wang W, et al. An incentive mechanism based on endowment effect facing social welfare in Crowdsensing. Peer-to-Peer Netw Appl, 2021, 14: 3929–3945
45 Li M, Weng J, Yang A, et al. CrowdBC: a blockchain-based decentralized framework for crowdsourcing. IEEE Trans Parallel Distrib Syst, 2018, 30: 1251–1266
46 Zhao R, Yang L T, Liu D, et al. A tensor-based truthful incentive mechanism for blockchain-enabled space-air-ground integrated vehicular crowdsensing. IEEE Trans Intell Transp Syst, 2022, 23: 2853–2862
47 Ling X, Le Y, Wang J, et al. Practical modeling and analysis of blockchain radio access network. IEEE Trans Commun, 2021, 69: 1021–1037
48 Weiss M B H, Werbach K, Sicker D C, et al. On the application of blockchains to spectrum management. IEEE Trans Cogn Commun Netw, 2019, 5: 193–205
49 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, 2018, 13: 32–39
50 Liang Y C. Blockchain for dynamic spectrum management. In: Proceedings of Dynamic Spectrum Management, 2020. 121–146