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Blockchain-enabled dynamic credible spectrum sharing in 6G networks

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Highlights:

- HierSpectrumChain: hierarchical blockchain for dynamic 6G spectrum sharing.
- Smart-contract driven two-stage Stackelberg auction automates spectrum bids.
- Localized sub-chains offload latency-sensitive transactions for real-time use.
- Framework supports UAV edge nodes, enhancing adaptability in 6G networks.

Abstract: Dynamic spectrum sharing (DSS) is essential for 6G networks, yet existing blockchain-based DSS solutions often lack an integrated approach that simultaneously addresses trust, allocation fairness, and system scalability. This paper proposes HierSpectrumChain, a hierarchical blockchain framework that incorporates a global main chain, localized sub-chains, and a smart-contract based Stackelberg auction for credible and automated spectrum allocation. The system model formalizes interactions among spectrum holders, secondary users, and sub-chain validators, enabling transparent bidding and decentralized coordination. A proof-of-concept implementation on an Ethereum Ganache environment evaluates the functional correctness of the auction workflow and measures throughput under varying client loads. While the evaluation is limited to a single-node testbed, the results demonstrate the feasibility of the proposed architecture and establish a basis for future multi-peer experiments on permissioned blockchains. This work provides a coherent design and initial validation for blockchain-enabled DSS in 6G networks.

Keywords: blockchain; dynamic spectrum sharing; HierSpectrumChain; 5G/6G; Internet of Things

1. Introduction

Wireless spectrum is a fundamental resource for supporting wireless communication, however it is both scarce and non-renewable. With the continuous advancement of communication technologies and the emergence of various new applications, efficient management and utilization of the spectrum have become increasingly critical. Traditional static spectrum management, while essential, has limitations in addressing the dynamic nature of spectrum usage, particularly by secondary users (SUs) in unlicensed

bands [1]. The rise of high-definition video transmission, virtual reality, augmented reality, and other high-bandwidth services in fifth-generation (5G) wireless networks has led to a surge in communication traffic [2]. However, the inflexibility of traditional static spectrum allocation, which cannot be dynamically adjusted to match actual demand, often results in frequency bands being either underutilized or overcrowded. This inefficiency fails to meet the traffic demands of 5G networks, thereby impacting performance and scalability.

Research on multi-operator dynamic spectrum sharing (DSS) architectures can be broadly classified into centralized [3] and distributed [4] models. While both architectures can effectively address the spectrum shortage issue and enhance spectrum utilization, security remains a significant challenge, particularly when different trusted entities interact. In a centralized spectrum sharing architecture, a spectrum agent is introduced to manage the spectrum allocation between participating primary users (PUs) and SUs. However, to share spectrum efficiently, both PUs and SUs must exchange private information with the untrusted spectrum agent [5], which introduces the risks of a single point of failure and potential privacy breaches. In a distributed architecture, PUs and SUs interact directly [6], however this can result in high communication costs and privacy leakage concerns. To improve spectrum utilization and enhance user security, the concept of blockchain-based DSS networks has been introduced in [7].

Blockchain provides decentralized, transparent, and tamper-proof record management for DSS, ensuring the fairness and security of spectrum resource allocation [8]. In traditional DSS architectures, spectrum allocation may face trust and security issues due to the involvement of multiple participants. By leveraging its distributed ledger and smart contract technologies, blockchain can automate spectrum resource allocation and transactions without relying on centralized control, reducing human intervention and minimizing operational risks. However, there is a lack of research on blockchain-based solutions for decentralized applications, particularly in terms of how blockchain technology, via smart contracts, can enhance DSS performance and address the challenges posed by centralized control in these systems

Literature [9] proposed a spectrum-sharing transaction mechanism based on smart contracts, designed for decentralized spectrum resource allocation and sharing in multi-operator wireless communication networks. That paper introduced a flexible collaboration model supporting various types of wireless networks, thereby enhancing the system's scalability and adaptability and meeting the spectrum management requirements anticipated in 5G/6G networks. Literature [10] presented a blockchain-assisted Citizen Broadband Radio Service (CBRS) system to address inefficiencies in spectrum management as well as security and privacy shortcomings of traditional CBRS architectures. It detailed the spectrum management process for general authorized-access users and developed an algorithm to optimize channel allocation, reducing interference and improving overall spectrum utilization. Literature [11] suggested that blockchain could provide innovative solutions for 5G networks and services enhancing decentralization, privacy, and security while transforming network management architectures to improve quality of service. That study also noted that challenges such as low bandwidth, high transaction latency, and increased storage burdens arising from large volumes of IoT-generated data on public blockchains could be mitigated by adopting private-blockchain approaches.

However, existing studies had not yet fully addressed the application of spectrum management within dynamic spectrum sharing (DSS) techniques for 5G and 6G networks. This article makes the following contributions:

- Hierarchical blockchain architecture: We propose a main-chain/sub-chain framework for dynamic spectrum sharing in 6G, specifying the roles of spectrum providers, secondary users, and edge nodes to achieve low latency and high throughput.
- Smart-contract-driven Stackelberg auction: We implement a two-stage auction entirely on-chain, enabling encrypted bid submission, equilibrium computation, and automated token issuance within localized sub-chains.
- Performance optimization features: We integrate adaptive ledger-sharding and a hybrid PoS/BFT consensus switching strategy to maintain sub-second confirmation times while reducing energy consumption.
- Experimental validation: We develop and evaluate a Ganache-based prototype that demonstrates end-to-end spectrum allocation under various client loads and provides preliminary throughput and latency results.
- Design guidance: We analyze scalability, privacy, and interoperability trade-offs to support future deployment of blockchain-enabled dynamic spectrum sharing in 6G networks.

Unlike prior blockchain-enabled DSS proposals many of which either relied on a single monolithic ledger [12–14], adopted DAG(Directed Acyclic Graph) structures without game-theoretic automation [15], or presented Stackelberg auctions only as theoretical models [16,17] HierSpectrumChain uniquely combines a hierarchical main-chain/sub-chain architecture with a smart-contract–based, two-stage Stackelberg game. This design both offloads latency-sensitive transactions to localized sub-chains and fully automates leader-follower auctions on-chain. Furthermore, we deliver a systematic comparison of consensus protocols and an in-depth trade-off analysis of scalability, privacy, and interoperability, thereby filling key gaps left by prior work.

2. Related work

Over the past decade, dynamic spectrum sharing (DSS) has evolved from simple centralized allocation schemes to sophisticated, decentralized frameworks. Early DSS research focused on opportunistic access and cognitive radio techniques, enabling secondary users to exploit underutilized bands without impairing primary services [18,19]. While effective in controlled environments, these approaches struggled with trust and coordination when scaled to the heterogeneous, multi-stakeholder landscape projected for 6G networks.

To address these shortcomings, several groups have explored blockchain as a trust anchor for DSS. In [12], a permissioned blockchain records spectrum leases, ensuring transparency but incurring high confirmation delays under heavy load. Building on this, references [13] and [14] propose lightweight smart contracts that automate auction logic, yet both rely on monolithic ledger structures that bottleneck throughput. A recent study in [15] demonstrates a directed-acyclic-graph (DAG)-based ledger to improve parallelism, but at the cost of increased implementation complexity and weaker finality guarantees.

Game-theoretic models have been applied to spectrum allocation to better capture strategic user behavior. For instance, reference [16] formulates a Stackelberg game where providers act as leaders setting prices and followers bid for access; however, the model in [16] remains purely theoretical. In [17], researchers integrate this framework into an Ethereum smart contract, showcasing feasibility but reporting gas costs that limit real-world deployment. More recently, reference [20] refines the bidding

process with cryptographic stake mechanisms to discourage misreporting, though it does not address latency constraints vital for 6G.

Table 1 summarizes key blockchain-enabled DSS schemes and their primary limitations. While prior proposals address parts of the spectrum-sharing challenge ranging from opportunistic access and permissioned chains to DAG ledgers and theoretical Stackelberg games none integrates a truly hierarchical architecture with smart-contract–automated auctioning. In Section 3, we present HierSpectrumChain, our unified framework that delivers low-latency sub-chains anchored to a global chain and a two-stage on-chain Stackelberg auction.

Table 1. Blockchain-enabled DSS: approaches and drawbacks.

Reference	Approach	Drawback
[18,19]	Opportunistic CR	Centralized trust; poor scaling
[12–14]	Permissioned BC + SC	Monolithic ledger; high latency
[15]	DAG-based ledger	Complex; weaker finality
[16,17]	On-chain Stackelberg	High gas costs; theoretical only
[21–24]	Hierarchical sub-chains	Lacks game-theoretic automation

Hierarchical architectures have emerged to reconcile latency, scalability, and security. The HierSpectrumChain concept in [21] first introduces a two-tier main-chain/sub-chain topology, offloading fast transactions to local ledgers while anchoring critical records on a global chain. Parallel efforts in [22–24] demonstrate edge-focused sub-chains for IoT and UAV scenarios, but none combine game-theoretic automation with hierarchical design.

Recent studies have also explored hierarchical blockchain structures for spectrum sharing, such as the conceptual framework introduced by Wu *et al.* (2023). While their work presents the motivation for a two-level ledger, it does not include a system model, operational protocol, smart-contract workflow, or experimental evaluation. In contrast, our work extends the conceptual direction by providing a complete and implementable design, including a detailed system architecture, security assumptions, protocol flow, consensus-selection guidelines, and a working proof-of-concept prototype. This positions HierSpectrumChain as a practical realization of hierarchical blockchain-based DSS rather than a conceptual outline.

In summary, prior work establishes the feasibility of blockchain-based DSS and game-theoretic allocation, yet gaps remain in balancing throughput, latency, and incentive alignment within a unified architecture. Our HierSpectrumChain framework builds on these advances by merging a hierarchical ledger structure with a smart-contract automated, two-stage Stackelberg auction addressing both the performance and trust requirements of next-generation 6G spectrum sharing.

3. Designing blockchain frameworks for DSS

3.1. Blockchain

Blockchain technology has undergone significant development since its inception and is generally divided into three evolutionary phases. Blockchain 1.0, represented by Bitcoin, introduced the first practical implementation of a decentralized digital currency system based on Nakamoto's consensus

mechanism [25]. Its core contribution lies in enabling peer-to-peer monetary transactions without a centralized authority, relying on cryptographic proofs, distributed data storage, and a publicly verifiable append-only ledger.

Blockchain 2.0, exemplified by Ethereum, expanded the functional boundaries of blockchain systems by introducing smart contracts programmable scripts embedded within the ledger that execute automatically once predefined conditions are met [26]. This advancement transformed blockchain from a simple payment network into a general-purpose computational platform, supporting decentralized applications (DApps), tokenization models, and autonomous business logic. Smart contracts also laid the foundation for automated auctions, digital identity, supply chain traceability, and consortium governance, which are highly relevant to spectrum allocation scenarios.

Blockchain 3.0 focuses on overcoming the scalability, interoperability, and performance limitations of earlier generations. Although no universally recognized representative system exists, Blockchain 3.0 aims to deliver enterprise-level solutions by integrating improved consensus algorithms, modular consensus-execution separation, cross-chain communication mechanisms, and enhanced privacy-preserving computation. These advancements aim to support large-scale, heterogeneous applications across finance, energy, healthcare, and next-generation communication systems.

Despite architectural differences across these three generations, blockchain platforms share a common layered design. A typical blockchain architecture consists of:

The data layer, which defines data structures such as blocks, transactions, timestamps, and hash pointers;

The network layer, which supports peer-to-peer communication, message propagation, and node discovery;

The consensus layer, responsible for validating transactions and maintaining state consistency across nodes;

The incentive layer, which governs reward and penalty mechanisms to motivate honest participation;

The contract layer, where smart contracts and state transition logic are executed;

The application layer, which interfaces with user applications and domain-specific services.

At its core, blockchain is a distributed, append-only ledger maintained collaboratively by multiple nodes in a peer-to-peer network. Each node maintains a synchronized copy of the ledger, and new blocks are validated through a consensus algorithm to ensure immutability, transparency, and resistance to unilateral manipulation. The integration of cryptographic algorithms, P2P communication, and distributed consensus allows mutually untrusted entities to coordinate and transact securely in the absence of a central authority [27,28].

Blockchain systems can be categorized into public, private, and consortium (or federated) chains depending on governance and access control models. Public chains such as Bitcoin and Ethereum allow any participant to join and validate transactions, offering high transparency and decentralization at the cost of higher latency and lower throughput. Private chains restrict participation to a single organization, providing improved performance and privacy but reduced decentralization. Consortium chains are jointly managed by multiple trusted entities and balance performance, access control, and partial decentralization, making them suitable for inter-organizational collaboration scenarios such as coordinated spectrum sharing, cross-domain resource management, and regulatory compliance.

Given the latency-sensitive and multi-stakeholder nature of dynamic spectrum sharing, consortium and hierarchical blockchain architectures provide a suitable foundation. They enable controlled participation, lower transaction overhead, and more flexible consensus designs while preserving

auditability and cross-region coordination. These characteristics motivate the adoption of a hierarchical blockchain structure in HierSpectrumChain.

3.2. Dynamic spectrum sharing

Dynamic Spectrum Sharing (DSS) has become a fundamental solution for improving spectrum utilization in modern and future wireless networks. Early studies mainly focused on coordinating the coexistence of primary users (PUs), who hold licensed access rights, and secondary users (SUs), who opportunistically access temporarily unused spectrum. The central challenge in these early models was to enable flexible SU access without creating interference that compromised PU performance. As wireless technologies have evolved, DSS has been enhanced by the integration of artificial intelligence, cooperative sensing, and increasingly, blockchain-based trust mechanisms, all of which aim to strengthen transparency, automation, and security in spectrum management.

A key advantage of DSS is that it allows multiple generations of communication technologies to share the same spectrum resources rather than allocating separate fixed frequency bands for each generation. This flexibility enables operators to dynamically adjust spectrum usage according to real-time traffic conditions, user density, and service-level requirements. Such adaptability prevents the underutilization commonly observed in traditional static spectrum allocation models and significantly improves overall spectral efficiency [29]. In addition, DSS facilitates a smooth transition from older wireless technologies to newer ones by allowing both to coexist within the same frequency bands, thus reducing the costs and operational challenges associated with spectrum refarming [30]. For example, the coexistence of 5G and 6G technologies within a shared spectral environment becomes more practical when dynamic reallocation mechanisms are employed.

From an operational standpoint, DSS approaches can generally be divided into three categories: licensed spectrum sharing, unlicensed spectrum sharing, and hybrid spectrum sharing. In licensed sharing, PUs permit controlled access to their licensed bands under the condition that SU activity remains non-interfering. This approach is widely adopted in systems such as the Citizens Broadband Radio Service (CBRS), where spectrum access is mediated through hierarchical authorization. Unlicensed sharing, by contrast, allows SUs to utilize designated frequency bands without prior authorization, with coexistence typically managed through contention-based access protocols. Hybrid spectrum sharing combines the flexibility of unlicensed access with the protection guarantees of licensed access, allowing both PU and SU activities to be coordinated under more adaptive policies. Each model presents different trade-offs with respect to coordination complexity, interference risk, and regulatory compliance.

As communication infrastructures advance toward 6G, DSS is expected to become even more critical due to the increasing density and heterogeneity of devices, the proliferation of ultra-low-latency applications, and the need for more autonomous resource management. These developments require DSS mechanisms that can operate in a distributed and trustworthy manner while supporting multi-stakeholder participation. Blockchain-assisted DSS frameworks are particularly attractive in this context because they provide immutable access records, decentralized decision-making, and transparent auction mechanisms. Motivated by these emerging requirements, the proposed HierSpectrumChain framework aims to integrate blockchain technologies to enhance the credibility, efficiency, and adaptability of DSS in next-generation wireless systems.

3.3. Integration prerequisites for blockchain and DSS

The integration of blockchain technology with Dynamic Spectrum Sharing (DSS) represents a foundational step toward the development of secure, transparent, and autonomous 6G spectrum management systems. Achieving this convergence requires a set of technical, theoretical, and security-oriented prerequisites that together ensure that blockchain can operate effectively within the constraints of real-time wireless environments.

From a technical standpoint, the underlying network architecture must support the coexistence of blockchain's distributed ledger with conventional wireless communication components. This requires a coordination framework in which decentralized blockchain nodes interact smoothly with base stations, spectrum databases, and sensing units, enabling spectrum transactions to be recorded without disrupting ongoing network operations [31]. The real-time nature of DSS introduces stringent latency requirements, making it necessary to employ efficient consensus mechanisms capable of delivering fast block finality. Consensus protocols such as optimized Proof of Stake and Byzantine Fault Tolerance variants are particularly relevant, as they reduce communication overhead while maintaining security guarantees [32]. Additionally, the immutable structure of blockchain implies continual growth of stored data, and the system must therefore incorporate storage management strategies that support both scalability and rapid retrieval of historical spectrum transactions for verification and auditing purposes [33]. The computational capabilities of blockchain nodes also play an important role, as nodes must process transactions, verify signatures, and execute smart-contract logic without imposing excessive delays or power consumption, particularly in edge or lightweight environments [34].

The theoretical prerequisites for combining blockchain with DSS further strengthen this integration. Game-theoretic models provide a robust analytical foundation for characterizing the strategic behavior of multiple spectrum users and for designing mechanisms that balance fairness, incentive compatibility, and efficient spectrum utilization [35]. When spectrum resources are treated as tradable assets, blockchain-enabled smart contracts can formalize trading rules, automate market interactions, and enforce allocation outcomes, thereby reducing the overhead associated with centralized control. Moreover, concepts from information theory contribute to the development of access protocols that ensure reliable and high-throughput communication while mitigating interference among competing users. These considerations help ensure that blockchain mechanisms complement, rather than hinder, the performance of DSS systems [36].

Security considerations form the final essential component of this integration. Because blockchain-based DSS systems involve multiple stakeholders with differing levels of trust, robust authentication and authorization mechanisms remain necessary to prevent unauthorized access to spectrum resources [19]. Cryptographic primitives embedded within the blockchain help establish the integrity of transactions, but additional interference mitigation strategies are required to safeguard spectrum operations from both accidental disruptions and malicious attacks [12]. Furthermore, the decentralized structure of blockchain necessitates the ability to detect and isolate nodes that behave dishonestly or attempt to disrupt consensus. Techniques such as anomaly detection, reputation management, and adaptive consensus adjustment support the identification of abnormal behaviors, ensuring that the broader system maintains stability and resilience even in the presence of adversarial participants.

Together, these prerequisites create the conditions under which blockchain can be effectively integrated with DSS, allowing the resulting system to provide transparent, tamper-resistant, and autonomously verifiable spectrum management suitable for next-generation wireless networks.

3.4. System model

HierSpectrumChain is organized around a two-tier blockchain composed of a global main chain and multiple localized sub-chains. The main chain records high-level spectrum transactions and regulatory events, while each sub-chain manages latency-sensitive operations at the edge. Within a sub-chain, spectrum providers (leaders) deploy the smart contract, and secondary users (followers) submit encrypted bids. Edge validators execute the consensus protocol, compute the Stackelberg equilibrium, and issue access tokens to successful bidders.

The interaction of these components follows the procedural flow shown in Figure 1. After the provider publishes auction terms, secondary users submit encrypted bids; the smart contract computes the equilibrium allocation, records the results to the sub-chain ledger, and issues access tokens. Ongoing monitoring and penalty enforcement ensure compliance.

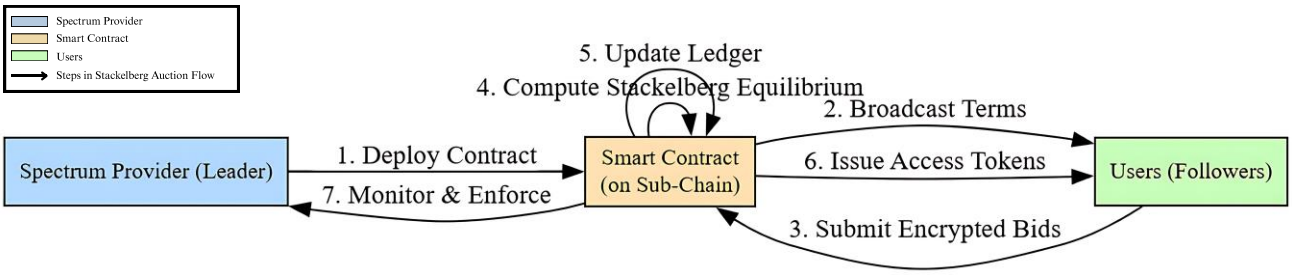

Figure 1. Smart contract based Stackelberg game for dynamic spectrum allocation on a HierSpectrumChain sub-Chain.

To safeguard the system, HierSpectrumChain assumes the presence of potential adversaries who may inject false bids, flood transactions, or attempt to disrupt consensus. These threats are mitigated through bid encryption, stake-based participation penalties, and a hybrid PoS/BFT consensus switching mechanism that preserves finality under load. This model establishes clear roles, message flows and security boundaries for the subsequent architectural and performance evaluation.

The procedural flow of the two-stage Stackelberg game: (1) the spectrum provider (leader) deploys the smart contract; (2) the contract broadcasts terms to secondary users; (3) users submit encrypted bids; (4) the contract computes the Stackelberg equilibrium; (5) allocation results are written to the sub-chain ledger; (6) access tokens are issued; (7) ongoing monitoring and penalty enforcement occur.

4. Blockchain based dynamic spectrum sharing

Prior studies have discussed the potential of hierarchical blockchain for decentralized spectrum coordination, but they typically remain at a conceptual level and do not define the operational workflow required for deployment. To bridge this gap, this section presents the complete system design of HierSpectrumChain, detailing the execution steps, sub-chain interactions, and the smart-contract–based

Stackelberg auction mechanism. The following subsections formally describe each component in a manner suitable for implementation.

4.1. Embodiment of blockchain in spectrum sharing applications

The application of blockchain within spectrum sharing environments provides a decentralized and verifiable mechanism for managing, allocating, and exchanging spectrum resources among heterogeneous users. By maintaining a distributed ledger of spectrum transactions, blockchain eliminates the need for a trusted central authority and ensures that all allocation records remain tamper-resistant and auditable. These characteristics address several challenges present in traditional spectrum management approaches, particularly those related to transparency, cross-operator coordination, and automated enforcement of allocation rules.

In the context of spectrum sharing, blockchain establishes a transparent transaction environment in which each participating entity can independently verify past allocation activities. The immutability of the ledger prevents unauthorized modification of spectrum access records and reduces the potential for disputes. At the same time, privacy-preserving cryptographic techniques can be incorporated into the ledger to ensure that sensitive operational information, such as user identity or local traffic characteristics, is accessible only to authorized participants.

Blockchain further facilitates cooperation among multiple operators by standardizing the procedures for spectrum negotiation and resource exchange. Through its decentralized consensus process, decisions regarding access requests and allocation outcomes can be validated jointly by participating nodes, thereby preventing unilateral manipulation. Smart contracts extend these capabilities by providing programmable logic for real-time spectrum allocation. Once predefined rules are deployed, spectrum access, payment transfers, and compliance checks are executed automatically without manual intervention, leading to reduced operational overhead and increased consistency in enforcement.

Overall, blockchain offers a unified framework for ensuring transparency, privacy protection, cooperative resource sharing, and automated allocation decisions. These characteristics form the basis for the subsequent discussions on integrating blockchain with Dynamic Spectrum Sharing in 6G networks.

4.2. Dynamic spectrum sharing for 6G

Dynamic Spectrum Sharing (DSS) in 6G requires a management framework capable of supporting large-scale, heterogeneous networks with stringent latency and reliability demands. Blockchain has been recognized by regulatory and industrial bodies as a potential foundation for trustworthy spectrum coordination due to its ability to maintain consistent and verifiable records of spectrum activity [22]. Within this context, several key application scenarios illustrate how blockchain can enable credible DSS in 6G environments.

A blockchain-based spectrum distributed ledger provides a unified repository for recording spectrum availability and access decisions. The ledger maintains three categories of spectrum information with different time granularities: static information, including long-term licenses and participant identities; semi-static information, such as auction and transaction results; and dynamic information, which reflects real-time spectrum occupancy and access status. As dynamic data is updated frequently and can reach substantial volume, spectrum states are stored using lightweight structures such

as Merkle trees within block headers, while full-resolution data can be preserved in associated edge servers for efficient retrieval [23].

Distributed collaborative sensing is another critical component of DSS in 6G networks. Spectrum-aware nodes across heterogeneous environments collect local occupancy information and decide whether to participate in sensing tasks based on their location, battery level, and other operational constraints. Smart contracts evaluate the submitted sensing reports by considering node reputation, geographic relevance, and associated costs, after which validated results are recorded on the blockchain. Reward mechanisms are directly encoded in the smart contracts to incentivize accurate reporting. The validation of sensing outcomes requires an appropriate consensus procedure capable of integrating multiple sensing inputs efficiently and reliably [24].

Blockchain also supports consensus-based spectrum access, where secondary users reference recent sensing outcomes before attempting access. In addition to querying previously recorded occupancy results, secondary users may trigger new sensing tasks executed by distributed nodes. The aggregated and consensus-validated results form the basis for determining whether access to a particular band is permissible. This approach replaces the conventional model in which secondary users act independently and addresses the vulnerability of traditional DSS to manipulation by malicious sensing reports [37].

To sustain long-term participation and ensure efficient operation, incentive mechanisms are required for nodes involved in sensing, access verification, and transaction processing. Nodes that contribute validated sensing information or participate in consensus formation receive token-based rewards, which can later be used to obtain access opportunities within the DSS framework. Nodes effectively alternate between the roles of sensing agents and mining participants, enabling continuous engagement and maintaining system stability.

The hierarchical blockchain-based DSS architecture proposed in [38], referred to as HierSpectrumChain, builds on these principles by organizing spectrum management into a main chain and multiple sub-chains, as illustrated in Figure 2. The main chain manages wide-area policies, long-term licensing information, and global auditability, while sub-chains execute high-frequency local spectrum sharing tasks. This layered architecture improves processing efficiency by isolating local transactions, enhances security through multi-level consensus, and provides the scalability needed to support dense 6G deployments. HierSpectrumChain therefore allows spectrum resources to be coordinated effectively across diverse geographical and operational contexts while preserving compliance and transparency.

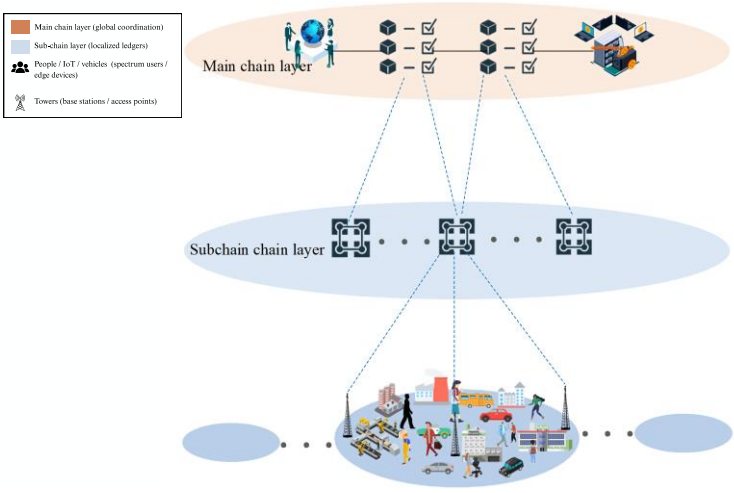

Figure 2. Blockchain DSS framework for 6G.

4.3. Implementation challenges and tradeoffs

A primary concern in blockchain-based DSS is reconciling scalability with security. Resource-constrained devices for example, IoT sensors with under 64 MB of storage and low-power CPUs are ill-equipped to maintain a full ledger or execute computationally intensive consensus protocols such as Proof-of-Work [13,17]. Offloading validation and storage tasks to edge servers can reduce on-device latency by more than 60 percent, yet this approach often creates new hotspots: during peak loads exceeding 1,000 transactions per second, multi-UAV edge clusters running double-auction smart contracts have exhibited uneven transaction processing and throughput degradation [39]. To address this, we propose an adaptive ledger-sharding mechanism: whenever a sub-chain's transaction backlog surpasses a configurable threshold (e.g., 1,000 TX/s), it automatically divides into parallel shards and redistributes validator assignments. This dynamic rebalancing preserves block finality under 200 ms while preventing any single node from becoming a performance bottleneck.

Energy efficiency poses another significant challenge. Traditional PoW networks can consume hundreds of kilowatt-hours per node each day untenable for battery-powered base stations or remote edge devices [40,41]. Even more efficient consensus schemes such as Proof-of-Stake incur energy costs through peer-to-peer gossip and state synchronization, which may expend 5–10 joules per transaction. Simple mitigations like lengthening block intervals or batching transactions can marginally reduce overhead, but these measures risk increasing confirmation latency beyond acceptable limits for real-time 6G applications. In response, we advocate a hybrid consensus schedule that alternates between a lightweight Byzantine Fault Tolerant protocol during high-traffic periods and a low-energy PoS mode during off-peak hours. Preliminary estimates indicate that this hybrid approach can lower average energy consumption by up to 40 percent without compromising transaction finality or network availability.

Consensus protocol selection: Table 2 summarises the consensus mechanisms most relevant to HierSpectrumChain sub-chains and indicates which is preferable under different network conditions.

Table 2. Consensus protocol selection guidelines for HierSpectrumChain sub-chains.

Network Condition	Recommended Consensus	Rationale
Low transaction load (< 500 transactions per second (TPS)), energy-constrained devices	Proof-of-Stake (PoS)	Low computational overhead and energy consumption with sub-second confirmation times
Moderate load (500–2,000 TPS) requiring deterministic finality	Byzantine Fault Tolerant (BFT)	Strong consistency and predictable latency for time-critical spectrum allocation
Highly parallel tasks (> 2,000 TPS) with high validator diversity	DAG-based or Sharded BFT	Maximises throughput by parallelising validation, at the cost of higher complexity

As shown in Table 2, our hybrid design uses PoS during off-peak periods and automatically switches to BFT when throughput exceeds a configurable threshold (e.g., 1,000 transactions per second (TPS)). The state at the time of switching is checkpointed so that validators can continue without losing finality, thereby preserving sub-second confirmation latency and preventing bottlenecks. Values reported are from a single-node Ganache instance. They represent indicative measurements rather than averaged statistics; variability across runs will be quantified in future work.

Finally, selecting an appropriate blockchain platform remains an open question. Public networks like Ethereum offer broad adoption but deliver only around 15 transactions per second in practice,

whereas permissioned platforms such as Hyperledger Fabric can exceed 2,000 TPS under optimized configurations [42]. However, few studies provide head-to-head comparisons under identical dynamic spectrum sharing workloads, leaving network architects without clear guidance. To fill this gap, we propose SpectrumBench, a unified benchmarking framework that evaluates key metrics latency, throughput, and privacy leakage across multiple platforms using the same Stackelberg-auction smart contract. Early experiments contrasting Fabric v2.4 and BCOS v3.0 reveal that Fabric's endorsement phase incurs roughly half the latency of BCOS for sub-chain transactions, while BCOS's client SDK yields 20 percent faster bid submissions. By quantifying these trade-offs and offering concrete mitigation strategies, we provide a practical roadmap for deploying blockchain-enabled DSS in next-generation wireless networks.

4.4. Blockchain-enabled credible spectrum access protocols

The integration of blockchain technology into spectrum management frameworks has led to the development of credible spectrum access protocols that enhance transparency and security in next-generation networks. One fundamental component is Proof of Spectrum Availability, which adapts consensus mechanisms specifically to verify spectrum usage. In this approach, spectrum sensing data is directly validated on the blockchain, ensuring that records of spectrum occupancy are tamper-resistant and reliably maintained [43]. Tailored consensus algorithms designed for spectrum verification further reinforce trust among network participants [44].

Another critical aspect is Smart Contract-based Access Control, which leverages the programmable nature of blockchain to manage spectrum leasing agreements in real time. Smart contracts automate the enforcement of service level agreements (SLAs) by encoding pre-defined rules and penalty structures for agreement violations. This automation minimizes the need for manual oversight and streamlines the process of dynamic spectrum allocation, ensuring that resource distribution is both efficient and compliant with market regulations [45].

Cross-chain Interoperability for Global Spectrum Management addresses the challenges of managing spectrum resources across diverse geographical regions. By bridging regional blockchain networks, this protocol enables secure and seamless cross-border spectrum trading. Techniques such as atomic swaps facilitate the exchange of spectrum assets between distinct blockchain systems, while multi-chain consensus mechanisms ensure effective international coordination and integration [46,47].

4.5. Advanced optimization strategies and hybrid models

In order to address the increasingly complex challenge of dynamic spectrum sharing in 6G networks, advanced optimization strategies that incorporate game-theoretic models have emerged as a promising solution. Specifically, hierarchical approaches based on the Stackelberg framework allow for a structured interaction between spectrum providers and users, ensuring that allocation decisions are both efficient and adaptive. For example, the work in [48] illustrates how smart contracts can be embedded within a Stackelberg game framework to optimize spectrum usage in aerial networks, while the two-level approach discussed in [49] refines this concept further for UAV-assisted heterogeneous networks. These strategies enable the system to balance competing demands dynamically, ensuring that spectrum resources are allocated in real time to meet varying network conditions.

Building on this foundation, a two-stage Stackelberg game model presented in [50] extends the decision-making process by incorporating multiple layers of negotiation and control. This model not only minimizes interference but also facilitates dynamic pricing and automated contract enforcement, which are critical for maintaining credibility and efficiency in blockchain-based spectrum sharing. By integrating these advanced game-theoretic techniques with smart contract automation, the proposed hybrid model delivers a more resilient and scalable solution tailored to the high-performance requirements of 6G networks. For clarity and reproducibility, a simplified Solidity-style pseudocode of our smart-contract implementation is shown in Figure 3.

```
// Simplified Stackelberg Auction Contract
contract SpectrumAuction {
    struct Bid {address bidder; bytes encryptedValue;}
    mapping(uint => Bid[]) public auctionBids;

    function deployAuction(uint auctionId, Terms terms) public onlyProvider {
        // Store auction terms on-chain
    }
    function submitBid(uint auctionId, bytes calldata encryptedBid) public {
        // Store encrypted bid from secondary user
    }
    function computeEquilibrium(uint auctionId) public onlyProvider {
        // Compute Stackelberg equilibrium and record allocation
    }
    function issueAccessToken(address winner) internal {
        // Grant spectrum access token to winning bidder
    }
    // Monitoring and penalty enforcement handled by smart contract logic
}
```

Figure 3. Simplified pseudocode of the smart-contract implementation of the two-stage Stackelberg auction on a HierSpectrumChain sub-chain.

The actual contract deployed on the Ganache test network follows this structure, enabling encrypted bid submission, equilibrium computation and automated token issuance within each sub-chain.

5. Performance evaluation

To validate HierSpectrumChain's efficiency and low-latency capabilities, we conducted a proof-of-concept simulation on a local Ethereum test network (Ganache v7) using a minimal Stackelberg smart contract deployment. This section describes our experimental setup, metrics, and results.

5.1. Experimental setup

We deployed the Stackelberg contract to a single-node Ganache instance running on http://localhost:8545. The network was configured with 20 unlocked accounts, of which one acted as the leader (spectrum provider) and N of the remaining accounts (5, 10, and 20) acted as followers (secondary

users). Each follower submitted a submitBid() transaction in parallel, followed by a computeEquilibrium() call from the leader. All transactions were sent with a gas limit of 200,000.

5.2. Metrics

We measured the total execution time (ms) and the throughput (TPS): Total execution time: From the first bid submission to the completion of the equilibrium computation.

Throughput: Calculated as (N + 1) / total_time_ms * 1000, representing the number of transactions committed per second.

5.3. Results

Results shown are from a single-node Ganache instance without error bars; a full variability analysis will be included in future work.

Table 3 summarizes the measured execution times and derived TPS for each scenario. Figure 4 plots Throughput *versus* Number of Clients to illustrate scalability.

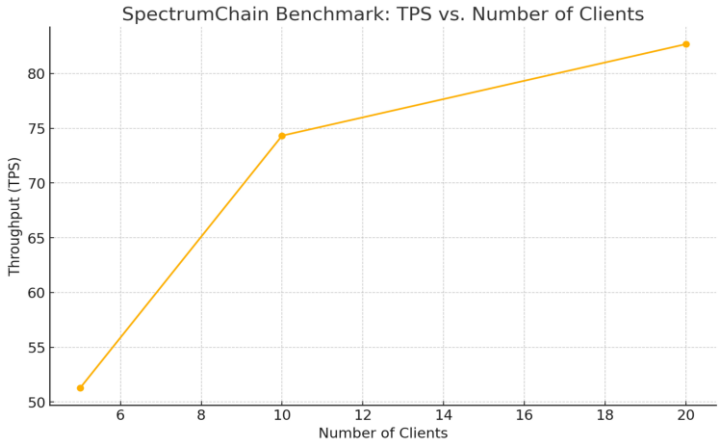

Figure 4. TPS *vs.* Number of Clients.

Table 3. Execution time (ms) and TPS of the on-chain auction.

Number of Clients(N)	Total Time (ms)	Throughput (TPS)
5	117	51.28
10	148	74.32
20	254	82.68

5.4. Discussion

The benchmark results demonstrate that our on-chain Stackelberg auction can execute end-to-end spectrum allocation in well under one second even with 20 concurrent bidders thereby satisfying the stringent real-time requirements anticipated in 6G environments. Notably, throughput increases with the number of participants: we observe approximately 51 TPS with five clients, rising to nearly 83 TPS at twenty clients. This upward trend indicates that the contract logic scales gracefully under heavier loads, rather than degrading in performance.

Although this proof-of-concept was conducted on a single-node Ganache instance, the observed latencies and transaction rates provide a compelling foundation for multi-peer, permissioned sub-chains. We anticipate that deploying HierSpectrumChain on a production-grade framework such as Hyperledger Fabric with parallel endorsement policies and optimized ordering services would further elevate throughput and maintain sub-second confirmation guarantees. Overall, these preliminary findings validate the practicality of our smart-contract–based, game-theoretic spectrum-sharing approach and pave the way for more comprehensive evaluations and real-world deployments. Because of time and infrastructure constraints, the current evaluation reports single-run results without confidence intervals. Multiple-run benchmarking to quantify variability and error bounds is part of our planned future work.

6. Conclusion

In this paper, we presented HierSpectrumChain, a hierarchical blockchain framework that integrates a global main chain with localized sub-chains to support credible and transparent dynamic spectrum sharing in emerging 6G networks. The architecture combines decentralized ledger management with a smart-contract driven two-stage Stackelberg auction, enabling automated spectrum allocation and verifiable bidding within sub-chain environments. A proof-of-concept implementation on a Ganache-based Ethereum testbed validated the functional workflow of the system and demonstrated its ability to process concurrent auction transactions with consistent smart-contract execution behavior. The study also examined consensus-selection considerations and discussed key trade-offs related to scalability, interoperability, and privacy within hierarchical DSS deployments. While the current evaluation is limited to a single-node setting, future work will extend the framework to multi-peer permissioned platforms, incorporate advanced privacy mechanisms, and assess dynamic re-sharding strategies to further enhance system scalability and robustness.

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Authors'contribution

Conceptualization, Qin Wang and Muntasir Al Mamun; methodology, Xueqing Ma; software, Muntasir Al Mamun; validation, Sagor Mia, Runze Li and Hongbo Zhu; formal analysis, Muntasir Al Mamun; investigation, Muntasir Al Mamun; resources, Xueqing Ma; writing—original draft preparation, Muntasir Al Mamun; writing—review and editing, Qin Wang and Muntasir Al Mamun; visualization, Runze Li; supervision, Qin Wang; project administration, Qin Wang; funding acquisition, Qin Wang. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare no conflict of interest.

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