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RESEARCH ARTICLE

BSM-6G: Blockchain-Based Dynamic Spectrum Management for 6G Networks: Addressing Interoperability and Scalability

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ABSTRACT The radio frequency spectrum serves as a fundamental resource for wireless communication, encompassing various frequency bands allocated for diverse services and applications. Dynamic spectrum management (DSM) is essential to optimise the utilisation of this limited and valuable natural resource, with the aim of improving performance and adapting to changing wireless communication demands. Traditional static spectrum allocation methods have shown inefficiencies, leading to spectrum scarcity and under-utilisation. To address these challenges, the integration of blockchain and Cognitive Radio (CR) technologies has emerged as a promising approach. Blockchain, with its decentralised and secure attributes, can improve transparency and trust in spectrum allocation processes, while CR enables intelligent spectrum sensing and allocation to maximise utilisation. However, this promising approach comes with its own critical challenges, especially when dealing with the 6th Generation (6G) mobile communication. These challenges are related to the fact that the blockchain ecosystem needs to be interoperable and scalable enough to be compatible with the 6G high-demand and substantial resources. Specifically, integrating blockchain with CR requires efficient interoperability techniques where blockchain can easily and effectively interact with the CR platforms as well as radio spectrum environments. Furthermore, the spectrum management system over 6G networks needs to be designed in a way where massive 6G resources can be accommodated and managed without having any service performance degradation. This paper introduces a novel radio spectrum management model in 6G networks, named as BSM-6G, which integrates blockchain technology with CR where interoperability is preserved and scalability is maximised. Specifically, the proposed BSM-6G model merges blockchain's transparent record keeping with CR's intelligent spectrum management capabilities. To overcome the interoperability issue, BSM-6G provides an interoperable blockchain Oracle approach which facilitates the real-time interaction among the blockchain platform, the CR, and any data sources off-chain. This paper details all the technical and procedural challenges when implementing the proposed interoperability Oracle approach. To address the scalability challenge, BSM-6G utilizes the Proof-of-History (PoH) consensus protocol to align with the requirements of DSM in advanced networks like Beyond 5th Generation (B5G) and 6G. Evaluation results indicate that BSM-6G offers viable and less complex blockchain Oracle integration architecture measured by the technical implementation of BSM-6G, as well as low interoperability cost measured by transaction response time and transaction fee cost. Compared to state-of-the-art spectrum-based blockchain systems, BSM-6G shows a high scalable DSM-based blockchain in 6G networks measured by transactions per second (TPS).

INDEX TERMS 6G mobile communication, blockchains, cognitive radio, interoperability, radio spectrum management, scalability.

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I. INTRODUCTION

The radio frequency spectrum encompasses the range of electromagnetic frequencies used for wireless communication and includes various frequency bands allocated for different services and applications [1]. The process of controlling and managing the use of the radio frequency spectrum is known as Spectrum Management, which is a limited and valuable natural resource [1]. Within the spectrum landscape, there are two primary categories: licensed and unlicensed bands [1], [2]. Licensed bands are allocated to specific Primary Users (PU)s, such as broadcasters, government agencies, and cellular and Citizens Broadband Radio Service (CBRS) operators networks [1], [3], [4]. These PUs have exclusive rights to operate within their assigned frequency ranges. On the other hand, unlicensed bands are open for use by Secondary Users (SU)s, who can leverage these frequencies for innovative applications and experimentation [1].

Dynamic Spectrum Management (DSM) has introduced to address the traditional static spectrum allocation methods which have proven to be inefficient, leading to spectrum scarcity and underutilization [1]. DSM refers to the techniques and strategies employed to dynamically allocate radio frequencies based on real-time demand and availability [5]. The goal of DSM is to enhance spectrum utilization, optimize performance, and accommodate diverse wireless communication services and applications [1], [5].

Cognitive Radio (CR) have emerged as a promising approach to enhance the radio spectrum sensing in DSM [1], [6]. CR is an intelligent wireless communication technology that enables devices to sense their environment, learn from it, and autonomously make decisions about spectrum utilization [7]. By leveraging CR, DSM aims to maximize spectrum utilization by allowing SUs to opportunistically access underutilized frequency bands while ensuring minimal interference to PUs in the landscape of 6G networks [4]. Blockchain offers several capabilities such as immutability, transparency, security, smart contracts, interoperability, and cost efficiency makes blockchain technology well-suited for adoption across multiple life sectors, offering innovative solutions to address various challenges and opportunities [8], [9], [10]. Due to blockchain technology capabilities, many DSM systems-based blockchain have been introduced to support the automation, transparency, trust, and accountability in spectrum allocation processes within the dynamic Beyond 5th Generation (B5G) and future 6th Generation (6G) networks [4], [11]. Recently, the integration of blockchain and CR have emerged as a promising approach where blockchain offers a trusted and transparent record for CR's intelligent spectrum sensing data [1], [6]. This integration improves the DSM performance as CR sensing data will be easily accessed and accurately retrieved to the blockchain using Oracles in blockchain-based process.

In this paper, we address the following problem. How can blockchain characteristics be combined with the existing intelligent spectrum techniques of CR in a way that offers both cost-effective interoperability and scalability within the framework of 6G networks? We hypothesize that a solution addressing this problem statement should consist of 1) a conceptual radio spectrum management framework which is based on blockchain and CR; 2) the use of novel mechanisms as part of this framework to enable the interoperability Oracle with blockchain and CR. The Oracle will enable the connection between the blockchain and the 6G radio spectrum sensing data maintained by CR, which needs to be interoperable with the blockchain platform that enables automated, trusted, and accurate decisions on the sensing data; and, finally, 3) the use of Proof-of-History (PoH) consensus mechanism within the blockchain model as a scalability strategy which contributes towards faster automated radio spectrum decisions in 6G networks. This paper introduces a novel radio spectrum management framework which incorporates blockchain and CR into 6G DSM systems. To the best of our knowledge, this is the first work in the context of DSM in 6G networks that focuses on designing a cost-effective and less complex interoperability technique using Oracle which facilitates the interaction between blockchain and CR.

II. MOTIVATION

Despite the promising potential of DSM using blockchain and CR, two primary challenges stand out: interoperability and scalability. As the number of connected devices and wireless services continues to increase in the context of future 6G networks [4], [11], developing scalable DSM systems capable of handling numerous users and real-time spectrum transactions with the ability to exchange data between different entities remains a significant challenge. On the other hand, applying a DSM model which employs blockchain technology and CR to enhance the management of the radio spectrum assets in 6G networks requires a proper framework that facilitates the interoperability among blockchain, CR, and spectrum assets in 6G networks. To ensure scalability and performance in 6G spectrum management, many previous DSM-based blockchain methods were designed in a way where blockchain integration with external platforms and services is facilitated with the goal of reducing the overhead caused by significant spectrum resources [12], [13]. This integration is achieved in various ways, including smart contracts and consensus protocols. However, these integration methods do not consider an interoperability framework which enables fast and uninterrupted spectrum service, as well as to facilitate seamless cooperation and coexistence between PUs and SUs. This requires blockchain protocols that can connect to external data, ensuring minimal interference to PUs while maximizing spectrum access for SUs, enabling effective spectrum sharing and utilization. Overcoming these challenges will be crucial to realizing the widespread implementation of DSM using blockchain and CR, ultimately, leading to more scalable and optimized spectrum utilization in wireless communication systems.

III. CONTRIBUTIONS

Aiming to mitigate the scalability and interoperability challenges in the context of DSM-based blockchain and CR in 6G networks, a novel DSM framework is introduced in this paper. Specifically, the DSM framework, named as BSM-6G, uses a new interoperability technique which allows the blockchain platform within BSM-6G to securely retrieve 6G radio spectrum assets using a blockchain Oracle. In addition, the interoperability technique ensures that the CR within BSM-6G enriches the radio spectrum sensing data which, on the other hand, contributes towards fast and accurate radio spectrum management decisions. BSM-6G aims to provide a cost-effective and less complex blockchain interoperability technique where all massive spectrum sensing data will be stored in an off-chain database. This means, the blockchain platform will exclusively be used for automated and fast decisions through making use of smart contracts.

To provide a scalable radio spectrum management system, PoH consensus mechanism [14] is employed as a mechanism to accommodate massive radio spectrum processes among numerous users in 6G networks. Specifically, BSM-6G employs PoH to boost the number of TPS, which leads to faster decisions on radio spectrum assets. This remarkable capacity aligns seamlessly with the data intensive demands of 6G networks, facilitating rapid and efficient decision-making in spectrum allocation.

We summarise our contributions as follows:

- We propose a dynamic radio spectrum management model, named as BSM-6G system, which preserves crucial spectrum management features: (i) Fast, accurate, and dynamic radio spectrum management in the context of 6G network through making use of an interoperability mechanism that facilitates the interaction between several platforms within BSM-6G which are blockchain, Oracles, and CR; and (ii) scalable radio spectrum management system where massive spectrum resources in the context of 6G networks can be managed without having any service performance degradation.
- We propose a comprehensive modular architecture for blockchain Oracles integration with the blockchain platform and the CR. The integration of Oracles aims to facilitate off-chain data interaction adds a crucial dimension to the DSM system. The system gains flexibility and real-world applicability by allowing secure retrieval and modification of off-chain data. This enables connections beyond the boundaries of the blockchain. Furthermore, this paper offers comprehensive technical insights into the implementation of the proposed integration of blockchain and Oracles.
- We provide an in-depth exploration of the PoH consensus protocol as a potential mechanism for high scalability, security, and low latency in BSM-6G. PoH is considered as an alternative mechanism to the previously investigated traditional consensus methods, aligning with the demanding real-time requirements of spectrum management in 6G networks.

Compared to existing work, the BSM-6G spectrum management system has several benefits, which we emphasize here: (i) it supports low-cost and less complex interoperability technique between DSM complex platforms; (ii) the system scalability and security is supported by a new blockchain design based on PoH consensus protocol; and (iii) the system is verifiable by all parties.

IV. PAPER ORGANIZATION

The structure of this paper is outlined as follows: Section V explores DSM techniques for enhanced spectrum utilization. Section VI reviews related works and highlights contributions to DSM in 6G networks using blockchain technology and CR. Section VII introduces the proposed system model, whereas Section VIII presents the system design, detailing the architecture's key components, including blockchain modules, CR modules, User Interface, and regulatory module interplay. Section IX covers radio spectrum allocation and sharing in the BSM-6G system, focusing on the interaction with the dApp module and various processes across system modules. Section X assesses Oracle interoperability by exploring Oracle's functionality and evaluating it through consensus mechanisms. Section XI addresses scalability evaluation by setting up a blockchain network, and quantifying transaction processing capabilities. Section XII focuses on the evaluation of spectrum resource utilization. Section XIII emphasizes the security evaluation aspect of the blockchain system for DSM, emphasizing its role as an immutable and open ledger for spectrum transactions. Section XIV discusses research challenges and opportunities to inspire future methodologies for advancing DSM in wireless networks. Finally, Section XV summarizes research contributions, achievements, and the significance of the proposed blockchain-based DSM model.

V. BACKGROUND KNOWLEDGE

For many years, spectrum management followed traditional static approaches [1], [15]. In this conventional system, specific frequency bands were assigned to particular services and users for extended periods, resulting in limited flexibility [1]. The inherent inflexibility of static management approaches proved to be a major drawback. As technology advances and the demand for wireless services grew exponentially, the static allocation of spectrum became increasingly inefficient, scarce and hindered further development [15], [16].

A. DSM TECHNIQUES: ENHANCING SPECTRUM MANAGEMENT

DSM techniques encompass a range of approaches, some of them developed and used by CR, including spectrum sensing, spectrum sharing, and spectrum access policies [1], [17]. Spectrum sensing involves the detection and identification of available spectrum opportunities through techniques like energy detection, cyclostationary feature detection, or cooperative sensing [18]. Spectrum sharing techniques enable the simultaneous use of spectrum by multiple users or services, ensuring efficient coexistence and interference management [16]. Spectrum access policies define the rules and regulations for accessing and using spectrum resources, including considerations of interference management, quality of service, and fairness among users [17].

In the context of 6G networks, DSM plays a pivotal role in addressing the spectrum scarcity challenges and accommodating the diverse requirements of various wireless services [11], [19]. CR techniques are often employed in DSM, allowing intelligent spectrum sensing, decision-making, trading, and access [19]. By dynamically adapting to the changing radio environment, CR-enabled DSM optimizes spectrum utilization, minimizes interference, and enhances the quality of service for different users and applications [11], [20]. Looking ahead to 6G networks, DSM is expected to become even more critical due to the anticipated exponential growth in connected devices, data rates, and emerging applications [4]. DSM approaches will be essential in assuring effective spectrum allocation and access due to the anticipated ultra-high data rates, ultra-low latency, and widespread connection of 6G [4], [19].

B. SPECTRUM MANAGEMENT USING BLOCKCHAIN AND CR

One of the most important books that encompasses the topics of DSM, blockchain-based and CR-based DSM is the book titled "Dynamic Spectrum Management: From Cognitive Radio to blockchain and Artificial Intelligence" by [1]. This book is a systematic overview of the technologies used for DSM and focuses on the need for efficient spectrum utilization. It emphasizes the shortcomings of traditional static spectrum allocation and highlights the benefits of DSA. The author, Y.-C. Liang, discusses the concepts of the methods and theories to intelligently sense the spectrum, the techniques to allow different communication systems on the same frequency, called spectrum access, and discusses the importance of new technologies for DSM such as blockchain and Artificial Intelligence.

Addressing blockchain technology offers the potential for decentralized, reliable, resilient and secure spectrum management by providing a transparent and tamper resistant ledger for recording spectrum transactions and ensuring trust among users [1], [2]. On the other hand, CR can identify underutilized or unused spectrum bands and opportunistically access them without causing harmful interference to PUs, who have primary rights to use those bands [1], [21].

Through comprehensive research and analysis, [1] sheds light on the technologies for DSM. Y.-C. Liang mentions that DSM enables more effective and flexible use of the scarce radio frequency spectrum resources and ultimately supports the rising demand for wireless communication services, represents a paradigm shift in spectrum allocation and utilization. It provides valuable insights into the complexities of DSM and serves as a foundation for developing efficient and flexible approaches to spectrum utilization, which will serve as the basis for the system modelling.

C. REGULATORY LANDSCAPE FOR DSM USING BLOCKCHAIN

Furthermore, regulations play a crucial role in governing spectrum management practices in countries [2], [22], [23]. These regulations are designed to ensure efficient and fair utilization of the limited spectrum resources while also addressing various technical, economic, and policy considerations. Several countries and research organizations worldwide have undertaken projects to explore the potential of DSM using blockchain and CR. Some notable examples include:

In the United Kingdom, the Office of Communications (Ofcom) has undertaken research projects that delve into the fusion of blockchain and CR for DSM. Their efforts centre around ensuring equitable and efficient spectrum allocation [1], [24]. Likewise, within the European Union, there has been active support for diverse research initiatives and consortiums, including the 5G-EVE project. These efforts span multiple member states and aim to explore the potential of utilizing blockchain for DSM applications [25].

Alternatively, in the United States, the Federal Communications Commission (FCC) has taken proactive steps by initiating projects and establishing test beds. These endeavours are aimed at assessing the feasibility and efficacy of DSM techniques, particularly in enhancing spectrum utilization and addressing interference challenges [1], [2].

VI. RELATED WORK

This section presents a condensed overview of the relevant related works that form the foundation of the BSM-6G. The integration of blockchain and CR technologies within DSM are explored for their potential applications, focusing on emphasizing interoperability and scalability challenges.

A. CONVERGING TECHNOLOGIES IN DSM: BLOCKCHAIN AND CR

Firstly, [15] conducted a comprehensive survey on blockchain-based DSM in wireless networks, discussing its potential for decentralized spectrum sharing and allocation. The study suggests using blockchain for securely storing spectrum management data and utilizing smart contracts to establish secondary spectrum markets; this suggests a unified strategy whereby spectrum sensing methods and geolocation database technology may be utilized as additives to one another for a more reliable DSM framework for our BSM-6G model. Additionally, [16] presented a techno-economic analysis of spectrum sharing using blockchain and smart contracts, proposing a model for swapping access rights within a well-known band and estimating usage costs, which transaction fees will be a basis of comparison for the costs associated with our system. Furthermore, [26] introduced a multi-blockchain scheme for Dynamic Spectrum Sharing (DSS) in the Citizens Broadband Radio Service (CBRS) system, addressing scalability and interference issues through a multi-blockchain architecture and cross-chain mechanism that help to address the issues for our BSM-6G model.

It is also necessary to discuss smart contracts in the DSM framework, which offer automated interactions in spectrum markets. [23] investigated smart contracts for dynamic spectrum marketplaces, proposing an approach for automated spectrum transactions and marketplaces. Furthermore, [27] proposed a smart contract-based approach for distributed spectrum sensing, using a reputation-based incentive mechanism to improve spectrum sensing involvement. Both papers on smart contracts present important characteristics such as blockchain networks, programming languages, and model flow, for the creation of an intelligent system with secure and dynamic blockchain-user access for future 6G wireless networks.

Additionally, within Distributed Ledger Technologies (DLT), there are consensus mechanisms to ensure blockchain validity. Reference [28] developed an interference-based consensus mechanism for DSM, promoting spectrum sharing and efficient transactions, by using this approach, detrimental interference brought on by spectrum merchants can be avoided. Moreover, [29] explored the Practical Byzantine Fault Tolerance (PBFT) consensus protocol for high-frequency spectrum management in IoT systems, addressing scalability and non-cooperative competition issues. Additionally, [30] proposed a Proof-of-Trust (PoT) consensus mechanism for DSM in IoT networks, enhancing cooperative sensing and trustworthiness [30]. These consensus mechanisms will facilitate a direct comparison with our BSM-6G model.

A DSS using Hyperledger Fabric (HLF) was implemented by [31], enabling cross-user trading of spectrum access rights. Reference [32] proposed a blockchain verification protocol for secure spectrum sharing in moving Cognitive Radio Networks (CRNs). Furthermore, [18] developed a blockchain-based security enhancement and spectrum sensing method for CRNs. The integration of DSS, spectrum access tokenization, along with CR sensing and sharing protocols, underscores its significance for the future of spectrum trading and management.

When examining the spectrum management dynamics in the blockchain-based DSM framework, it is essential to take into account the methods and procedures that PUs and SUs employ to establish transaction fees for the use of spectrum. The market appeal and financial sustainability of spectrum trading are significantly influenced by these costs. In order to address this feature, our study explores a variety of models and methods, referencing important studies in the area.

An ideal non-cooperative game theory approach to spectrum management was developed by [33], in which the major user or service provider sets the dynamic pricing for each channel. Through the implementation of a bid-price system, secondary users will be able to request spectrum access based on their ability to pay; the highest bidders will be given preference for channel access.

Reference [34] went into further detail about spectrum pricing approaches and stressed the significance of taking market and economic variables into account in addition to technology aspects when setting prices for spectrum. They put up a number of guidelines for spectrum pricing, including distributing spectrum according to its best value, encouraging adaptability in utilisation, and guaranteeing pricing equity.

Last but not least, [35] provided a thorough analysis of pricing and economic models for resource management, especially as they relate to 5G networks. Their classification of economic models for user association, spectrum allocation, and other resource management problems helped us better grasp how the BSM-6G framework's possible pricing mechanisms would work.

We explored various pricing models, including auction-based, fixed, and dynamic pricing, and assess their impact on the economic dynamics within DSM. This holistic approach ensures that the model not only addresses the market demands but also aligns with regulatory standards, ensuring viability and compliance across different market scenarios.

B. B5G AND 6G: ADVANCING WITH DSM

The role of blockchain in 6G spectrum resource sharing and allocation has been discussed and highlighted, has attracted several recent research studies. In [36], the integration of blockchain and 6G network spectrum sharing and resource management is analysed and discussed in details, as well as future research directions were provided. Furthermore, [4] reviewed blockchain-enabled DSA and network slicing for B5G and 6G, addressing challenges and trade-offs such as ultra-high data rates, ultra-low latency, and widespread connection of 6G. Moreover, [20] surveyed blockchain integration with 5G networks, highlighting challenges and opportunities for blockchain technology. Additionally, [19] explored blockchain's role in addressing challenges of 6G networks and identifying application opportunities like virtual reality, holographic communications, and massive machine type communications. These studies collectively establish a robust foundation for a resilient, adaptable, and forward-looking DSM framework.

In the context of 6G spectrum management using blockchain, several models and techniques have been proposed with the aim of providing dynamic and secure spectrum sharing and allocation. A blockchain-based spectrum allocation scheme for 6G communications was proposed by [3], which employs blockchain to enhance trust among spectrum operators within 6G networks. Specifically, the proposed model gathers telecom operators, bidders, and government regulates in a blockchain platform in which smart contract are run among them as auctioneers. Given the 6G substantial resources and demand, there is a serious concern arises in relation to the scalability of this proposed model. On the other hand, a new dynamic 6G spectrum management model is proposed in [12] which integrates blockchain and hybrid cloud services with the goal of building a public engagement platform for IoT devices registration and management. This model employs reinforcement learning for spectrum sharing and management, including resource scheduling and classification. Similarly, a hybrid blockchain is utilised in DSM in 6G, where spectrum resources of Ubiquitous IoT (UIoT) devices can be subdivided into multiple dimensions with the goal of enabling random and reliable access to massive UIoT data [13]. Moreover, a DSM based multi-layer blockchain architecture is proposed in [37] where IoT distributed devices can engage with distributed local blockchains, aiming to overcome the scalability challenge. However, blockchain integration with IoT external platforms and services requires an efficient and well-designed interoperability technique which facilitates cost-effective and scalable integration.

Other studies have taken an alternative approach, focusing on smart contract and consensus protocols to enhance the performance and security of DSM. Reference [38] proposed a blockchain-based framework for decentralized network management in 6G mobile networks, including three types of smart contracts are introduced. These smart contracts aim to facilitate dynamic Mobile Network Operators (MNOs) for end users. In the same context, a new consensus protocol, named as proof-of-strategy, is proposed in [39] which is integrated with the spectrum allocation process. According to the proof-of-strategy consensus protocol, each node needs to figure out the optimal strategy in an existing strategy group with the goal of protecting the system in case of single point of failure. However, these models add an extra overhead on blockchain platform where massive 6G spectrum resources which are used for the dynamic selection and allocation are stored on the blockchain.

In summary, there have been several previous attempts to address scalability, security, and performance challenges of DSM using blockchain technology in 6G networks. These attempts considered either integrating blockchain with 6G external platforms and services to enhance scalability and trust, or designing new consensus protocols and smart contracts to improve DSM performance and security. However, these attempts have not considered a cost-effective interoperability technique when integrating blockchain with external spectrum services. Furthermore, the Proof of History (PoH) consensus protocol has not been considered as a mechanism to overcome the scalability issue and enhance overall DSM performance. Therefore, it is evident that there is a room for improvement in the area of DSM-based blockchain in 6G networks. Table 1 presents a compilation of the related works that explore and propose models of DSM within the context of B5G, and 6G networks.

VII. BLOCKCHAIN-BASED DSM FOR 6G NETWORKS (BSM-6G)

Expanding on the thorough examination offered in the previous section, it is clear that there are serious issues with the combination of blockchain technology and 6G DSM, especially regarding scalability and interoperability. To satisfy the increased capacity demands of 6G resources, the dynamic spectrum-based blockchain that is envisioned for 6G requires efficient and rapid processes for blockchain transaction verification and block formation. In addition, a simpler and more affordable interoperability strategy is desperately needed to enable smooth communication between the spectrum blockchain, 6G network resources, and cognitive sensing data.

Our study presents a novel Blockchain-based DSM model called BSM-6G that is optimised for 6G networks, addressing these issues head-on. By highlighting the contributions of numerous academics in the industry and introducing a revolutionary Oracle interoperability design that is carefully engineered to enable effective integration between CR and the blockchain platform, the BSM-6G model expands on recent advancements in blockchain technology. This interface allows 6G cognitive sensing data to be integrated onto the blockchain platform, going beyond traditional paradigms.

Moreover, the Proof of History (PoH) consensus process, an advanced technique intended to improve the blockchain platform's scalability, is incorporated into the BSM-6G architecture. By using PoH, transactions are validated at the best possible latency times, which promotes equitable and effective spectrum sharing in the dynamic 6G environment. The BSM-6G model gains a critical layer from this novel consensus process, improving its ability to manage an increasing number of devices and services.

In essence, the BSM-6G model is a ground-breaking strategy that advances the capabilities of 6G spectrum management by introducing a symbiotic interaction between blockchain and CR technologies, in addition to addressing the recognised issues of scalability and interoperability. The combination of blockchain and CR technologies paves the way for an all-encompassing and cutting-edge solution made specifically to meet the demands of 6G networks.

A. MODEL OVERVIEW

The BSM-6G system has the following main components, as pictured in Figure 1: Cognitive Radio, Blockchain module, Regulators module, and dApp. The details of how these components work are deferred until Section VIII.

- **Cognitive Radio (CR) module**: The CR module is responsible for collecting the radio spectrum status from the 6G networks and making them available in databases.
- **Blockchain module**: an interoperability mechanism (IM) is maintained in this module to allow interaction and spectrum data exchange between Oracles and the blockchain platform. More explanations on how the IM works and the spectrum decision-making in blockchain platform are deferred to Section VIII
- **Regulator module**: This component is responsible for radio spectrum regulations in relation to radio spectrum usage and sharing. This module has a direct contact with the CR, where radio spectrum availability is finalised based on the regulation and compliance data.

TABLE 1. Motivating the need for BSM-6G by comparing the contributions, strengths, and weaknesses of existing DSM systems under the headings: 6 Generation (6G), Beyond 5 Generation (B5G), Cognitive Radio (CR), Blockchain (B), Smart Contracts (SC), Consensus Mechanisms (CM) and Oracle (O).

	Contributions for DSM								
Author	6G	B5G	CR	B	SC	CM	O	Strengths	Weaknesses
[3]	✓	X	X	✓	X	X	X	Proposes a scheme that can guarantee transparent stakeholder communication and safe and reliable band distribution among telecom providers.	The efficacy and viability of Block6Tel in real-world circumstances would require additional study and experimentation. Serious concerns arise regarding the scalability of this proposed model due to the massive 6G resources and operations that need to be completed on the blockchain.
[11]	X	X	X	✓	✓	✓	X	Addresses a research gap by examining how blockchain technology can promote better spectrum sharing.	Only provides a stylized model and a small-scale test scenario to demonstrate the proof of concept, which may limit the generalizability of the findings
[13]	X	X	✓	✓	X	X	X	Proposes a blockchain-based security enhancement and spectrum sensing method for managing the spectrum and identifying malicious users in cognitive radio networks (CRN).	It would be beneficial to have more information on the technical aspects and practical feasibility of the proposed model.
[18]	X	X	X	✓	✓	X	X	Proposes an alternative, technological and low overhead approach to spectrum allocation and markets, while imposing necessary requirements on transactions.	Does not address the potential concerns related to the decentralized versions running on blockchains, such as scalability, privacy, and regulatory issues.
[21]	✓	X	X	✓	✓	✓	X	Presents a centralized spectrum management solution for the citizens broadband radio service (CBRS) to overcome spectrum scarcity issues.	Does not provide different scenarios, tests, and the impact of user mobility in spectrum trading.
[22]	✓	X	X	✓	✓	X	X	Proposes a smart contract-based distributed spectrum sensing scheme for spectrum sharing. It leverages the interaction between spectrum sensing and incentive mechanism for users.	Does not provide detailed information on how the proposed scheme addresses the issues of accuracy and participation in spectrum sensing.
[23]	✓	X	X	✓	✓	✓	X	Highlights the advantages of using blockchain in spectrum management, such as decentralization and tamper-resistance, which can address the security risks and low allocation efficiency of traditional centralized systems.	The proposed model does not provide real-world scenarios to support the proposed blockchain-based spectrum management architecture.
[24]	✓	X	X	✓	X	✓	X	Introduces the use of a multilayer PBFT consensus protocol to address the scalability problem during the consensus process.	Does not discuss potential challenges or limitations of implementing the proposed system in real-world scenarios.
[25]	X	X	X	✓	✓	✓	X	Proposes a model for dynamic spectrum access (DSA) in IoT networks, which addresses the challenges of trustworthiness of sensing nodes' spectrum sensing results and privacy protection of sensing nodes' identities.	Does not provide detailed information on how the proposed Proof-of-Trust (PoT) consensus mechanism ensures scalability and high transaction-per-second (TPS) in the blockchain.
[26]	X	X	X	✓	✓	✓	X	A unique model for spectrum sharing using HLF blockchain was proposed and confirms that blockchain technology has the potential to solve issues of trust, security, transparency, traceability, and scalability for truly DSS.	Do not discuss alternative solutions or approaches to address the spectrum scarcity and under-utilization problem.
[27]	X	X	✓	✓	X	X	X	Addresses the need for a secure and efficient medium-access protocol for accessing wireless bandwidth among competing CRs.	Does not provide detailed information on the implementation and evaluation of the proposed blockchain verification protocol.
[29]	✓	X	✓	✓	X	X	X	Examines the spectrum sharing process and proposes a reinforcement learning (RL) based radio spectrum resource sharing framework for eURLLC.	Does not provide an evaluation to support the blockchain-based hybrid cloud architecture model. There is no well-designed interoperability technique that facilitates the integration of blockchain with external IoT platforms and services.
[30]	✓	X	X	✓	✓	✓	X	Proposes a model that protects the confidentiality and security of contracts while offering tamper-proof features and the efficiency of a private blockchain.	Does not provide an evaluation to support the efficiency of the hybrid blockchain technology model. There is no well-designed interoperability technique that facilitates the integration of blockchain with external IoT platforms and services.
[31]	✓	✓	X	✓	✓	✓	X	Proposes a promising Dynamic Resource Sharing model using Blockchain and AI, introducing a two-tier hierarchical structure to improve scalability.	Does not provide detailed information on the implementation of the proposed model. There is no well-designed interoperability technique that facilitates the integration of blockchain with external IoT platforms and services.
[32]	✓	X	X	✓	✓	✓	X	Proposes a novel direction for blockchain integration into the mobile network infrastructure, which can potentially bring benefits in terms of spectrum and infrastructure sharing.	Does not provide specific details or examples of how the proposed architecture would work in practice. Scalability issue as it adds additional overhead on the blockchain platform where massive 6G spectrum resources used for dynamic selection and allocation are stored on the blockchain.
[33]	✓	X	X	✓	✓	✓	X	Proposes a model to reduce administrative expenses of dynamic access systems, providing the new consensus method, proof-of-strategy, which is designed to combine with the process of spectrum allocation.	Further research, experimentation, and the use of blockchain tools would be necessary to determine the model's effectiveness in real-world scenarios. Scalability issue as it adds additional overhead on the blockchain platform where massive 6G spectrum resources used for dynamic selection and allocation are stored on the blockchain.

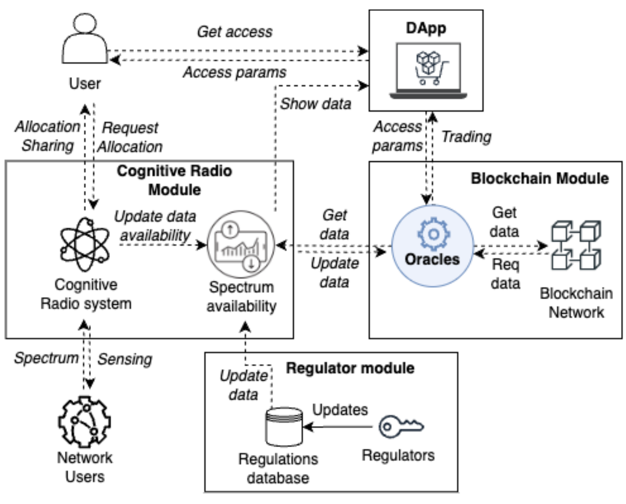

FIGURE 1. BSM-6G model.

- **End user interaction layer**: This layer is a Decentralized Application (dApp). The dApp has a direct interaction with the blockchain and CR modules, with the goal of allowing SUs and PUs to securely access and share the available radio spectrum.

In order to make sense of the process of sharing spectrum resources between PUs and SUs, certain standards and protocols must be established. This includes setting up an open pricing system that is dependent on the availability of spectrum and the state of the market. The price structure may be fixed or dynamic. Moreover, it is imperative to provide a comprehensive explanation of all transaction processes, such as bidding, negotiation, and finalisation of spectrum allocation. The dApp should automate these processes to guarantee effectiveness and compliance with legal requirements. Through the provision of an intuitive interface, the dApp plays a crucial role in enabling PUs and SUs to publish, bid, negotiate, and complete spectrum resource transactions in a transparent and controlled manner. By incorporating these detailed steps within the dApp, the BSM-6G model ensures a clear and structured approach to spectrum resource exchange, maintaining the integrity and efficiency of the DSM system.

VIII. SYSTEM DESIGN

The following subsections explain each phase of the BSM-6G protocol more in depth.

A. COGNITIVE RADIO (CR)

The CR module is a crucial part of the DSM system for 6G networks. By offering capabilities for intelligent decision-making, spectrum sensing, and allocation, this module is essential for maximizing spectrum efficiency and adaptability. The CR gives the system the ability to allocate spectrum intelligently and dynamically because of its innovative approaches like real-time spectrum detection and Artificial Intelligence (AI) based algorithms. The CR module provides efficient spectrum usage and improves overall network performance in the complex and varied 6G radio environment.

Advanced spectrum sensing methods, energy detection, sequential energy detection, cyclostationary detection, and cooperative sensing, are available in the CR Module. This module is inspired by the CR module presented in [21]. It continuously scans various frequency bands for signals while monitoring the radio environment. The CR learns about the status of spectrum band availability and occupancies using real-time spectrum sensing. It can identify transient changes brought on by DSS arrangements and can detect variations in spectrum availability caused by the presence or absence of PUs. Additionally, the CR module uses machine learning and AI algorithms to make wise spectrum allocation choices. The CR can identify patterns, trends, and correlations in spectrum occupancy, interference, and user behaviour by examining historical and real-time spectrum sensing data.

Furthermore, the CR follows rules and procedures to reduce interference with other wireless devices and PUs of the spectrum. The CR may cooperate with other devices to maximize spectrum use while avoiding contention thanks to cooperative spectrum sharing techniques as [40] described in the paper. DSA enables the CR to flexibly access unused frequency bands without interfering with the activities of its PUs. Lastly, the CR module's AI and Machine Learning algorithms assist in locating and reducing interference with PUs' CRs and SUs' CRs. To maximize spectrum consumption, the module separates hazardous interference from regular radio signals and works cooperatively with other equipment.

B. BLOCKCHAIN MODULE

The proposed system's Blockchain module is a key component in enabling scalable, safe, open, and decentralized spectrum management for 6G networks. The consensus mechanism and the Oracles make up its two primary parts, each of which enhances the system's scalability, interoperability, and security.

Regarding the consensus mechanism, it is a crucial feature of the Blockchain module that secures network participants' agreement on the truthfulness of transactions and the status of the blockchain ledger. The proposed model prominently integrates PoH mechanism as a foundational element within its framework. The innovative PoH consensus mechanism was designed and developed by Anatoly Yakovenko, the founder of Solana Labs [41]. Within the context of BSM-6G, validators play a crucial role in ensuring the integrity and accuracy of the blockchain. Validators are entities selected based on their staked tokens, and they are responsible for transaction processing and block validation. Their active participation is fundamental to the functioning of the PoH mechanism. In BSM-6G, validators are typically organizations or nodes that hold a stake in the network, usually in the form of tokens specific to the blockchain platform being used (such as SOL tokens in the case of Solana) [41]. These validators are incentivized to perform effectively through the prospect of earning rewards for high performance and facing potential penalties for underperformance.

Block validation is achieved through PoH, which allows validators to verify the sequence of events and the passage of time without external timestamps. Validators follow a rigorous process to validate a block, which includes confirming the signature of a legitimate leader node and ensuring the validity of all transactions by respecting the rules of the protocol. Valid blocks are voted on by validators and, once a large majority of votes is reached, the block is confirmed and becomes part of the blockchain, where all contained transactions are executed seamlessly.

The PoH consensus mechanism, tailored for DSM, is meticulously designed to ensure precise event sequencing within the blockchain while obviating the necessity for external timestamps. Central to this mechanism is the Verifiable Delay Function (VDF), a cryptographic tool characterized by its time-intensive computation yet rapid validation capability [14]. In routine network operations, each node performs the VDF at intervals, resulting in a distinctive time-stamped hash. This hash, appended to the local blockchain copy along with the current time, represents the outcome of the VDF calculation. Validators play a critical role in the confirmation of valid blocks, and once a substantial majority of votes is secured, the block is confirmed and seamlessly integrated into the blockchain, triggering the execution of all contained transactions [14]. Through the consistent execution of the VDF on the previous block's hash and its comparison with the timestamp of the new block, nodes confidently establish the validity of the block, contributing to the robustness and reliability of our DSM blockchain system.

For the BSM-6G model, the objective is to establish a secure and reliable system, necessitating a diverse set of entities to act as validators. These entities encompass regulatory bodies, PUs, SUs, blockchain network nodes, and community nodes. The aspiration is to achieve a robust and decentralized system by encouraging an increased number of active participants. The broader the engagement of members, the higher the level of security and decentralization inherent in the system. The adoption of PoH within the proposed DSM system, BSM-6G, carries profound implications, generating a strategic synergy that offers an array of invaluable advantages. These benefits play a pivotal role in shaping the system's scalability and its adeptness at addressing the intricate landscape of 6G networks.

Foremost among these advantages is the exceptional throughput that PoH bestows upon the system. Empowered by PoH, the system exhibits an unprecedented transaction processing potential, in theory capable of reaching an astonishing 710,000 TPS [41]. This remarkable capacity aligns seamlessly with the data-intensive demands of 6G networks, facilitating rapid and efficient decision-making in spectrum allocation. Including the PoH mechanism in our DSM system is a carefully thought-out decision that brings numerous benefits. This combination makes the system perfect at being superfast, using resources wisely, staying safe, and responding quickly. As a result, it's all set to make a big difference in how the complex world of 6G networks is managed.

Oracle blockchain interoperability is essential to the BSM-6G system because it maintains scalability and reduces complexity while facilitating smooth real-time communication between off-chain data sources and the blockchain platform, Cognitive Radio (CR). Serving as an essential conduit between the blockchain network and outside systems, the Oracle component gives the blockchain access to current data, enabling a flexible and adaptable spectrum management environment.

Additionally, the Oracle uses the dApp to ease trade exchanges. The Oracle makes sure that transactions made by Primary Users (PU) or Secondary Users (SU) within the dApp are automatically updated on the blockchain. This helps to the accuracy and effectiveness of spectrum management inside the BSM-6G system, in addition to improving the transparency and traceability of spectrum trading activities.

Through the utilisation of real-time data obtained from the Oracles, the BSM-6G system's blockchain network may make well-informed, intelligent, and reliable decisions, thus improving the overall precision and efficacy of spectrum management procedures. In addition to ensuring the accuracy of spectrum-related data, this combination of Oracle-based blockchain interoperability helps to foster the dynamic adaptation needed in a 6G environment that is changing quickly.

The functionality of the Oracles is depicted in Algorithm 1, providing essential data access between the blockchain network and external data sources.

Algorithm 1 Oracles Component

```
procedure Spectrum_Availability_Oracle
    Search Spectrum Availability database with spectrum information
    Include band details
end procedure
procedure dApp_Trading_Oracle
    Facilitate trading between the blockchain network and Spectrum Availability
    Allow seamless transfer of information
    Updates Spectrum Availability database
end procedure
```

C. REGULATORS MODULE

In the context of DSM, the BSM-6G framework's Regulators Module is crucial to guaranteeing smooth compliance with 6G regulatory norms. The rules and regulations controlling spectrum utilisation that are prescribed by regulatory agencies are actively monitored and enforced by this module, which is meticulously constructed to go beyond simple observation. The Regulators Module's complex functionality includes a deep comprehension of 6G specification standards, which allows it to operate through the complexities of spectrum allocation in the developing 6G environment.

This module carefully analyses and considers the particular details specified in 6G regulatory requirements to go deeper into compliance. This entails a detailed analysis of usage procedures, guidelines for spectrum distribution, and any developing standards that specify what constitutes acceptable spectrum transactions and deployments in the 6G spectrum. The proactive approach of the module guarantees that all aspects of spectrum utilisation in the BSM-6G system comply strictly with the laws, hence reducing the possibility of any deviations.

Moreover, the Regulators Module is made to be flexible and open in recognition of the wide range of regulatory frameworks found in many nations. Any regulatory agency may alter and customise it in accordance with their regulations, covering every facet of DSM. Because of its flexibility, the BSM-6G framework can be easily integrated with a wide range of regulatory settings, considering local differences and DSM rules. The system facilitates inclusion and collaboration between regulatory authorities globally and the BSM-6G framework by promoting an open and customisable approach. This allows for a harmonious alignment with various regulatory landscapes. By achieving this, the BSM-6G system turns into a flexible and globally applicable solution for efficient, legal, and localised spectrum management in the context of the global 6G paradigm.

D. DAPP

The functionality of the dApp is to serve as the user interface and interaction layer for the overall system. It acts as a bridge between the blockchain network and the end-users, enabling them to access and interact with the blockchain's functionalities in a user-friendly manner, making the process efficient, transparent, and secure.

The dApp facilitates various operations related to the trading within the DSM system. Users can use the dApp to perform tasks such as listing, and purchasing available frequency bands, checking real-time spectrum information, and monitoring their transactions on the blockchain.

IX. BSM-6G RADIO SPECTRUM ALLOCATION AND SHARING

The BSM-6G system provides PUs and SUs an opportunity to allocate and share available radio spectrum in 6G networks throughout interacting with the dApp module, which is considered as a frontend system. Upon interacting with the dApp, several processes need to take place across all BSM-6G system's modules. The following steps, as shown in Figure 2, describe the flow of processes and interaction within the BSM-6G system to deal with PUs and SUs spectrum allocation and sharing requests:

1) User Authentication: Users who wish to participate in the DSM system must access the system through the dApp. The dApp serves as the user interface, allowing users to verify available frequency bands and interact with the blockchain network seamlessly.
2) User Authorization: Upon authentication, the dApp determines whether the user is a PU or a SU. Based on this classification, the dApp grants appropriate permissions. PUs are granted listing permissions, allowing them to list their frequency bands for sale, while SUs are granted purchase permissions, enabling them to buy available frequency bands.
3) Regulatory Compliance Check: The Blockchain communicates with the Regulations Database. This database contains the latest spectrum regulations and updates provided by regulatory authorities. The blockchain verifies whether the user's actions comply with the applicable regulations.
4) Spectrum Availability Verification: The Blockchain, through the Spectrum Availability Oracle, checks the real-time spectrum availability in the dApp. This information is previously updated by the CR, which employs advanced spectrum sensing techniques to monitor the radio environment and detect changes in spectrum availability.
5) User Decision: Based on the real-time spectrum availability displayed in the dApp, the user can make one of two choices: (1) Use the spectrum if they have already been authorized, proceeding to Spectrum Allocation and Coordination, or (2) Engage in trading activities, such as listing or purchasing frequency bands.
6) Smart Contract Execution: If the user chooses to engage in trading, the blockchain executes the corresponding smart contract. The smart contract stores the transaction parameters on the blockchain and provides access credentials to the dApp.
7) Spectrum Allocation and Coordination: The dApp shares the access parameters with the CR, which verifies the user's access credentials to the spectrum. If validated, the CR performs spectrum allocation and coordination to assign the user their allocated spectrum, updating the real-time spectrum availability in the dApp.

The access credentials for PUs and SUs can be granted by the designated regulatory entity responsible for providing such access. These credentials are directly provided to the user's wallet address, thus ensuring the system's incorruptibility and security. The cycle continues until the user's access credentials expire or are no longer valid for spectrum usage. In such cases, the user must repeat the trading process through the dApp to obtain new access credentials. Furthermore, the system must be regularly monitored. System administrators can use monitoring tools to identify areas of improvement and make necessary adjustments to reduce latency. Potential bottlenecks can help in optimizing performance and latency.

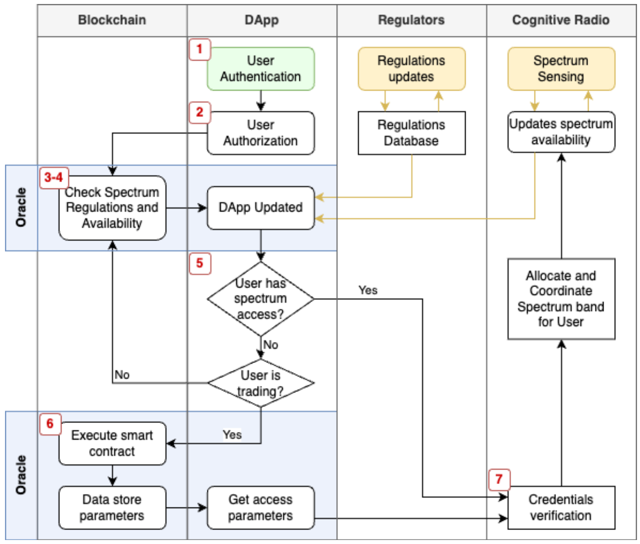

FIGURE 2. BSM-6G spectrum accessing and sharing. PUs are granted listing permissions, allowing them to list their frequency bands for sale, while SUs are granted purchase permissions, enabling them to buy available frequency bands.

In the subsequent two sections, an evaluation of Interoperability (Section X) and Scalability (Section XI) will be conducted. For detailed information on the configurations, a dedicated GitHub repository has been established and can be accessed at https://github.com/davidcuellard/BSM-6G.

X. INTEROPERABILITY EVALUATION

This section presents the evaluation experiment, which aims to verify the cost and feasibility of applying the BSM-6G interoperability. The evaluation methodology involves the development of a prototype system which represent the BSM-6G. Specifically, the prototype is used to conduct several experiments which focuses on measuring the time and resource costs associated with the proposed interoperability technique. The time cost will be depicted through the distribution of time differences among different transaction types, whereas the resource's cost is measured by both the Gas price, and the transaction fee. Comparing BSM-6G with other DSM solutions based on time and cost of spectrum operations is crucial to verify whether BSM-6G is cost effective and scalable interoperability solution. In comparison to existing spectrum management systems, integrating DSM based blockchain with external services (e.g. Oracle) often adds layers of complexity due to the adopted interoperability techniques. This can sometimes result in longer processing times and increased operational costs, particularly during the initial setup phase or when executing complex transactions. The interoperability evaluation aims to verify whether BSM-6G can offer cost-effective operations measured by time and cost of these automated transactions. In real-world applications, the implications of these metrics can vary depending on the specific use case and operational requirements. For instance, in scenarios where real-time spectrum allocation is critical, longer processing times associated with blockchain-based systems may be less desirable.

On the other hand, the feasibility of BSM-6G's interoperability is tested by developing the prototype system which illustrates all relevant technical details of the proposed interoperability implementation. Furthermore, this section explores various aspects, including the experiment's setup, accompanied by its results, and a discussion that covers user connectivity from the blockchain to off-chain data through the utilization of an Oracle.

Extensive and multi-layered technical features and methodology of the evaluation ensure a comprehensive investigation of the cost-effective interoperability of the BSM-6G model. The creation and implementation of a prototype system that closely resembles the functional and technical aspects of the BSM-6G model served as the centrepiece of our evaluation procedure. This prototype played a key role in carrying out controlled experiments, which were essential in measuring the costs in terms of resources and time related to the suggested interoperability mechanism.

A careful examination of transaction durations was a key component of our methodology in order to precisely estimate the time expenses. This was accomplished by keeping track of how long it took for different kinds of transactions to finish, with a particular emphasis on the exchanges made possible by the blockchain's smart contract. Using the BSM-6G framework, this approach enabled us to obtain a comprehensive picture of the latency associated with various transactional activities.

The gas price and transaction fee served as the two main criteria that drove the resource cost analysis concurrently. With the help of this two-pronged strategy, we were able to comprehend the financial effects of carrying out transactions inside the BSM-6G system as well as the effectiveness of resource usage. Through analysing these expenses in conjunction with transaction durations, we were able to obtain a comprehensive comprehension of the financial and functional effectiveness of our interoperability method.

Additionally, the prototype system, which was created to accurately capture the technical nuances of our interoperability proposal, was used to test the practical feasibility of BSM-6G interoperability. This evaluation component was essential to confirm the practical applicability of our model and ensure that the suggested technical solutions are theoretically and practically sound. Included in the prototype was a full description of the system's features, such as the seamless fusion of blockchain technology with off-chain data sources, with an emphasis on the role of Oracles in filling this gap.

A thorough knowledge of the interoperability of the BSM-6G model was made possible by the findings and understandings obtained from this holistic evaluation technique. These results validate the model's promise as a reliable solution for 6G networks by proving its ability to provide efficient and economical communication between blockchain platforms and external data systems.

A. PROTOTYPE MODEL

Figure 3 illustrates the interoperability testing model, showcasing three primary entities: regulator, smart contract owner, and user. It is postulated that the spectrum availability database undergoes continuous updates facilitated by the CR module through automated processes employing the technologies expounded upon in Section VIII-A. Simultaneous activities occur between these entities, which contributes to the comprehensive evaluation of interoperability. A brief description of Figure 3 is as follows:

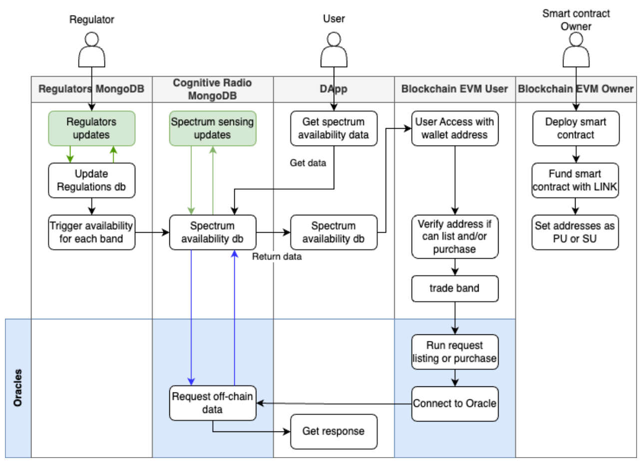

FIGURE 3. Interoperability: Testing model.

- *Smart Contract Owner*: undertakes the deployment of the intelligent contract, equipped with the functions named in Section X-B3. Additionally, the Smart Contract Owner is responsible for funding the smart contract with LINK tokens and incorporating the addresses of both PUs and SUs.
- *Regulator*: updates the Regulations Database, a pivotal trigger for band availability adjustments. This is achieved by configuring the regulatory rules to enable bands categorized as "Secondary" and relevant to 6G networks. This setup facilitates the activation of 39 distinct frequency bands, all encompassed within the frequency spectrum spanning 7GHz to 24GHz.
- *User*: who may function as either a PU or SU, interacts with the dApp and gains access to the comprehensive Spectrum Availability database, encompassing its diverse properties. Upon identifying a suitable band, the User can initiate interactions with the blockchain

through their digital wallet. The system verifies their eligibility to either list or purchase a band. If the requirements are met, trading can commence.
In instances where the prerequisites are not fulfilled, the User can still attempt to proceed, but the smart contract's functionality prevents invalid transactions, thereby conserving transaction fees. Upon triggering a listing or purchase request, the blockchain establishes communication with the Oracle Operator. This entity subsequently retrieves off-chain data from the Spectrum Availability database updated by the CR. The Oracle Operator returns a response, as outlined in TABLE 2 and TABLE 3.

Each of the 39 available bands will be tested. Firstly, a category request, then the listing request, and finally the purchasing request. In the testing process, a user initiates a request to the Oracle, which then communicates with the configured Chainlink Operator. This testing process provided valuable insights into the system's interoperability, showcasing its ability to handle various transaction types and interactions with the Oracle.

B. PROTOTYPE IMPLEMENTATION

The BSM-6G prototype system is implemented in this section with the goal of highlighting the key technical implementation details of the proposed interoperability approach. The exploration encompasses a range of crucial components:

1) DATABASES IMPLEMENTATION

1) Rest API endpoints:
   a) Spectrum Availability: This endpoint enables the display of bands that have been chosen for further analysis.
   b) Listing: This endpoint, employing the unique identifier, state, and address associated with the query, effects changes in the "bands.listed" attribute, thereby listing the specific band.
   TABLE 2 presents different scenarios of listing a band based on the combination of "To List" (whether the band should be listed), "Listed State" (current listed state of the band), and "Purchased State" (current purchased state of the band). The "Response" column provides the corresponding response for each scenario.

TABLE 2. Listing scenarios.

To list	Listed	Purchased	Response
TRUE	TRUE	TRUE	Error, band cannot be listed and purchased.
	TRUE	FALSE	Band is listed. No update needed.
	FALSE	TRUE	Band cannot be listed because it is purchased.
	FALSE	FALSE	Band listed new state: TRUE
FALSE	TRUE	TRUE	Error, band cannot be listed and purchased.
	TRUE	FALSE	Band listed new state: FALSE
	FALSE	TRUE	Band is not listed. No update needed.
	FALSE	FALSE	Band is not listed. No update needed.

   c) Purchasing: Similarly to the listing endpoint, the purchasing endpoint utilizes specific identifiers, state, and addresses to modify the "bands.purchased" and "bands.listed" attributes. This process effectively facilitates the purchase of the designated band.
   TABLE 3 outlines various scenarios of purchasing a band based on the combination of "To Purchase" (whether the band should be purchased), "Listed State" (current listed state of the band), and "Purchased State" (current purchased state of the band). The "Response" column provides the corresponding response for each scenario.

TABLE 3. Purchasing scenarios.

To purchase	Listed	Purchased	Response
TRUE	TRUE	TRUE	Error, band cannot be listed and purchased.
	TRUE	FALSE	Band listed new state: FALSE and purchased new state: TRUE
	FALSE	TRUE	Band is purchased. No update needed.
	FALSE	FALSE	Band not listed.
FALSE	TRUE	TRUE	Error, band cannot be listed and purchased.
	TRUE	FALSE	Band is not purchased. No update needed.
	FALSE	TRUE	Band purchased new state: FALSE
	FALSE	FALSE	Band is not purchased. No update needed.

2) Regulators Trigger Creation: To ensure regulatory compliance, a trigger was established for the regulators' rules. Changes in the states of these conditions within the regulators' rules database are automatically reflected in the "bands.regulatorsPermission" attribute for each respective band.

2) ORACLE IMPLEMENTATION

For the Oracle module, the Chainlink Foundation services were employed, needing the setup of a custom node and the creation of an "External Adapter" for interfacing with off-chain data and executing queries endpoint.

1) Metamask: Metamask was utilized to make transactions and contract interactions.
2) Blockchain Network: In this context, SeopilaETH was chosen due to its compatibility with Chainlink. Consequently, it was also necessary to have LINK tokens.
3) Running a Chainlink Node, to enable communication between the smart contract and the Oracle. It was necessary to set up an Ethereum client in Alchemy (SeopilaETH) and run an Oracle Node.
4) External Adapter: To enable the communication between the API and the Chainlink node using JSON format.
5) Operator Jobs: These jobs initiate off-chain data requests from the Spectrum Availability database.

3) SMART CONTRACT FUNCTIONALITIES

Using Remix IDE to create the smart contract, which forms the backbone of the DSM system that interacts through the Oracle.

a: TRANSACTIONS

- Set and Remove PUs and SUs: The smart contract provides the functionality for the contract owner to set and remove addresses for PUs and SUs. This feature ensures that only authorized PUs have the ability to list and purchase bands, while only authorized SUs can purchase bands.
  By managing these authorized addresses, the contract owner maintains control over the participants who can engage in the respective activities.
- Request Category of a Band (requestCat): Any user can query the smart contract to obtain the category of a specific band.
- Request Listing (requestListing) and request Purchase (requestPurchase): Only authorized users are empowered to execute the listing and purchasing processes by running these functions.

b: CALLS

- Check Authorized Addresses for Listing and Purchase.
- Get message Category (requestCat response).
- Get message Listing (requestListing response).
- Get message Purchasing (requestPurchasing response).

With the successful implementation of these smart contract functionalities, the system is now poised for comprehensive testing and a further discussion.

4) DECENTRALIZED APPLICATION (DAPP)

Figure 4 depicts a React-based application that was developed. The dApp was deployed using Netlify and can be accessed at https://bsm-6g.netlify.app/

Within this interface, iframes containing charts generated from MongoDB are displayed. These iframes have been configured to refresh automatically every 30 seconds. The application showcases three distinct charts, each serving a specific purpose:

- *Spectrum Availability Table:* Presents a table detailing the Spectrum Availability. Users have the option to sort the table based on their preferred column, allowing for easy access to relevant information.
- *Pie Chart of Band Availability:* Provides an illustrative representation of available and unavailable bands. This visual representation offers quick insights into the distribution of bands within the spectrum.
- *Regulators Rules Table:* Displays the status of various regulatory rules. This information serves to verify which rules are currently active and which ones are not, providing a comprehensive overview of the regulatory landscape.

Furthermore, a button to request a category and establish a connection to the Metamask wallet was included. Because the Operator Node is local, a response can only be received if it is active; if not, the request will be sent out, but no answer will be received. These charts, embedded within the React application, offer a dynamic and user-friendly interface that facilitates the visualization and understanding of critical information related to spectrum availability, band status, and regulatory rules. The automatic refresh of the charts enhances the usability and real-time relevance of the application, ensuring users are equipped with up-to-date insights for informed decision-making.

C. RESULTS AND DISCUSSIONS

While the evaluation methodology primarily aimed at validating the technical implementation of the proposed interoperability design as well as testing the off-chain data retrieval and successful interaction, it also encompassed an in-depth analysis of critical parameters such as time, gas price, and transaction fee. This analysis is achieved by a series of controlled experiment scenarios using the developed testing model.

1) TIME ANALYSIS

To assess the response time, capturing the duration from contract interaction approval in Metamask to result appearance, crucial data from each interaction was collected. Two significant aspects were tracked for each interaction:

1) The Timestamp was taken from the Block Explorer at https://sepolia.etherscan.io/.
2) Using the Operator GUI transaction's timestamp.

Figure 5 depicts the distribution of time differences across various transaction types. Additionally, Table 4 presents the relevant statistics for time difference. The average total time was observed to be 31.40 seconds. It's worth noting that extended durations were encountered, reaching up to 63.617, 50.660, and 51.522 seconds for requestCat, requestListing, and requestPurchasing, respectively. Conversely, minimum times of approximately 25.5 seconds were noted for each transaction type.

TABLE 4. Summary statistics for time difference.

Tx Type	requestCat	requestListing	requestPurchasing
Count (Tx)	39	39	39
Mean (s)	31.187	32.234	30.790
Std (s)	9.622	7.714	7.036
Min (s)	25.479	25.480	25.513
Max (s)	63.617	50.660	51.522

This analysis highlights the transaction response times that were observed. The results show relatively similar response times across various transaction types, where RequestListing and requestPurchasing show the highest response times.

2) GAS PRICE ANALYSIS

The evaluation of interoperability in the context of DSM for 6G networks also encompassed an analysis of gas fees incurred during various transaction types within the blockchain-based system. Gas fees, denoted in Gwei (1 Gwei is 10^{-9} ETH), represent the amount of cryptocurrency users need to pay to miners to process and include their transactions in a block.

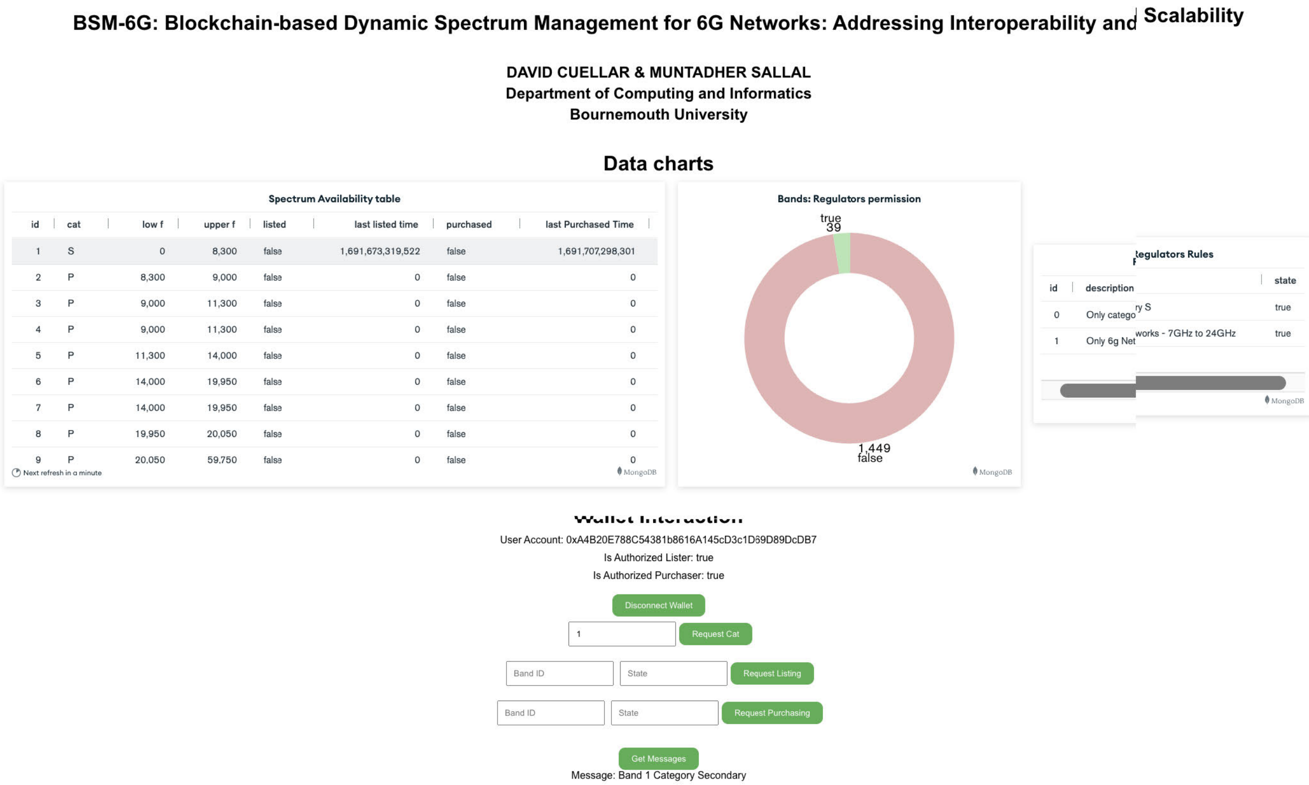

FIGURE 4. BSM-6G dApp preview (link https://bsm-6g.netlify.app/).

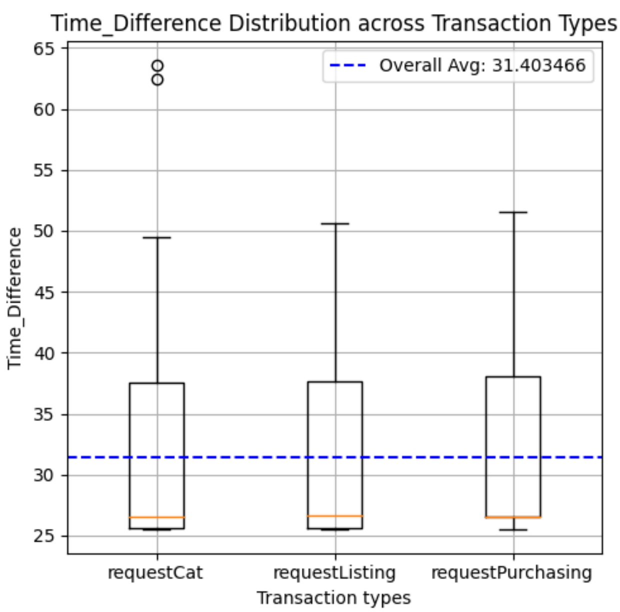

FIGURE 5. Interoperability: Time difference distribution across transaction types.

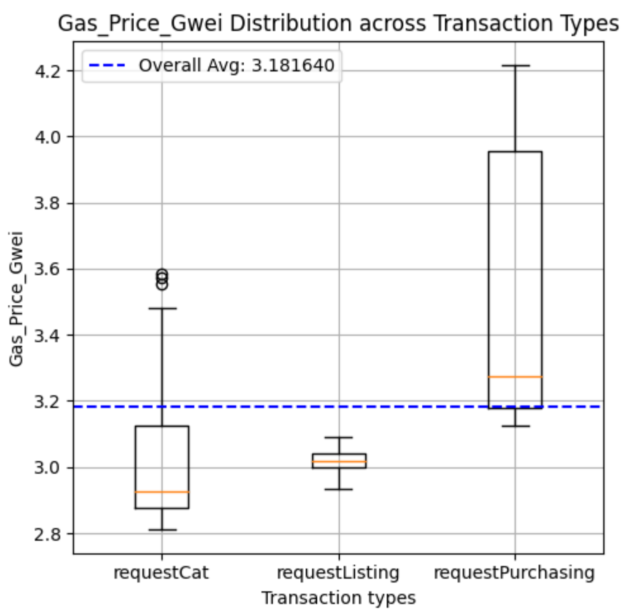

FIGURE 6. Interoperability: Gas fees distribution across transaction types.

To ascertain the gas prices, the transactions were verified using https://sepolia.etherscan.io/. As gas prices are dynamic and can vary based on factors such as transaction complexity, pending transactions on the blockchain, and time of day, the analysis considered a range of gas prices over the testing period. The results, displayed in Figure 6, depict the distribution of gas fees across transaction types, while Table 5 provides summary statistics for gas prices.

TABLE 5. Summary statistics for Gas price.

Tx Type	requestCat	requestListing	requestPurchasing
Count (Tx)	39	39	39
Mean (Gwei)	3.040	3.019	3.486
Std (Gwei)	0.244	0.034	0.395
Min (Gwei)	2.810	2.932	3.125
Max (Gwei)	3.584	3.091	4.217

TABLE 6. Summary statistics for Tx fees.

Tx Type	requestCat	requestListing	requestPurchasing
Count (Tx)	39	39	39
Mean (ETH)	0.000562	0.000589	0.000677
Std (ETH)	0.000045	0.000021	0.000077
Min (ETH)	0.000520	0.000569	0.000606
Max (ETH)	0.000664	0.000712	0.000823

The observed gas fees exhibited a relatively narrow range, spanning from 2.810 to 4.217, with a total average of 3.18. Notably, the transaction type *requestPurchasing* incurred the highest gas fees. This could be attributed to the larger response size required when the Chainlink Operator adjusts both "listed" and "purchased" values. The highest gas fee recorded was almost twice the lowest observed gas fee, suggesting the greater computational requirements of the *requestPurchasing* transaction type. Conversely, *requestListing* transactions showed consistent gas fee values with a minimal standard deviation of 0.034.

3) TRANSACTION FEE ANALYSIS

The transaction fee directly correlates with the gas price, as it is calculated as the product of gas price and gas used by the transaction. This fee is paid by the user to the blockchain in exchange for executing the contract interaction.

In Figure 7, the Time Difference Distribution Across Transaction Types is illustrated, and in Table 6, Summary Statistics for Transaction Fees are provided.

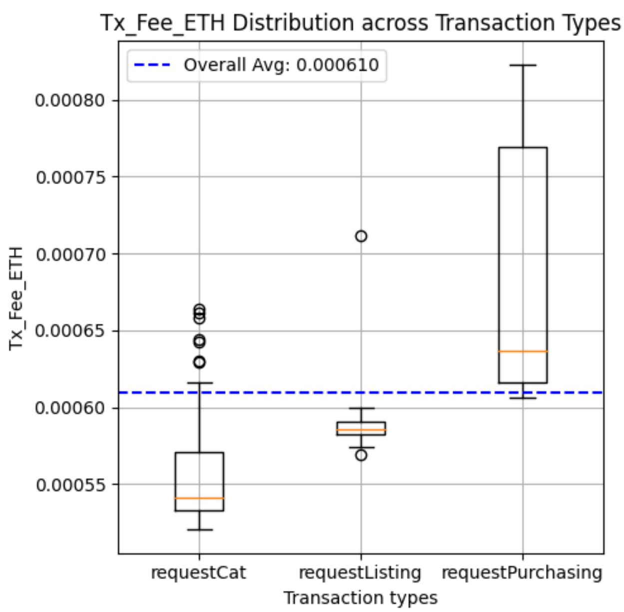

FIGURE 7. Interoperability: Transaction fees distribution across transaction types.

The results for different transaction types vary between 0.0008 and 0.0005, with an overall average of 0.000610. Further dissection of the data reveals the minimum and maximum transaction fee values, shedding light on the range of fees users might encounter for each transaction type. Remarkably, "requestCat" emerges with the lowest minimum transaction fee at 0.000520 SepoilaETH, portraying the cost efficiency associated with obtaining information about band categories. In contrast, "requestPurchasing" boasts the highest maximum transaction fee at 0.000823 SepoilaETH, hinting at potential scenarios where the acquisition cost for purchasing a band can be relatively higher.

Among the transaction types, it is notable that "requestPurchasing" demonstrates the highest mean transaction fee, amounting to 0.000677 SepoilaETH. Conversely, the transaction type "requestCat" exhibits the lowest mean transaction fee, measured at 0.000562 SepoilaETH, implying a relatively lower cost associated with acquiring information about the category of a particular band. In summary, related to Gas and transaction fees, it can be deducted that these costs are realistic as it is attributed to the selected blockchain network (Ethereum) and the smart contract type and the connection with the Oracle.

XI. SCALABILITY EVALUATION

The evaluation of scalability stands as a critical endeavour to thoroughly scrutinize the efficiency and suitability of the consensus mechanism inherent to the proposed system model. In this context, PoH consensus mechanism takes centre stage, with its theoretical capacity of 710,000 TPS warranting empirical validation within the context of our DSM for 6G. This assessment is of paramount importance as it delves into how the consensus mechanism performs under augmented workloads while upholding its operational efficiency. The process encompasses meticulous system setup and strategic tool selection, ensuring a comprehensive examination of the system's scalability capabilities.

Turbine block propagation, an advanced implementation technique, is a crucial component of our scalability evaluation [42]. By dividing transaction batches until the bandwidth used by header information surpasses that of the transaction data itself, this technique greatly improves scalability. Scalability can be extended to potentially hundreds of thousands of validators by utilising this strategy. By ensuring that every participating node adopts the same methodology as the leader node, this strategy effectively addresses scalability on a far wider scale than that of typical blockchain systems.

The scalability evaluation was based on a rigorous experiment model in terms of methodology. In order to replicate real-world DSM transactions, the experiment started 500,000 smart contract interactions, simulating a high volume of transactions. This particular scenario was created with the express purpose of simulating how off-chain data is retrieved and interacted with, much as it would be in actual DSM interactions involving the Spectrum Availability database. Because there were so many transactions, the system was put through a rigorous stress test, which let us see how well the PoH consensus mechanism performed under heavy strain.

Numerous preliminary procedures were carefully followed in order to guarantee the accuracy of this scalability study. These included creating keypairs for account access, coordinating batches of transactions, and making sure there were enough resources for these keypairs by utilising funders with SOL tokens from faucets. One important aspect of data gathering was the 'Start Sampling' transaction, which was started every second by the client demo. Together, these efforts produced a simulation that successfully reflected the spectrum allocation requirements of a 6G network, offering an accurate and thorough evaluation of the system's scalability.

A customised configuration of the Solana cluster, selected for its high-performance and quick transaction processing capabilities, added assistance to the experiment's implementation. In this configuration, a validator node was launched, a test environment was initialised, and regular expressions were used for data extraction and cleaning. Because of this careful methodology, the average TPS for all samplers could be computed, providing a useful overview of the system's overall transaction processing effectiveness.

Our scalability examination was distinguished by a thorough and multifaceted methodology that included both realistic simulations and theoretical approaches. We conducted a thorough test of the PoH consensus process by using sophisticated propagation techniques and simulating a large volume of transactions. This thorough approach guaranteed a solid evaluation of the suggested BSM-6G model's scalability, which is essential for its use in the demanding and dynamic world of 6G DSM.

A. EXPERIMENT MODEL

As depicted in Figure 8, the benchmarking process commences by the client demo initiating an extensive influx of 500,000 transactions (smart contract interactions) to the local testnet validator. This strategic approach essentially treats these transactions as implicit contract interactions with the Oracle, intended to replicate the process of retrieving and engaging with off-chain data. To contextualize this scenario within our proposed DSM framework for 6G networks, these interactions would closely resemble the mechanisms involved in accessing and interacting with the Spectrum Availability database.

For the effective execution of this benchmarking, several preparatory steps are undertaken. Firstly, the client demo orchestrates the creation of transaction batches, adhering to the predefined transaction count. This transaction count determines the number of transactions grouped within each batch, facilitating streamlined processing. Furthermore,

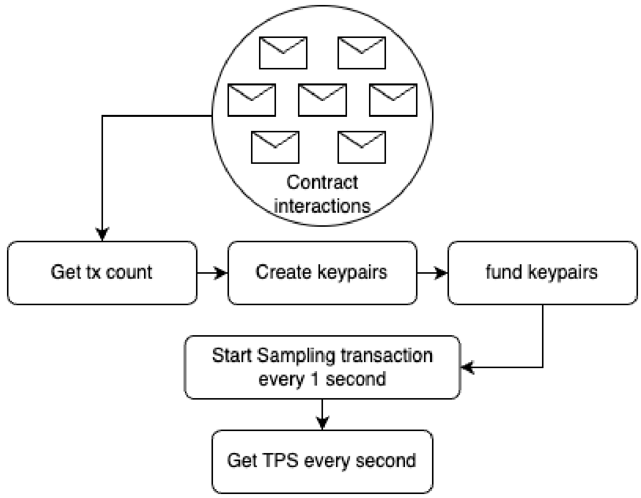

FIGURE 8. Scalability: testing model.

keypairs, each comprising a public key and its corresponding private key for account access, are generated in multiples of the transaction count. These keypairs are integral for accessing the system's various functionalities.

To ensure the operational capacity of these keypairs, the validator node initiates funding requests to the funder using faucet SOL tokens. The funder supplies the necessary resources for these keypairs, enabling their seamless integration into the benchmarking process. Once funded, the benchmarking process advances to the subsequent phase, where the client demo commences the "Start Sampling" transaction every one second. This transaction type plays a pivotal role in gathering the required benchmarking data. Through the combination of these orchestrated steps, the benchmarking process effectively simulates and evaluates the system's responsiveness and performance under varying transaction loads, providing valuable insights into the scalability of the proposed DSM framework for 6G networks.

B. EXPERIMENT IMPLEMENTATION

The chosen blockchain platform for this study is Solana, a high-performance blockchain known for its scalability and fast transaction processing capabilities, which uses PoH as its consensus mechanism.

For the experiment, it was necessary to configure the Solana cluster as follows:

1) Set up a Solana Cluster and configure it in local
2) Initialize Test
    a) Start the faucet service.
    b) Launch a validator node.
    c) Initialize Benchmarking Test
    d) Run the test with different number of transaction counts (tx count) to send per batch.
3) Data Extraction and Cleaning: To extract the relevant data, regular expressions were employed to go through

the text and isolate the TPS values associated with each sampler.

4) Calculating the average TPS across all samplers and the overall efficiency of the system's transaction processing capacity. Additionally, the total number of transactions processed and the count of failed samplers were derived from the extracted data.

C. RESULTS AND DISCUSSIONS

1) TRANSACTIONS PER SECOND (TPS) ANALYSIS

In Figure 9, the benchmarking results of the cluster are displayed, showcasing various tx count. An interesting observation is that lower tx counts tend to exhibit fewer sampler failures. This phenomenon can be attributed to the nature of the testing environment. Specifically, during the benchmarking process, the tx count values of 50, 500, 1,000, and 3,000 were utilized to gauge the local node's response to the load.

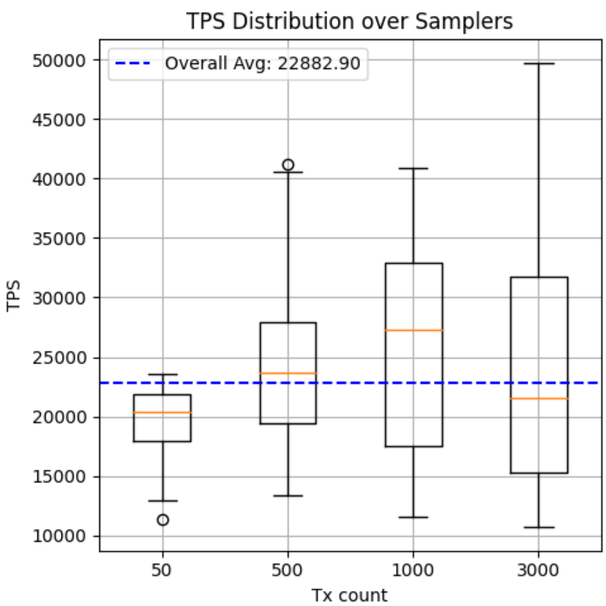

FIGURE 9. Scalability: TPS Distribution over samplers – Cluster benchmarking.

TABLE 7. Summary statistics for different tx count.

Tx count	50	500	1,000	3,000
Success (Sample)	59.00	51.00	42.00	26.00
Failed (Sample)	0	8	17	33
Mean (TPS)	19,240.41	23,949.46	25,946.66	24,107.30
Min (TPS)	11,385.44	13,331.67	11,549.98	10,693.84
Max (TPS)	23,601.18	41,200.85	40,923.74	49,720.00
Total (Tx)	1,135,183	1,221,422	1,089,759	626,789

Solana's claim of achieving up to 710,000 TPS is noteworthy [41]. However, it's essential to highlight that real-world results have shown slightly different figures. In BSM-6G based Solana blockchain has demonstrated a peak TPS of just over 5,000, while during testing, it reached up to 65,000 TPS [43]. Within the testing, Table 7 shows the benchmarking principal statistics, a compelling result was achieved where 49,720 TPS was sent with a tx count of 3,000. It's worth noting that this specific scenario had the highest sampler failures, totalling 33.

Interestingly, the scenario with the fewest sampler failures was observed at a tx count of 50, registering zero failures. Nevertheless, its minimum and maximum TPS were 19,249.41 and 23,601.18 respectively. This outcome remains impressive when compared to the capabilities of other prominent blockchain networks. For instance, Bitcoin, Ethereum, Ripple, and Avalanche networks typically handle 3-7, 15-25, 1,500, and 5,000 TPS, respectively [44].

Table 8 presents a comparison of the mechanisms proposed by various authors in Section VI. It is evident that even though PoF and PBFT achieve up to 10,000 TPS, this number falls short of both our PoH test result of 49,720 TPS and the theoretical ceiling of 710,000 TPS. Furthermore, it's important to note that PBFT's fault tolerance is 33%, indicating lower security. Additionally, PoT boasts a TPS of 100,000, which is impressive, yet lacks information regarding its fault tolerance and doesn't surpass the 710,000 TPS offered by PoH.

TABLE 8. TPS comparison.

Author	Consensus Mechanism	Max. TPS Testing	Max. TPS Theoretical	Features
Proposed	PoH	49,720	710,000	High scalability High security
[38]	PoF	-	10,000	High scalability High security
[29]	PBFT	-	10,000	High scalability Low security
[30]	PoT	-	100,000	High scalability -

In Figure 9 the overall average was 22,882.90. The substantial TPS demonstrated by BSM-6G based Solana positions it as a viable candidate for a scalable DSM system. The blockchain network's capacity to handle a significant number of transactions within a short timeframe aligns well with the demands of DSM. Swift transaction processing is a fundamental requirement in managing the dynamic allocation of spectrum resources efficiently.

It was noted that up to 3,000, the local node managed the benchmarking tasks effectively. Beyond this threshold, however, the local node's performance began to deteriorate. This degradation in performance beyond 3,000 transactions can be attributed to the increased strain on system resources, leading to slower processing speeds and potential bottlenecks that hindered the node's ability to handle the high transaction load efficiently.

Additionally, it's worth mentioning that BSM-6G based Solana has demonstrated remarkable scalability in terms of TPS. Furthermore, these testing outcomes contribute significantly to the DSM initiative. The high TPS achievable with BSM-6G based Solana implies that complex DSM operations can be executed rapidly. For instance, in spectrum management tasks involving real-time decision-making

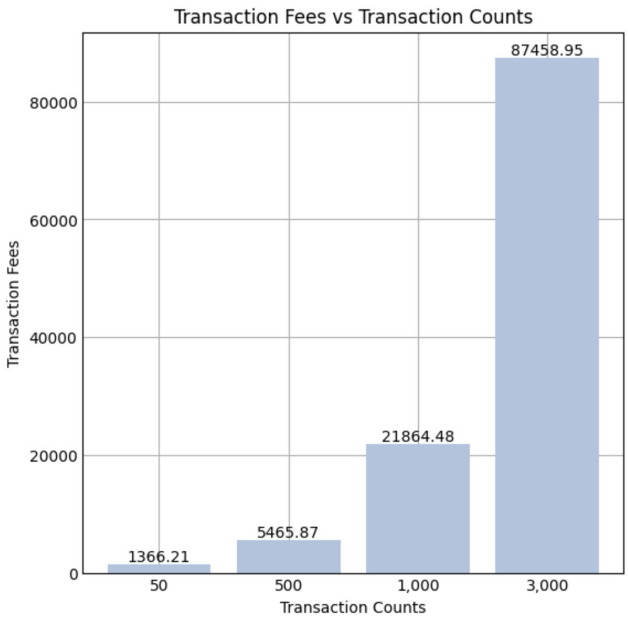

FIGURE 10. Scalability: Transaction fees in each tx counts.

and allocation adjustments, the network's responsiveness becomes a critical factor.

2) TRANSACTION FEES ANALYSIS

Transaction fees represent the nominal charges imposed to process instructions within the Solana blockchain network [14]. With each transaction potentially containing multiple instructions, the process involves routing the transaction through the current leader validation-client. Once confirmed and integrated into the global state, the corresponding transaction fee is paid to the network. This fee structure functions to uphold the Solana blockchain's economical design.

In Figure 10, the transaction fees are displayed. Within the specific case being considered, the validator node initiated requests to the funder, aligning with distinct tx counts: 50, 500, 1,000, and 3,000; These requests resulted in the validator imposing transaction fees amounting to 1,366.21, 5,465.87, 2,1864.48, and 87,458.95, respectively, to facilitate the execution of the complete benchmarking process.

Transaction fees serve as a mechanism for preserving the network's integrity. By attaching fees to transactions, the network guards against potential misuse and spam, ensuring optimal resource utilization. This aligns with DSM operations, where efficient resource allocation is vital for effective spectrum utilization.

It's important to recognise that transaction fees not only improve general efficiency and discourage misuse, but they also contribute to the network's sustainability. These fees serve as a safeguard against unfair usage and support system stability in situations where transactions are frequent or intense. In the context of DSM, transaction fees play a crucial role in encouraging responsible usage, especially in situations where high-frequency real-time modifications are necessary to meet dynamic spectrum demands.

The system's ability to adapt to different transaction sizes and meet a range of operational needs is demonstrated by the observed linear increase in transaction fees. The tiered structure of transaction fees gives users a way to make decisions based on their individual needs as the system changes and adapts. In addition to promoting a just and flexible environment and assisting in the sustainability of the BSM-6G system, this dynamic pricing model makes sure that the network is resilient and effective even in situations where demand is high.

While transaction fees foster network sustainability, they entail associated costs for participants. In scenarios involving frequent or intensive transactions, these costs can accumulate. In the context of DSM, particularly if operations necessitate a high frequency of real-time adjustments, the cumulative cost factor warrants consideration.

In summary, the benchmarking results provide a significant insight into the scalability potential of the BSM-6G based PoH consensus mechanism, particularly within the realm of DSM. The network's exceptional throughput capabilities, as demonstrated in the benchmarking process, are notably relevant to the real-time spectrum allocation requirements of next-generation communication networks such as 6G. The inherent scalability of PoH mechanism positions it as a promising candidate for supporting a more efficient and effective DSM system.

This mechanism's ability to handle a substantial number of transactions within a short time frame aligns well with the dynamic nature of spectrum management in rapidly evolving communication environments. As the demands for real-time decision-making and resource allocation intensify in 6G networks, the benchmarking outcomes highlight the significance of adopting a consensus mechanism that can accommodate the high transaction volumes required for optimal DSM operations.

XII. EVALUATION OF RESOURCE UTILIZATION

The evaluation of spectrum utilisation and cost is carried out in this section. Stackelberg game scenario is considered while calculating the payoffs and cost, following the strategy adopted in [45] and [46]. Specifically, the payoffs of the spectrum buyer are calculated based on the identification of optimal resource allocation through making use of two factors, utility performance of the buyer, and the payment of the purchased resource. On the other hand, the seller payoffs are defined based on the price of the spectrum resources requested by the buyers. According to Stackelberg game, the spectrum network elects a leader which is the regulator in Stackelberg game, making decisions on how to allocate or utilize spectrum resources. The other players, often secondary users or spectrum licensees, then make their decisions based on the leader's actions. The leader is elected based on a reputation mechanism proposed in [47]. Precisely, the reputation scheme is run independently by all spectrum followers to finalise the reputation score for each spectrum leader candidate at the end of every epoch. The reputation score is calculated based on several reputation parameters such as number of transactions, and reputation scaling factor.

A. EXPERIMENT IMPLEMENTATION

In this section, simulations were carried out to evaluate the performance of the system of the Stackelberg game in terms of payoffs (demand relationship between the buyer and seller) and spectrum resource cost. The simulation network was implemented following the simulator design proposed in [48] and [49]. Specifically, the simulation model is developed in Python for object-oriented structure and modularity. Based on the concept of discrete event simulation, the behavior of the spectrum buyer and seller is modeled as an ordered sequence of well-defined events. These events, which take place at discrete points in simulation time, comprise a specific change in the system's state. Regarding the blockchain system, Solana blockchain is employed in the simulation configuration. We set the coverage area to 500 meters, 10 mobile virtual network operators (MNVOs) with 450 users randomly distributed. Random user mobility model is adopted to capture the spectrum user mobility [50]. We set the simulation to have 1000 trading epochs. A trading epoch is the time where spectrum resources are requested by spectrum users.

B. RESULTS AND DISCUSSIONS

Figure 11 shows the total payoff for the buyers and sellers over a varying number of trading epochs. The trading epoch represents the time where buyers requests spectrum resources and a level of interactions is initiated between the buyers and sellers. Results indicate that the our proposed system achieves higher payoffs compared to the HDFLNS-BC [45]. This means that BSM-6G achieves higher level of interactions

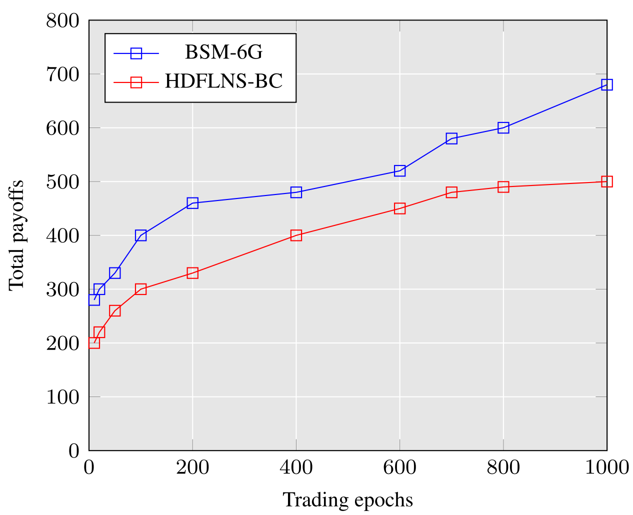

FIGURE 11. Comparison of the empirical distribution of payoffs measured in the BSM-6G with the empirical distribution of payoffs measured for the HDFLNS-BC protocol.

where the number of transaction handled per epoch is significantly improved. The reason behind this improvement is the fact that BSM-6G uses PoH consensus protocol which facilitates a significant volume of transactions, allowing for the optimization of payoff functions to enhance overall performance.

On the other hand, Figure 12 shows the average cost across each trading epoch. The results indicate two main findings: 1) cost resources in BSM-6G increase gradually as the number of epochs increases; 2) BSM-6G provides fewer cost resources compared to HDFLNS-BC. The price of spectrum resources is crucial as it has a great impact on the level of payoffs. Specifically, a low spectrum price encourages buyers to request more resources, which leads to higher payoffs. This means BSM-6G improves spectrum trading by providing a low cost of resources, which contributes towards enhancing payoff functions.

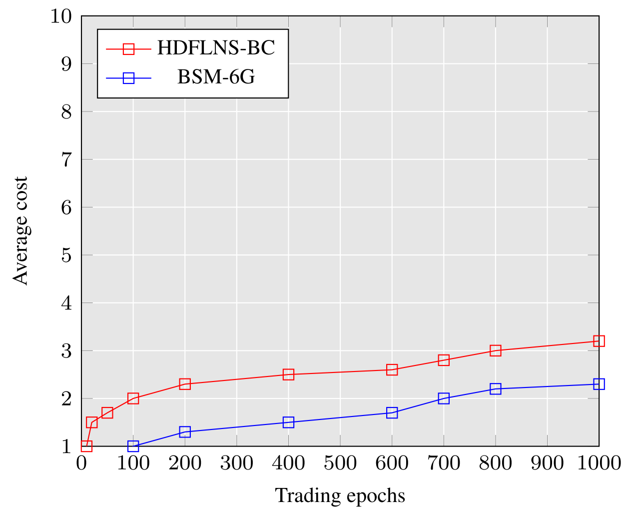

FIGURE 12. Comparison of the empirical distribution of average cost measured in the BSM-6G with the empirical distribution of average cost measured for the HDFLNS-BC protocol.

XIII. SECURITY EVALUATION

The blockchain system for DSM is essential to keeping an immutable and open ledger of spectrum transactions. All network transactions involving spectrum are tracked by the blockchain, which functions as a digital ledger. Each transaction made by users when using the dApp is cryptographically recorded as a block in the blockchain.

The parties involved, the particular spectrum band, the parameters of the transaction, and other pertinent information are all included in these transactions. The system enforces stringent access control mechanisms, ensuring that only authorized addresses have the privilege to initiate listing or purchase actions. This restriction adds a layer of security, mitigating the risk of unauthorized manipulation of the system's spectrum availability data. The owner of the system retains the exclusive capability to designate and modify authorized addresses, thus preserving the integrity of the system's operations.

To further enhance security, a proactive approach was adopted by creating distinct Operator's jobs for each individual user. This stratified approach minimizes the scope of access, ensuring that only users with specific authorized addresses can utilize their designated jobs. By segregating jobs in this manner, the system safeguards against potential data breaches or unauthorized interactions with the off-chain data, thereby fortifying the overall security posture.

Furthermore, the blockchain's consensus mechanism, driven by PoH, ensures the integrity and security of each transaction before its inclusion in the blockchain. With PoH, the system cryptographically verifies the passage of time between events, providing a tamper-proof historical record. This robust verification process ensures that transactions are valid and legitimate, bolstering the overall security of the network. The sequential execution of cryptographic functions guarantees that events occur in the intended order and cannot be manipulated, thereby preventing unauthorized modifications and ensuring the reliability of the Blockchain.

Due to the transparency of the blockchain, an open and auditable system is provided by allowing all network users to access and observe the whole transaction history. Users can track the movement of spectrum resources, ensuring that band usage and distribution are fair and legal. The integrity and immutability of records, along with this transparency, help to foster a sense of confidence among network users.

PUs and SUs can trade spectrum with confidence, knowing that every transaction is securely documented and cannot be altered. In addition, the PUs receive incentives (tokens) to enable unused band spaces, expanding the use of the spectrum to the interested SUs. The blockchain's elimination of middlemen increases trust and lowers transaction costs. The blockchain module, which keeps an unchangeable log of spectrum transactions, is the foundation of the DSM system. The blockchain fosters confidence among users of 6G networks and makes efficient and dependable spectrum trade possible by guaranteeing the integrity, transparency, and security of records.

XIV. RESEARCH CHALLENGES AND OPPORTUNITIES

This paper opens up new possibilities for research and development in the field of DSM in the context of changing 6G networks. While the current work provides valuable insights and contributions, there are several challenges and limitations that warrant exploration and refinement in future studies.

- Enhancing Oracle Automation: One avenue for future work involves the optimization of the Oracle's automation process. This could involve the development of a mechanism that periodically updates the state of purchased bands, thereby revoking access and ensuring timely and accurate data representation.
- Refined Band Listing and Purchase Mechanism: The existing approach facilitates the listing and purchase of entire frequency bands. To further enhance spectrum utilization and accommodate a larger number of users, future work could involve the design of a system that subdivides frequency bands into smaller portions, allowing for the sale and usage of specific segments of a band. This approach could potentially increase the efficiency of resource allocation.
- Development of a Custom Blockchain Network: Exploring the creation of a dedicated blockchain network utilizing the PoH consensus mechanism presents an interesting avenue for future research. This custom blockchain could incorporate its Oracle system for off-chain data retrieval and interaction, potentially leading to even more optimized and tailored performance for DSM within advanced networks.

XV. CONCLUSION

We proposed a DSM system based on blockchain and CR, called BSM-6G. The primary advantage of this system is that it preserves scalability and cost-effective, as well as less complex blockchain interoperability in the context of 6G spectrum management. It achieves this by using oracle blockchain interoperability to ensure the real-time interaction among the blockchain platform, the CR, and any data sources off-chain, and to preserve blockchain scalability. An additional feature of BSM-6G is that it uses Proof of History (PoH) consensus protocol to support faster spectrum decisions, meeting the significant resources and demands in the 6G networks. In this paper, the blockchain interoperability within BSM-6G was implemented where comprehensive technical details were provided and discussed with the goal of testing the level of complexity of the proposed Oracle interoperability design. To demonstrate that the provision of these features is achieved by BSM-6G, we provided a detailed evaluation and analysis of BSM-6G to establish how it preserves cost-effective interoperability and scalability. Empirical evidence of the performance characteristics of BSM-6G was then provided. We evaluated its performance on a prototype system, by measuring the time and cost of spectrum operations, in particular the time and cost required for the Request Category of a Band, Request Listing (requestListing) and request Purchase (requestPurchase). In summary, the average time required by BSM-6G to perform spectrum operations (Request Category, list and purchase a Band) was 31.40 s and the associated average cost of gas was 3.18 for each contract. The scalability of the system was then investigated by examining the number of transactions that BSM-6G can process per second (TPS) as well as the average transactions fees as the transactions size increased. We provided evidence that the transaction fees were an approximately linear function of the transactions' population size over the range of population sizes examined. In summation, BSM-6G delivers the following key features: cost-effective and less complex Oracle interoperability, and initial results suggest that the system is scalable.

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