Trusted 6G-Envisioned Dynamic Spectrum Allocation: A Reference Model, Layered Architecture, and Use-Case

Pronaya Bhattacharya, Farnazbanu Patel, Vishaka Ralegankar, Bhaumik Thakkar, Sudeep Tanwar, and Mohammad Abouhawwash

Abstract Spectrum allocation among multiple telecom providers is challenged with a fair spectrum allocation process and collusion among multiple telecom parties involved in spectrum bids. As spectrum licensing have shifted toward decentralization, blockchain-based spectrum allocation can address the limitations through a fair and trusted bidding process, and spectrum allocation which is transparent to all bidders. Moreover, the spectrum allocation process has shifted to dynamic spectrum allocations, and thus in the coming future, owing to the inherent advantages of sixth-generation (6G) networks, with high network reliability, user bandwidth, high-precision, ultra-high reliability, and extreme flexibility, all presented as networked-in-a-box service, dynamic spectrum allocation in 6G-envisioned networks is a reality in near future. In light of these facts, we present in this paper, a comprehensive examination of the integration of a blockchain-based scheme for dynamic spectrum access in 6G-envisioned communications. We present the layered reference architecture and highlight a case study of future blockchain-based spectrum access for 6G-serviced network access. The paper serves as starting foundation toward the build of effective blockchain-based spectrum allocation schemes with effective networked serviced applications.

P. Bhattacharya (✉) · F. Patel · V. Ralegankar · B. Thakkar · S. Tanwar
Institute of Technology, Nirma University, Ahmedabad, Gujarat, India
e-mail: pronoya.bhattacharya@nirmauni.ac.in

F. Patel
e-mail: 19mcei04@nirmauni.ac.in

V. Ralegankar
e-mail: 20mced18@nirmauni.ac.in

B. Thakkar
e-mail: 20mcec17@nirmauni.ac.in

S. Tanwar
e-mail: sudeep.tanwar@nirmauni.ac.in

M. Abouhawwash
Durban University of Technology, Durban, South Africa
e-mail: abouhaww@msu.edu

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1 Introduction

Over the past decade, there has been a surge in telecommunications networks that have surged the requirements of spectrum allocation bands among telecom service providers. Currently, with a large number of users, fourth-generation (4G) long-term evolution (LTE) networks are facing bottlenecks to service the growing demands. By 2021, 4.5 billion mobile subscribers are registered globally. Figure 1 presents the scenario. Owing to the shift, the telecom industries have shifted toward spectrum licensing in the fifth generation (5G) bands. 5G offers effective service orchestration through a combination of different band frequencies to increase the coverage range. 5G commercial networks are expected to operate in the 3.3–3.8 gigahertz (GHz) range, with support of lower bands that include 1500 megahertz (MHz), 2.1 GHz, and 2.3 GHz for poor connection areas [2]. Thus, 5G is expected to provide faster and reliable network services that would support different verticals in smart cities, like smart factories, smart and autonomous vehicles, and healthcare industries. However, it also requires telecom providers to access higher-frequency bands to make the vision a reality.

However, spectrum frequencies are limited resources, and thus, an effective sharing mechanism is required. With the advent of a shift of network services at the

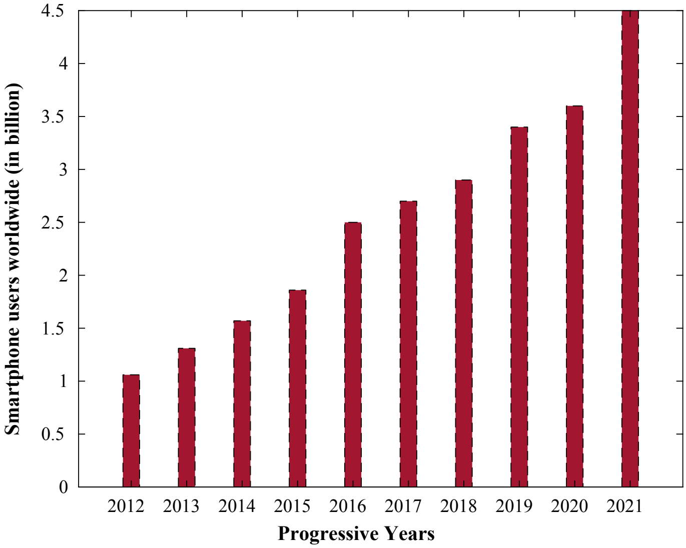


Fig. 1 Global increase of mobile users [1]

edge [3], latency in networked applications has also become a prime requirement. 5G services like ultra-reliable low-latency communications (eMBB) and massive machine-type communications (mMTC) offer an end-to-end latency of 5 ms and high connection density of 1 million devices/km^2. However, with the rise of automation, and an increase in massive device-to-device (D2D) connectivity in Internet-of-anything (IoE) ecosystems, networks would require extreme dense connections, edge intelligence support, and high reliability.

Thus, researchers have shifted toward sixth-generation (6G) networks, that is envisioned to support ultra-high data rates in the range of terahertz (THz) range, radio latency of 100 μs, and connection density of 10^7 devices/km^2 [5]. 6G services can be easily stacked to support the spectrum access. Moreover, 6G fine-tunes the edge computing requirements through artificial intelligence (AI)-enabled radio access, and thus, industries have shifted toward investment in 6G projects [6]. 6G supports effective features like omnipresent global coverage in space–air–ground–water communication, at ultra-high reliability of 99.9999999 %. 6G is expected to support verticals like holographic and 3D integrations as well [7]. Table 1 presents an overview of the mobile communication shift from second generation (2G) communication to 6G.

In terms of application viewpoint, 6G would support low-rate and long-distance Internet-of-things (IoT) applications, process automation of cyber-physical systems in the industry, digital twins, holography, AI support with the complex machine and deep learning models, extended, virtual, and mixed reality applications, and automatic vehicular networks. Owing to the AI-enabled radio, it resolves the issues of fixed spectrum allocation in decentralized environments and covers for underutilized spectrum limitations. However, static spectrum allocation is mostly centralized, and thus, blockchain is a viable choice of fair spectrum allocations owing to the inherent benefits of fairness, immutability, and chronological access [8]. Moreover, in spectrum allocation, we consider a permissioned blockchain, where government, telecom providers, and spectrum licensing stakeholders are allowed to participate in the bidding process.

1.1 Research Contributions

Following are the research contributions of the paper.

- A reference model of 6G-envisioned blockchain-based spectrum allocation is presented, and a layered stack reference is proposed.
- A case application based on the proposed reference scheme is presented that discusses a reputation-based scorecard registration of new user in the proposed ecosystem.

Table 1 An overview of mobile communications shift from 2G to 6G [4]

Generation	2G	3G	4G	5G	6G
Year	1990	2000	2010	2018	2030
Technology	DBN-CD	DBB PD (IPv4)	LAN/WAN, Unified IPv4/IPv6, WLAN	LAN/WAN/PAN, Unified IPv4, WLAN, advanced OFDM	Blockchain-based spectrum, artificial intelligence, quantum communication, laser and VLC, THz communication
Technique	SISO	SISO	MIMO	m-MIMO	SM-MIMO, UM-MIMO
Frequency	850–1900 MHz	1.6–2.5 GHz	2–8 GHz	3–300 GHz	95 GHz–3 THz
Spectral efficiency	0.17 bps/Hz	1.3 bps/Hz	30 bps/Hz	120 bps/Hz	5–10 times that of 5G
Latency	300–1000 ms	100–500 ms	< 15 ms	< 100 ms	$< 10-100\ \mu s$
Connection density	Limited	100/km^2	1000/km^2	1,000,000/km^2	10,000,000/km^2
Mobility	–	–	350 kmph	500 kmph	1000 kmph

1.2 Article Structure

This paper is divided into five sections. Section 2 presents the state-of-the-art schemes that are proposed related to 6G and blockchain-based schemes. Section 3 presents the layered reference model of 6G-envisioned blockchain-assisted dynamic spectrum allocation, which is supported by a layered reference stack architecture in Sect. 4. Section 5 presents the case-study of the proposed scheme, and finally Sect. 6 concludes the paper.

2 State of the Art

In this section, we present the recent state-of-the-art schemes that integrate blockchain and 6G in telecommunications. Saravanan et al. [9] proposed the integration of blockchain for telecom providers to simplify their phone usage charging and billing operations. Via blockchain, the third-party intermediaries are removed, and inconsistencies in the management of large customer databases are simplified. The paper proposes that blockchain ledger can manage user call records in an immutable manner, and through smart contracts, roaming agreements between inter-telecom providers are also managed, and balance transfers are automated. This reduces the overall transactional fees of third-party payment gateways and improves the complexity of the overall billing ecosystem. Xu et al. [10] proposed a resource management scheme for spectrum allocation for mobile operators and presented a reference framework that manages resources and sharing in 6G-IoE ecosystems. The authors proposed a network slicing-based approach in 6G, and a slice-broker-based scheme to manage the 6G resource orchestration. The resource transfer is managed as transactional ledgers in the blockchain. Zhou et al. [11] presented a privacy-preserved 5G human-to-human (H2H), and machine-to-machine (M2M) scheme, where a cost-effective solution is presented to optimally utilize the spectrum resources. The paper introduces a two-phased scheme. In the first phase, H2H users and 5G-enabled base stations execute a smart contract for transactional payments, and spectrum is released. The spectrum is allocated to M2M devices, with an incentive-based design.

Zhang et al. [12] proposed a distributed citizens broadband radio access (CBRS) spectrum sharing scheme to address the limitations of administrative costs, and privacy-based attack scenarios by an adversary. The authors include a low-powered consensus mechanism known as proof-of-strategy that finalizes the spectrum allocation, even in case of node failures. Patel et al. [14] proposed a 6G-based blockchain-based spectrum allocation scheme between dynamic service operations in a cell-free spectrum. The paper proposes a dynamic auction and bidding process of spectrum allocation. Hewa et al. [13] proposed a survey that introduces blockchain potential in 6G verticals such as health care, Internet-of-vehicles, infotainment, augmented and virtual reality, and M2M communication. The challenges of 6G and potential pitfalls are identified, and blockchain-based solutions are proposed to allow distributed 6G protocols and standards.

Table 2 State-of-the-art approaches of integration of blockchain and 6G in telecommunications

References	Year	Major contributions	Application domain
[9]	2017	Blockchain-based consumer balance transfers, carrier billing, roaming settlements through decentralized application deployments	5G-based telecom service
[10]	2020	The complexities of adapting blockchain for spectrum sharing in 6G are discussed	6G-envisioned spectrum sharing and access and blockchain for license transfers
[11]	2020	H2H and M2M enabled spectrum sharing ecosystem, with blockchain-based transactional ledgers	Fair spectrum sharing through blockchain-based 5G dynamic spectrum access
[12]	2020	Optimal CBRS design service model through blockchain and 6G-radio access model	6G-CBRS allocation scheme with trusted blockchain ledgers
[13]	2020	6G technical key performance indicators (KPIs) compared against 5G KPIs in terms of specification, regulation, standardization, and design in different driving verticals	6G-benefits in IoT, industry 4.0, virtual reality, and autonomous driving
[14]	2021	In 6G ecosystems, blockchain-enabled trusted dynamic frequency spectrum allocation and auction scheme among telecom providers	6G-based dynamic spectrum allocation and bidding process via blockchain-based auctions
[5]	2021	6G-benefits and reference architecture in telecom servicing, IoE, and inherent limitations, with architectures of blockchain to mitigate the limitations	6G-IoE standards, interfaces, and protocol regularization via blockchain

Jiang et al. [5] proposed different 6G frontiers in different verticals of smart cities and discussed the requirement of 6G to handle a high volume of data traffic. Potential use cases and scenarios are discussed, and a tentative roadmap of 6G standardization is presented. The details of the recent schemes, their contributions, and application domains are discussed in Table 2.

3 A Reference Model of Blockchain-Based 6G-Spectrum Allocation

In this section, we present the founding concepts of blockchain and 6G services. The section presents a reference architecture that discusses the potential benefits of blockchain in 6G applications that handle the issues of trust, privacy, and secure transfer of resources among communicating entities. We start initially with the discussion of 6G emergence and then move toward the usage of blockchain to support secured 6G services. The details are presented as follows.

3.1 The Emergence of 6G and Blockchain in Communications

With the increase of communication networks, and stringent requirements of bandwidth, latency, and availability of resources, to support applications like extended reality, autonomous driving, Internet-of-drones, real-time sensing and control, an eight-year program, termed as *6Genesis* Flagship started with an estimated fund of 290 million dollars. The project started in 2018 by Finland, and soon researchers worldwide started with the design of protocols and standards for 6G communication networks. The key visions of 6G communication highlighted in Table 3.

Initially, started as cryptographic ledgers [15], blockchain gained prominence owing to its inherent benefits of trust, immutability in block creation, and verification and thus has become a driving force in different verticals like smart grids, autonomous vehicles, and Internet-of-things [16]. To secure the 6G connectivity perimeter, blockchain can mitigate security attacks like distributed denial-of-service, impersonation, replay, and certificate-based attacks [13]. Thus, blockchains empower decentralized cooperative applications and also ensure that data is exchanged by all parties involved.

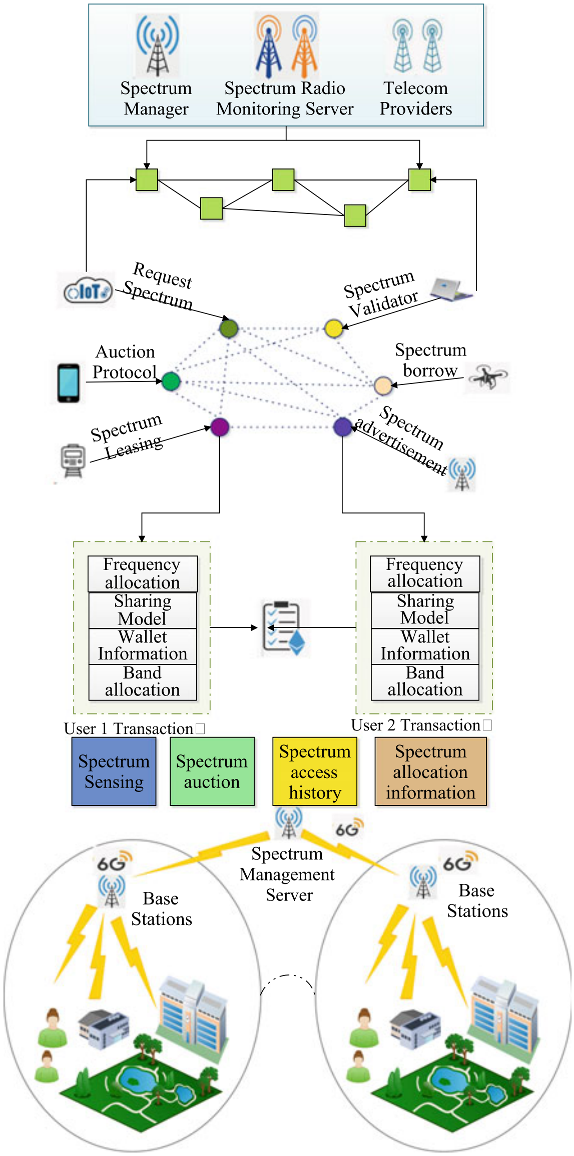
Table 3 Visions of 6G communication [4]

Key parameters	6G vision
Mobility (km/h)	1000
Peak spectral efficiency (b/s/Hz)	60
End-to-end latency (ms)	0.1
Reliability	10^{-9}
Connection density (device/km^2)	10^7
Area traffic capacity (Mbps/m^2)	1000
Channel bandwidth (GHz)	100
Spectral efficiency (b/s/Hz)	3
Energy efficiency (Tb/J)	1
User data rate (Gbps)	>10 Gb/s
Peak data rate	>100 Gb/s
Receiver sensitivity	< -130 dBm
Coverage	$>99\%$
End-to-end delay	<1 ms

3.2 A Proposed Reference Model

In this subsection, we present the reference model of blockchain-based 6G-spectrum access. Figure 2 presents the details of the proposed model. In the proposed model, we consider entities $E = \{E_{BS}, E_{SMS}, E_{AC}, E_{SL}, E_{TP}, E_{SB}, E_{SV}, E_{SR}\}$, where E_{BS} denotes the base stations (BSs) that are integrated with 6G services to support

Fig. 2 A reference model of blockchain-based 6G-spectrum access



dynamic spectrum access. E_{SMS} denotes the spectrum management server, E_{AC} denotes the spectrum auctioneer, E_{SL} denotes the spectrum leaser, E_{TP} denotes the telecom provider, E_{SB} denotes the spectrum borrower, E_{SV} denotes the spectrum validators, and E_{SR} denotes the spectrum requester, respectively. Depending on the specifics of spectrum resource allocations, the utilization of spectrum is only done post the auction process. To maintain the regulations and control in spectrum allocation, we consider E_{SRMS} that denotes the spectrum radio monitoring server, which is a government regulating body to manage and distribute the spectrum to E_{TP}, E_{RS}, E_{BS}. As the considered ecosystem is a multi-party decentralized system with different stakeholders like industrial applications, spectrum auctioneers, and buyers, borrowers, spectrum leases, and spectrum advertisers, we require trust in the ecosystem. For the same, we consider a consortium-based permissioned approach, where the transaction updates are shared only by registered stakeholders in the chain.

For the spectrum ledger, we consider the ledger L with the required fields, namely $\{\mathrm{AO}, \mathrm{AI}, \mathrm{SMod}, \mathrm{FA}, W_{\mathrm{U}}\}$, where AO denotes the asset (spectrum resource) ownership, AI denotes the asset meta-information, SMod is defined as the sharing model (competitive or collaborative), FA denotes the frequency allocated, and W_{U} denotes the wallet information of the user. The transaction ledgers are maintained through distributed offline storage (interplanetary file systems), where the ledger records are accessible by the IPFS key and the private key of the user only. We hash the stored record, $H(R)$, and store the record R indexed with its hash-pair $H(R)$. In the main chain, we store $H(R)$ only as a transaction, so that the record R may be retrieved by a search of the hash in the chain. Moreover, effective consensus schemes are required to be designed for E_{SV}, so that their incentives are maximized. Validators E_{SV} are chosen based on a reputation score R so that they add the transactions in a fair manner in the blockchain [17].

In the reference architecture, we consider servicing E_{BS} that provides network service to user sets $U = \{U_1, U_2, \ldots, U_n\}$. We consider a cell-based 6G grant spectrum access scheme, and two regions, R_1, and R_2, respectively. Any nth user in region R_1 is mapped to E_{BS} through a mapping $M_1 : U_n \rightarrow \mathrm{BS}_n^1$, and similarly, any user U_n in R_2 is mapped to BS_n^2, through mapping $M_2 : U_n \rightarrow \mathrm{BS}_n^2$. The user requests $R = \{R_1, R_2, \ldots, R_n\}$ are collected region-wise and send to E_{SMS} through directed 6G uplink frequency f_{u}. At E_{SMS}, the collected requests R are serviced as digital assets, and spectrum allocation requirements are advertised in the network, termed as spectrum advertisements. E_{SMS} handles the function of intelligent spectrum sensing through AI models and maintains spectrum access historical ledger entries by corresponding E_{BS}. The spectrum auction $A(S)$ is initiated at E_{SMS} depending on the base network requirements sent by E_{BS}. For the same, a list of freely available frequency $F(f_{\mathrm{r}})$ is maintained, which is collected through network entities like IoE networks, satellites, free users, vehicular networks, and others. The finalization and broadcast of available spectrum bands are termed spectrum leasing. For the leasing process, an auction strategy is set up between spectrum bidders and spectrum borrowers, with the peer-profit optimization strategy. The auction can be modeled through a cooperative game-theoretic approach, to maximize the incentives of both bidders and borrowers, through the designated set of auctioneers. Once the spectrum auction process is over, the spectrum grant is maintained as transactional ledgers in IPFS and meta-information are chronologically recorded in the blockchain. To spectrum transaction information is maintained in consortium blockchain, and the available usage and regulations are reflected all authorized nodes in the chain by E_{SRMS}. This ensures the transparency of spectrum allocation to all E_{TP} and mitigates the possible collusion among malicious bidder nodes.

4 The Layered Reference Stack of Blockchain-Based 6G-Spectrum Allocation Scheme

In this section, we propose the layered stack model of the proposed reference architecture that handles the issues of static spectrum allocation. Figure 3 presents the details. We consider a four-layered scheme, and the details are presented as follows.

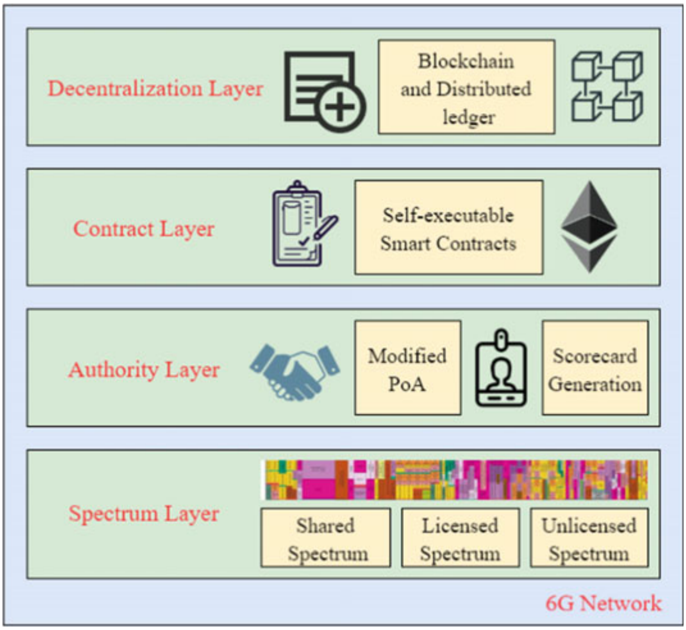


Fig. 3 Spectrum allocation using blockchain

4.1 Layer 0: The Spectrum Layer

At *Layer 0*, we assume the spectrum details are present, which is a cluster of frequency ranges $R(f)$, and consist of electromagnetic waves. Through $R(f)$, different communication devices such as TV, radio, mobile to send wireless messages across a certain distance d. The details of available spectrum bands are managed by E_{SMS}, and the allocation of bands to different servicing E_{BS}, of different E_{TP} is leveraged through a spectrum validator E_{SV}. The spectrum band is mainly divided into three regions as follows.

- **Licensed**: In the licensed band, a chunk of the radio spectrum is assigned to E_{SMS}, or E_{SRMS}, and is licensed as asset ownership by AO. Any user has to send a spectrum access request to AO, and the spectrum grant is defined for a definite time period T. Here, the access request is placed by E_{TP}, so they buy the licensed frequency ranges from $F(f_{\text{r}})$, for a given price, and allocate frequencies to E_{BS} through the servicing downlink F_{d}.
- **Unlicensed**: In this band, the available frequencies can be used by any user, and normal users also have access to the unlicensed spectrum. This type of spectrum does not involve a specific type of permission from either E_{SMS}, or E_{SRMS}. The applications of the unlicensed spectrum are IEEE 802.11 access, TV white spaces, and wireless personal area networks, like IEEE 802.15.x.
- **Shared**: In this band, the frequencies are shared among different users, and each user utilizes a chunk of the frequency band. This type of paradigms helps the users and devices to completely utilize the spectrum band.

4.2 Layer 1: The Authority Layer

The shared spectrum suffers from a lot of obstacles. Generally, the practice involves the centralization of shared spectrum management (by CBRS) [18]. Here, an intermediary is needed to manage the complete flow of control in the shared environment. The centralized systems suffer from various issues such as lack of adaptability, overburdening on the central authority, one-sided communication, and biases in decision making [14]. These issues lead to poor utilization of resources and a less secure system. In the proposed scheme, the authority layer validates the authority of the users in the ecosystem. For consensus, we consider a modified version of the Proof-of-Authority (PoA) consensus mechanism. The primary PoA works by allowing nodes to create initial blocks that have demonstrated their authority. Any new user in PoA has to prove the identity to get access to the spectrum. Once the identity authentication gets done, a scorecard is generated for the user. This process is iterated for each user in the network to prove the genuineness of the identity of the users.

4.3 Layer 2: The Contract Layer

To break the tie created by a centralized environment, the user needs a mechanism that can automate the flow of taking decisions in a very honest manner. For that, we use smart contacts. Smart contracts are self-executing code without any third-party (such as humans) interactions. In the proposed model, smart contracts ensure the storage of authorized user data published on IPFS, and meta-information stored in distributed ledgers. The access of IPFS is restricted through identity authorization and IPFS key.

4.4 Layer 3: The Decentralization Layer

At *Layer 3*, we consider the distributed blockchain ledger. New blocks are added only after E_{SV} validates the transaction entries. Every authorized user has a copy of ledger L, and L gets updated once the state of IPFS changes, to reflect new contracts executed in the network. Through 6G, ease of access and scalability of node communication are improved.

5 Case Study: A Scorecard and Reputation-Based Spectrum Allocation

In this section, we propose a case study that presents the usage of the shared spectrum. Figure 4 presents the details. The shared spectrum can be allocated to the user using the integrated technology discussed in Sect. 4.

In the use-case, we consider entity A_1 that wishes to access the joint spectrum for communication purposes. A_1 first registers himself in the network and has to undergo the PoA consensus where E_{SRMS}, or E_{SMS} validates A_1 identity to all users. Then, A_1 is granted access to spectrum resources. This whole registration process is automated via a *DApp* that executes a smart contract at the back-end between E_U and E_{SMS} and publishes the transactional state to IPFS. Also, other E_U ledgers are updated with the new entry in their ledgers. Here, A_1 is presented with a scorecard, and based on future transactions performed by A_1, the reputation score increases, and the access-grant time of shared spectrum is reserved for A_1 also increases. This reward-based technique ensures the authenticity of the users is managed in real-time through 6G service sets.

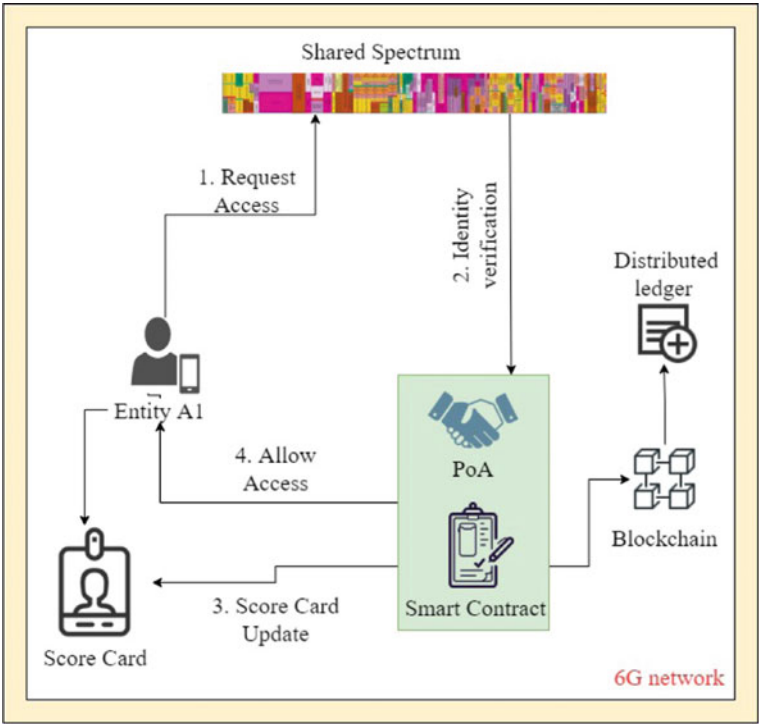


Fig. 4 Spectrum allocation using blockchain

6 Conclusion

The spectrum allocation process among competitive telecom providers and users is a complex problem. The problem is further intensified in decentralized environments owing to the issues of trust, alterations, and collusion-based attacks. Thus, in this paper, we have presented a reference model for blockchain-assisted dynamic spectrum access at the backdrop of 6G-envisioned communications. Through blockchain, a trusted chronology is maintained among distributed telecom stakeholders, and provenance is established. Owing to the high influx of network traffic, and users, 5G services would face bottlenecks in the near future. Due to this, we considered a 6G service set that provides intelligent and real-time network orchestration to users in the proposed ecosystem. A reference model is presented, and a supportive layered stack model is also proposed. Then, we present a reputation-based scorecard for registration of new users in the ecosystem that ensures the genuineness and transparency via PoA consensus in the spectrum allocation ecosystem.

As part of the future scope, the authors would investigate a deep reinforcement learning framework that manages the reputation of a user in the ecosystem and also would propose a cooperative game-theoretic approach to model and maximize incentives of the auction process.

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