Distributed Ledgers for Spectrum Authorization

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***Abstract*—The rising demand for wireless services can only be met if the available spectrum is shared effectively, and spectrum underutilization is avoided. This paper examines how a DLT-based spectrum authorization system may be designed considering its protocol, data, and network operational layers. Decentralization, automation, and verifiable trust achieved by this system facilitate spectrum sharing and trading, catering to business objectives in addition to the influences from regulatory and technological developments. To this end, we elaborate on the technical feasibility, scalability and business incentives for such a system to stimulate the multiple cross-industry stakeholders to use the radio spectrum more efficiently for 5G and beyond.**

***Index Terms*—Distributed Ledger Technology, smart contracts, spectrum authorization, 5G, emerging technologies**

I. Introduction

Aitken [1] states: "Scarcity is an elusive concept when applied to radio spectrum. On the one hand, there are ultimate limits set by the laws of physics, and on the other hand, there is an artificial scarcity created by human institutions". This artificial scarcity characterizes the present connectivity market, formed by incumbent mobile network operators (MNOs) with high upfront investments in infrastructure and extended-term exclusive spectrum licenses auctioned by the regulators. As the demand for spectrum continues to rise with 5G and beyond, this approach is not sustainable. It leads to wasted resources as the license holders do not continuously use their full spectrum allocation. Unlicensed spectrum is not a solution either; even though it offers lower entry barriers, it has the downside of no quality-of-service (QoS) guarantees [2].

A middle ground can be achieved by spectrum sharing and market-based approaches to spectrum allocation. Spectrum sharing improves spectrum usage efficiency by enabling access when incumbent systems are not active. Market-based approaches, on the other hand, take advantage of liberal licenses that allow trading and reallocation of spectrum in a fast time scale resulting in more dynamic spectrum allocations [3]. In this paper, we consider a single spectrum authorization platform for spectrum sharing and trading to coordinate stakeholders.

Technical advancements, e.g. in geolocation, spectrum sensing and databases, already enable more dynamic and flexible spectrum authorization. However, the success of a solution depends on the nature of the demand: how many players wish to share spectrum, the diversity of different service and deployment types, their capacity and QoS requirements and the complexity of coordinating deployments [4]. Spectrum users should be able to decide on their use continuously, not just at the time of the initial assignment. Adequate compensation mechanisms for sharing arrangements also play an essential role [5]. While most MNOs have embraced the mobile virtual network operator (MVNO) model to increase and diversify their revenue streams, few choose to share their networks or spectrum with direct rivals unless mandated by regulators.

In the absence of trust, and unwillingness to manage centralized systems, decentralized solutions become attractive. As also discussed in [6], [7], Distributed Ledger Technology (DLT)[1] can establish the necessary incentives for spectrum sharing and trading by facilitating:

- *Trust through inter-organizational record-keeping and transparency:* The ledger acts as an authoritative transaction log for collectively recording and notarizing data. The origin and movement of spectrum assets can be tracked in the ledger via virtual certificates of authenticity.
- *Automation via smart contracts:* Spectrum can be traded between participants using smart contracts on a ledger-based marketplace. This marketplace enables moving from a long-term contracts model towards a transaction-driven on-demand platform model. Automating agreement processes between companies and their partners and customers via smart contracts is expected to reduce the processing time and the administrative costs to initiate, negotiate and finalize contracts [8].
- *Decentralized optimization of multi-party coexistence:* Data about spectrum availability can be collectively managed and used to overcome frictions in coexistence and to improve interference.

In this paper, we take the discussion initiated in [6], [7] a step further and describe the governance, and protocol, network, and data operation layers of a DLT-based spectrum authorization system following the guidelines in [9].

The rest of the paper is organized as follows. Section II presents the state-of-the-art spectrum authorization solutions. Section III gives a general overview of DLT and outlines a spectrum authorization system over DLT. Section IV elaborates on the technical feasibility, scalability and business incentives of such a system. Section V concludes.

II. Overview of Spectrum Authorization Models

As shown in Figure 1, spectrum authorization can be categorized into licensed, shared, and unlicensed solutions with

† Part of this work was carried out when the author was with Nominet.

[1] While blockchains are a subset of DLT, we use these two terms interchangeably as the literature refers to most DLTs as blockchains.

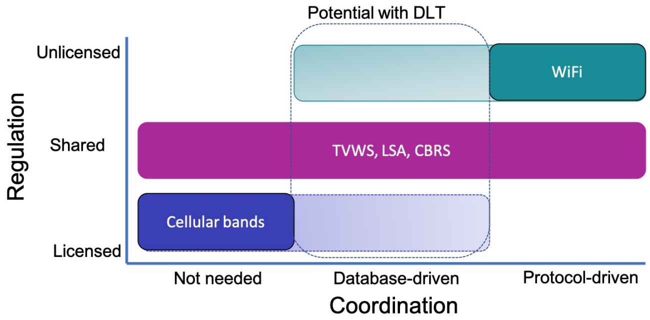

Fig. 1. Spectrum sharing: the current state and its potential with DLT.

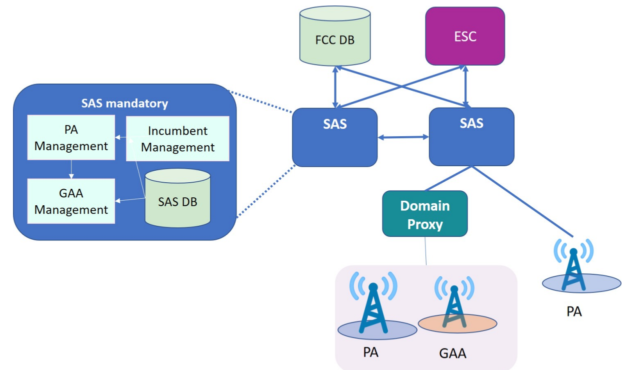

Fig. 2. CBRS system showing SAS interactions for incumbent protection, GAA and PA management. FCC DB is a repository for tracking information on devices, incumbents, and PA licenses. Environmental Sensing Capability (ESC) is a network of sensors monitoring frequency use in protection zones.

varying levels of coordination. Higher levels of coordination and sharing are expected to gain more acceptance as technical solutions mature and regulatory and business incentives emerge. Incumbents of the licensed spectrum can only be willing to share if there are benefits in the form of revenue increase, e.g. through direct payments from new users, or cost savings, e.g. on spectrum fees paid to the regulator for the underused spectrum. For users of spectrum sharing, the incentives include certainty of access to the spectrum, QoS, and return on investment [5]. Similarly, unlicensed spectrum users choose to coordinate to limit unwanted interference as their needs for certainty and QoS increase. DLT may be useful in nudging users to share and coordinate their spectrum use, by enabling transparency, automation and decentralization.

Spectrum sharing currently is managed through regulatory frameworks with three general levels of access rights: primary access, secondary access, and collective use [10]. TV White Space (TVWS) framework, which covers the temporarily or locally unused broadcast television channels in the 470-694 MHz bands, can be considered as the first generation of spectrum sharing. Regulators such as the FCC (USA) and Ofcom (UK) allow unlicensed access to TVWS. In the UK, a dynamic TVWS geolocation database coordinates the sharing of the spectrum. A TVWS device sends an access request, including its device identifier, device type and location, to the database. The database responds based on the interference at that specific location considering the information about the TV stations, antenna heights, antenna patterns, used channels and transmission powers. Hence, interference from TVWS devices on the incumbents is limited, while TVWS devices access the spectrum opportunistically without interference protection.

In Europe, the next generation of spectrum sharing is evolving in two ways: the Collective Use of Spectrum (CUS) allows multiple users without a license simultaneously and Licensed Shared Access (LSA), where users have individual rights to access a shared spectrum band [11]. LSA was mainly conceived to provide access to licensed 2.3-2.4 GHz bands. Using LSA, an incumbent shares its spectrum with new LSA licensees according to a sharing framework negotiated between them, and following the guidance of the national regulatory authority. The critical characteristic of LSA is the guaranteed protection from interference and predictable QoS for both the incumbent and the LSA licensee. LSA introduces two new system-level elements [12]: *LSA Repository* and *LSA Controller (LC)*. The Repository stores information about the availability and protection requirements of the LSA spectrum as well as the operating terms and rules to guarantee interference-free operation to the incumbent. The Controller grants access permissions to the LSA bands based on the information obtained from the Repository. Both the Controllers and the incumbents maintain the Repository to keep an up-to-date view of the interference environment.

CBRS is a three-tiered spectrum access system (SAS) model for the 3.5 GHz band in the USA (see Figure 2). The first Incumbent Access (IA) tier consists of the incumbents including authorized federal users and Fixed Service Satellite (FSS) earth stations. The second Priority Access (PA) tier covers critical access users such as hospitals, utilities and governmental users and non-critical users such as MNOs. The third General Authorized Access (GAA) tier can be residential, business and other users, including wireless telephone and internet service providers. The GAA tier uses the spectrum on an opportunistic basis without interference protection. To access the spectrum, the GAA users only need to access the SAS database and register their band-specific usage. SAS is central to controlling interference, enforcing protection criteria and exclusion zones for higher priority users.

Compared to these current solutions, the benefits of a DLT-based system may not be immediate. However, the strength of a DLT-based system is its potential to enable multiple sharing approaches, e.g. both primary or secondary cooperative sharing [6], using the flexibility brought by smart contracts. Interference protection algorithms, run as smart contracts, can immutably translate the rules, environmental inputs, and interference analysis into responses to spectrum requests. Additionally, by decentralizing the spectrum database, DLT achieves better transparency. In [5], [13], [14], stakeholders see transparency as significant as coexistence and interference problems. Mainly, those who demand more spectrum are unaware of where the spectrum is unused, while those holding idle spectrum are unaware of those that might be willing to pay for sharing. The next section explores how DLT can help create an authorization system that handles these issues.

III. A DLT-based Spectrum Authorization System

This section first presents an overview of DLT. The second part follows the terminology and the general framework proposed in [9] to describe the key elements of a DLT-based spectrum authorization system.

A. An Overview of DLT

A *distributed ledger* [9] is an electronic records system that enables a network of independent participants (nodes) to establish an agreement on the records stored. These nodes need to agree on the ordering of the records and cryptographically validate the transactions in them. The records are made persistent by replicating the data across multiple nodes, and tamper-evident by linking them with cryptographic hashes. The shared result of the agreement (or consensus) process is the ledger and serves as the authoritative version of the records.

Distributed ledgers use complex cryptographic data structures. In Bitcoin, this data structure is a blockchain, which compiles transactions into blocks of records. A *transaction*, in general, signifies any proposed change to the ledger and is digitally signed by its creator. In Bitcoin, a transaction represents the transfer of Bitcoins between different users.

The Bitcoin blockchain is created by chaining blocks using two cryptographic measures:

- Each block contains the hash of the previous block.
- Adding a block requires solving a cryptographic puzzle (called mining).

The blockchain data structure is incredibly hard to change: a change in one block requires mining the changed block as well as all the blocks accumulated on top of it. Furthermore, a network-wide consensus is needed to accept any block to the blockchain. Other DLTs use similar approaches to maintain the security of their distributed ledgers.

DLT also supports smart contracts, which are computer scripts residing on the DLT, and run when triggered by the system. Note that smart contracts are not legal contracts, but can be evidence of a legal contract, or a technological means of implementing an agreement within one [9].

DLT is by design a multi-user system enabling continuous, decentralized interaction among heterogeneous groups. Decentralization is indeed a critical feature of DLT. However, as a DLT system consists of multiple processes and subsystems, decentralization is not a simple binary property. The degree of decentralization depends on how different components and their interactions can be managed, and a range of options are possible within public, private or hybrid solutions.

Public solutions, like Bitcoin, are fully-decentralized open systems, and primarily record transfers of ownership of endogenous resources. On the other hand, private systems are closed using fine-grained authorization, typically reference objects external to the system, and depend on gateways for enforcement. In hybrid systems, records may reference both endogenous and exogenous data, e.g. a DLT system may issue a security that exclusively exists within the system's boundaries but, the same system may use off-chain cash flows, requiring a connection to an external system. Hybrid systems are fast-developing as corporations are increasingly attempting to convert existing assets on to a DLT [9]. Similarly, a spectrum authorization DLT is expected to require a hybrid system, which is discussed next.

B. A Spectrum Authorization System using DLT

DLT facilitates the necessary cooperation to exchange both spectrum assets and inter-organizational data between non-trusting, competitive, but cooperative stakeholders [15]. In the following, we present the system model, the governance, and the operational layers of a hybrid DLT system.

1) Assets and token model: To represent spectrum assets on a DLT, they need to be well-defined in space and time scale, and the smaller the scale, the more fluid is the resulting spectrum market [3]. Using this scale, the spectrum rights are tokenized, i.e., the legal ownership rights to the asset are represented as asset tokens that can be traded on the DLT-based system. The system may also support utility tokens, which are earned as a result of service, e.g. sharing spectrum with secondary users or spectrum sensing [16]. These tokens may be used towards gaining access to a service within the DLT system. Utility tokens can also be exchanged for asset tokens. If a market for these tokens emerges, these tokens can be traded for fiat or cryptocurrencies.

2) Governance: The system is managed through a consortium in a regulated multi-enterprise set-up. Both on-chain and off-chain governance are expected to describe the full set of processes and norms for the consortium. On-chain governance is part of the prococol layer of the DLT system and is linked to the alteration component (see Section III-B3). The consortium is also expected to agree on processes and responsibilities off-chain, e.g., based on a regulator's rules on spectrum sharing, which is discussed next under Administrators.

Several actors are needed to operate this system and fall into four principal groups: administrators, developers, gateways, and participants [9] (see Figure 3).

- **Administrators:** The administrators group may include different entities like spectrum license holders, spectrum license requesters, and the national regulatory agency. These entities form a private DLT consortium, where the regulator acts as the spectrum asset *issuer*. Spectrum license holders such as network operators act as *exchanges*. The regulator establishes rules for network access, spectrum pricing, competition, privacy and data protection [17]. The regulator (or a contracted technology partner) authenticates potential consortium members and transfers asset tokens to the exchanges. Note that regulators do not need to be record producers on the DLT, but they are expected to perform audits and observe market trends.
- **Developers**: Initially, the DLT system may require intensive software development, including the core protocol,

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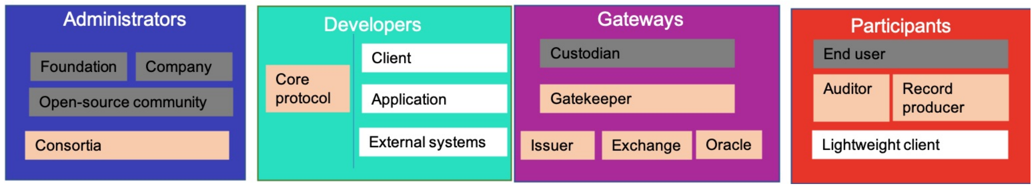

Fig. 3. The actors of a DLT system. The actors that are not expected to play a significant role in spectrum authorization are grayed out. The developers of the core DLT protocol, the gatekeepers to the system, auditors and record producers are part of the consortium and colored the same. The consortium may be open to other actors.

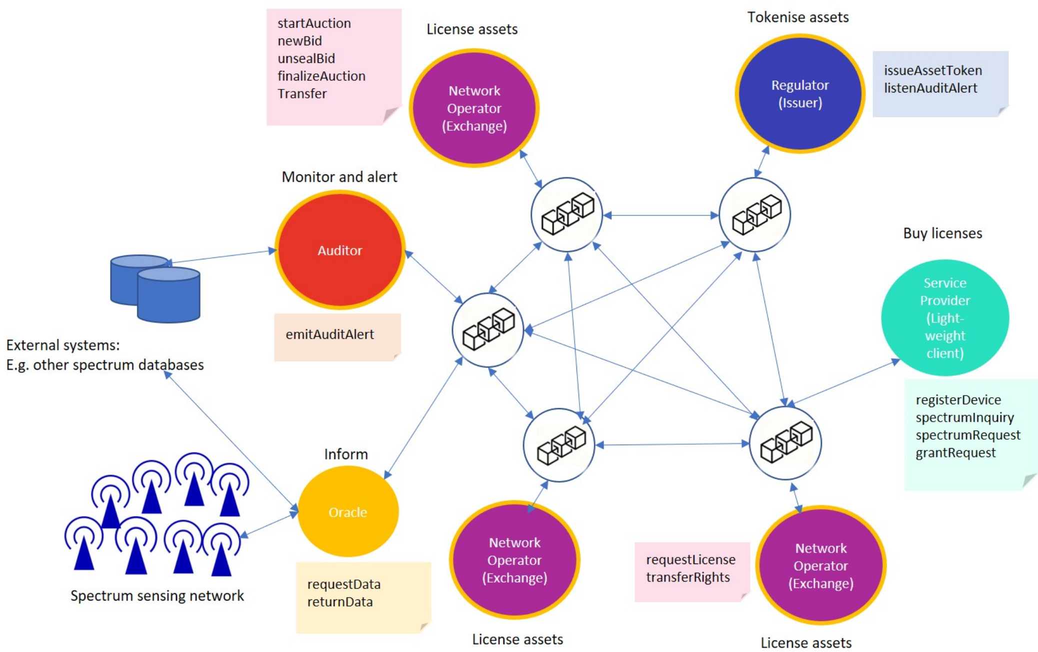

Fig. 4. The interaction of the different actors within the DLT system. The proposed system accesses external systems for auditing and interference management. Smart contracts are used to issue asset tokens, and for spectrum trading.

software clients, applications, and external systems. The consortium is expected to maintain the core protocol[2] and keep the system up-to-date. Therefore, a dedicated consortium member may take the developer role, proposing changes, which are 'ratified' by other members independently. Other software and external system development can be run independently of the consortium.

- **Gateways**: The consortium assigns a gatekeeper to manage access to the closed system. The verification of participant devices may also be critical to ensure that a grant to operate is not given to a device that is not compliant with the technical rules of the band. The DLT system needs also gateways to communicate with the external systems. Static and dynamic inputs on the spectrum environment, which include terrain and clutter data and sensing data, are produced and maintained off-ledger via, for example, spectrum databases or spectrum sensing networks [16]. Information from these external systems can be brought on to the ledger via *oracles*.
- **Participants**: The DLT system needs *record producers* and *auditors* to keep the system functional and secure. The members of the consortium should fill these roles. Other participants include lightweight clients run by *service providers* providing an interface to customers, e.g. allowing them to renew spectrum grants.

While DLT helps eliminate intermediaries, the following actors may also be needed. A *transaction enabler* may provide easier access to the spectrum assets by aiding the discovery and use of smart contracts helping to match resources and needs. A *band manager* may help plan and package a block of spectrum for trading, and act as the first port of call to investigate and resolve interference caused by its customers.

Figure 4 shows the main actors and their interaction with the proposed system. The figure also shows an exemplary list of functions in smart contracts deployed by the different consortium members. The distributed ledger, combined with the smart contracts, enables the following for its users:

- **Inter-organizational record keeping and trans-**

[2]Initial code base and architecture specifying the rules of engagement within the system as well as the rules for its alteration [9]

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parency: All the consortium members should be able to propose their records to add to the ledger, validate and audit them.

- **Automated transactions for spectrum trading and sharing:** Exchanges and service providers may deploy different contracts to trade spectrum and grant spectrum requests. A service provider contract may include functions for registering devices, receiving spectrum inquiries and granting spectrum. A spectrum exchange may grant another user transmission rights limited by time, geography, or throughput. Proof-of-time and location for emissions can be collected through the spectrum sensing networks. Transactions can also be conditional on verification of payment, or device compliance with transmission protocols. Exchanges may support different models for trading their spectrum (e.g. auction-based). The different incentives and business models for smart contracts are discussed in Section IV-B.
- **Multi-party coexistence optimization:** This is necessary to protect incumbent licensees or other users from interference caused by entrants with lower priority (and, in some cases, to coordinate users with the same priority). The impact of emissions on interference should be analyzed, but such an analysis may not be suitable to run over the DLT. The necessary information, timestamped and geocoded, can be brought over by oracles, and protection algorithms can be run as part of smart contracts [6].

3) The Operational Layers of the DLT system: A DLT system can be divided into three operational layers [9]. The protocol layer defines how the system operates and has two main components: genesis and alteration. The network layer is composed of three components, including communications, transaction processing, and validation. The data layer is divided into operations and journal components. Figure 5 shows the proposed configuration for different components of the respective layers.

Figure 5 also highlights other platforms that fulfill similar features. The platforms considered include Bitcoin, Ethereum, Ripple, and Verified.me based on the analysis in [9].

Protocol layer. The genesis component describes how the DLT system bootstraps. The spectrum authorization system should be self-sufficient but interfaces to external systems through oracles, and other types of gateways. The code base is expected to be closed-source but may be developed based on an existing framework. The consortium defines the formal rules of the network and administers the DLT.

The alteration component describes how the protocol layer evolves with time. Core protocol change proposals go through the consortium and are most possibly closed to externals. For proposing changes, several models can be tried. The voters can be given equal or different voting weights, prioritizing a minority of voters based on their stake in the system. Given the closed-source nature of the code base, the anarchic and open alteration configurations seen in Bitcoin should be avoided, and the best fit is the platform supported by Verified.me, which employs a formal change management process.

Network Layer. The communication component describes how the network is accessed, and data propagates within the network. The network access can be restricted partially or totally, requiring a gatekeeper to on-board new members. In the partially-restricted configuration, applications from prospective participants are decided by on-chain voting or consensus.

The consortium members are expected to be full nodes performing all or a subset of the necessary functions, such as receiving, validating, and broadcasting transactions and records. Lightweight nodes can be supported to allow participants to create transactions, but they cannot join in record validation or production. API access can be given to customers so that they can connect to a full or light-weight node.

For data broadcast, the proposed system supports a hybrid model, where certain transactions require global consensus. To achieve a higher spectrum market fluidity, and cater to almost real-time transactions, a multi-channel model is also envisioned, which allows transacting parties to create their private state channels and rely on local consensus.

For the transaction processing component of the network layer, only a subset of nodes acts as record producers. The system needs to decide a consensus algorithm, which is essential to resolve disputes regarding competing or conflicting versions of valid records. The record producers are not expected to need intrinsic monetary incentives, but incentives may be extrinsic (e.g. service fees) and non-monetary (e.g. reputation). External systems, such as sensing networks, are typically paid services.

Transaction validation is essential to keep the system secure in any system, regardless of the system in question is open (e.g. Bitcoin) or closed (Verified.me). Ledger operations may introduce latency in registering transactions, e.g. due to block latency when nodes wait for enough requests to fill a block to deem it a candidate for the ledger, and a consensus is reached. However, provisional records should finalize after a short time window, or otherwise, this would lead to missed communication opportunities, and failing customer requirements. Hence, a trade-off between overhead and latency needs to be struck to enable near-to-real time operations in the DLT [6]. The platform used by Verified.me is again the best fit, but its exact consensus algorithm is unknown.

Data layer. This layer describes the data input and the execution environment. The envisioned system needs to accept data from both internal and external sources. Also, if the multi-channel model is supported, then some data from these private DLT channels may need to be on the ledger as well. The journal component describes the state of the records before they enter the ledger, and in the proposed system, these may hold internal, external and smart-contract related data.

The spectrum trading related agreements are executed as smart contracts. Most smart contract executions take place on-chain, but heavy-weight interference calculations are carried out off-chain and brought into the DLT system via oracles.

These configuration decisions reiterate the need for a hybrid DLT. A closed system of spectrum exchanges, certified by the regulator, is needed to ensure the legitimacy of trading. With

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Layer	Component	Function or capability	Configuration	Example platforms with similar features
Protocol Layer	Genesis	Inter-system dependency	Self-sufficient system that interfaces with other external systems.	
		Codebase creation	Closed source, may be based on existing framework.	
		Rule initiation	Formal protocol specification.	
	Alteration	Protocol governance	Consortium	
		Protocol change	Filtered or authorized alteration. Changes are pushed to clients.	
Network layer	Communication	Network access	Semi-open or closed. A form of gatekeeping is used.	
		Data broadcast	Possibly both universal and multi-channel data diffusion.	
		Transaction initiation	Network participants can create transactions.	
	Transaction processing	Record proposal	Possibly permissioned to a subset of participants.	
		Conflict resolution	Exact consensus algorithm needs to be defined.	
		Incentivized transaction processing	Possibly non-monetary such as reputation within the DLT. Externally, paid services.	
	Validation	Transaction validation	Auditors/listeners validate each transaction visible to them.	
Data layer	Operations	Input	Internal sources: transactions, records, automated executables; External sources: Sensors, information providers; Hybrid sources: Generalized state channels.	
		Programmatically executed transactions	Stateful.	
		Locus of execution	General purpose virtual machine on chain, some logic executed off chain.	
	Journal	Reference	Internal, external or hybrid data or self-referential as in smart contracts.	

Fig. 5. The layers of the DLT system and possible configurations within each layer to support spectrum authorization. The final column shows which of the example platforms, Bitcoin, Ethereum, Ripple, and Verified.me (in the given order), share similar features.

such built-in trust, the latency, bandwidth and energy cost of running the DLT system can be lowered, avoiding costly proof-of-work consensus mechanisms. For spectrum trading, the DLT system would require multiple contracts deployed by independent parties and is expected to need stateful transactions and endogenous and exogenous sources for data. Also, like Verified.me, some business logic may need to be implemented off-chain. None of the compared platforms singly provide all the necessary features, and therefore, we need new solutions to realize a DLT-based spectrum authorization system.

IV. Discussion: Challenges and Limitations

This section presents a discussion on DLT-based spectrum authorization in three dimensions: DLT-specific concerns, business viability, and spectrum sharing aspects. Innovation is needed in all three to build a successful solution.

A. Business: Ecosystem Readiness

Spectrum trading requires a sufficient number of market participants to be viable, and the amount of tradable spectrum should be balanced with the demand. A DLT-based system may help lower the barriers, attracting new market participants.

Developments show different rates of interest from the different actors. The regulators have been adopting a wait-and-see approach, but some, like the National Frequency Agency of France (AFNR) is considering blockchains to manage the unlicensed spectrum [18]. Telecom operators know that their customers want to connect anytime, anywhere, seamlessly, and securely, and may not even care which provider supplies their service. Therefore, using DLT for provisioning, and trading agreements through smart contracts is an attractive option. However, current work is in its infancy, and the consortia like Carrier Blockchain Study Group mainly focus on issues like secured global digital payments.

B. Business/DLT: Incentives and Business Models

The envisioned DLT system supports both asset and utility tokens. Participants are rewarded with utility tokens for sharing their spectrum or providing sensing data. Smart contracts establish the required payment mechanisms. Utility tokens and asset tokens may be traded, if a market for them emerges.

In situations which a buyer does not know the seller's cost and the seller does not know the buyer's willingness to pay, bilateral trading is known to be inefficient. However, if a market is liquid with negligible transaction costs, and there are a large number of potential buyers and sellers, problems disappear. Smart contracts here may help by driving the cost of business transactions down.

However, how the incentive and operational cost structure might work to support the DLT-based operation would certainly need more study [6]. In current systems such as LSA, spectrum trading or licensing for spectrum incumbents, is entirely voluntary. To incentivize spectrum sharing, the regulator may need to set new rules or increase license fees [19].

The DLT system is not expected to require internal incentives for its private consortium members (e.g. transaction fees or cryptocurrency rewards for record producers) to keep the system running [20]. Network operators may support the network either by funding development and maintaining nodes. The consortium may establish DLT membership fees to recover DLT management and running costs. Membership fee plans may be set according to the contribution to the DLT system and spectrum sharing.

C. DLT/Business: Scalability

A scalable business model builds on a scalable infrastructure and processes. DLTs admittedly have scalability problems with leading public DLT platforms capable of only 10s of transactions per second. Private DLTs may improve on these speeds to 1000s of transactions by adopting different trust and consensus models.

In the considered system, the ledger serves mainly as an authoritative summary and index for essential data. Other data, such as inter-SAS communication or interference measurement reports in a CBRS system [15] may be too costly to maintain in a DLT. This type of data is brought on the ledger only when needed. As the research on DLT state channels matures, we expect the DLT system to support multi-channel data dissemination for more efficient spectrum coordination. Another solution to improve scalability is to archive historical data.

On top of DLT scalability, business scalability is achieved via the automation of processes via smart contracts, which are discussed next.

D. DLT/Business: Viability of Smart contracts

Smart contracts are expected to be a good fit to implement Service Level Agreements (SLAs), e.g. between small cell providers and MNOs [21]. However, the usefulness of smart contracts may be limited due to issues with legal enforceability and transactional confidentiality. For smart contracts to carry any weight, clear regulatory frameworks need to be defined for the implementation of agreements. Hence, the proposed system expects the involvement of the regulator in the DLT consortium. Other recommendations include inserting a dispute resolution mechanism into the smart contract code, duplicating the contract in natural-language documentation, or maintaining "split" contracts with broader obligations, not representable in code, are written in natural language [22].

If implemented correctly, smart contracts may increase the speed of numerous business processes. The expected reduction in business costs is also due to transparency and immutability. Record transparency enables businesses to analyze and review the past behavior of potential trading partners without having to rely on reputation or recommendations of others, which may be especially important for newcomers to the market [23]. Transaction costs may also reduce as responsibilities and obligations are codified and executed with certainty. However, [24] argues such rigidity may not be desirable where business adaptability is needed, eventually driving the cost of setting up the actual contracts. For the spectrum sharing context, the uncertainty over contract terms may be bounded due to regulation, and therefore, cost savings may still be achieved.

E. DLT/Business: Security and Privacy

It is envisioned that exchanges need to register with the regulator to request exchange privileges and are issued asset tokens before they can operate on the DLT-system. It is also expected that a DLT-gateway authenticates and authorizes all participants, e.g. using Public Key Cryptography. For exchanges to authenticate (preferably anonymously) and verify each other's legitimacy, an anonymous digital signature technique as in [25] may be used.

The system should use encrypted channels for communication to ensure confidentiality. Data shared via off-chain communication is timestamped [26] and recorded on the chain via its hash.

In terms of smart contract security, given the permissioned nature of the DLT, the risk of a participant intentionally introducing malicious code is diminished. Also, all actions, e.g. transactions, modifying the network configuration or deploying a smart contract, are recorded on the DLT, making it very hard to cover tracks.

F. Spectrum sharing/Business: Limits on Sharing and Coexistence

When opening the spectrum to trading, the amount proposed for trading cannot be too small to be practical, resulting in the inefficient use of spectrum. Similarly, the leftover spectrum from trading cannot be too small such that it changes the essence of the spectrum owner's initial license. Also, for coexistence in cross-border areas, border protection, and international obligations must be met. Finally, the regulator should ensure the competition is not distorted by speculation, or against the interest of national security [27], e.g. by transaction validation rules or by triggering audit breach events.

G. Spectrum sharing/DLT: Cognitive Radios

While regulation moved away from the concept of cognitive radio (CR) [14], in the future, CRs may be used for dynamic spectrum access. In the DLT context, a CR can interact with the DLT to learn about the current spectrum sharing agreements. Then, it can determine its best operational carrier frequency and also, lease it directly from the DLT. This ability would enable even more dynamic spectrum authorization, reconfiguring network deployments according to local spectrum availability [28].

V. Conclusions

In theory, when there are no transaction costs, the overall proceeds from the spectrum can be maximized by spectrum users exchanging use rights between them, either for money or by barter, which consequently resolves interference between them [29]. DLT-based systems can approach this maximum using smart contracts that lower the managerial and legal costs of transactions. DLT also enables the flow of information about the availability, liquidity and predictability of shared spectrum, creating a transparent market. Furthermore, automation with cryptographic verifiability increases and builds trust between key stakeholders, which is an essential trigger for any spectrum sharing. Therefore, simplification of trading rules would enable and, possibly, incentivize licensees to invest in this DLT system, in which a spectrum owner or licensee is granted the legal authority to act as the exchange of its licensed spectrum. Hence, the spectrum owner can decide the extent it leases its spectrum and how it arranges these leases to the third-parties while keeping the regulator as part of the stakeholder consortium. Such a DLT-based system can introduce the urgently needed transparency and flexibility into spectrum authorization.

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