POST: Programmable Open Spectrum Twin for Enhanced Spectrum Sharing in 6G Bands

Sayanta Seth, Ta-Seen Reaz Niloy, Md. Zoheb Hassan, and Vijay K. Shah

Abstract

This paper puts forward an advanced dynamic spectrum sharing framework, POST (Programmable Open Spectrum Twin) for 6G bands. By combining O-RAN (Open Radio Access Network) and DT (Digital Twin) technologies, POST addresses the limitations of legacy spectrum-sharing systems like TV White Space (TVWS) and Spectrum Access System (SAS) and even recent developments like Proactive Spectrum Adaptation Scheme (ProSAS). Key features of POST include real-time monitoring and prediction of spectrum-sharing scenarios, creation of new spectrum opportunities for 6G cellular infrastructure and the future provision of protection of incumbent users in the mid bands. POST integrates AI/ML for intelligent decision-making, enabling dynamic resource optimization and proactive interference management. Unlike the state-of-the-art, POST offers enhanced real-time adaptability, improved interference mitigation, scalability in complex environments, and "what-if" simulation capabilities for policy testing. These innovations position POST as a crucial technology for fostering sustainable spectrum utilization and establishing a robust foundation for 6G and beyond networks.

Introduction

With the expansion of wireless communication networks, sixth-generation (6G) networks will cover a broad frequency range beyond traditional cellular bands. Specifically, mid-band frequencies from 7 to 15 GHz, including 7.125 — 8.5 GHz, 10.7 — 13.25 GHz, and 14 — 15.35 GHz, are expected to play a crucial role [1]. While exclusive spectrum licensing remains ideal, dynamic spectrum sharing (DSS) is essential for rapid and flexible access to these new bands. Given the presence of federal incumbents, such as government and satellite systems, innovative sharing solutions are required to unlock their potential for next-generation wireless deployment. DSS enables cost-effective capacity expansion by utilizing underutilized frequency bands without displacing incumbents [2]. Effective interference management, compliance enforcement, and coexistence strategies are essential for accommodating 6G wireless networks in mid-bands.

Legacy spectrum-sharing systems, such as Spectrum Access System (SAS) in Citizens Broadband Radio Service (CBRS) band and Television White Space (TVWS) band, face limitations in dynamic environments. SAS suffers from high operational latency, requiring up to 240 seconds for channel evacuation, making it unsuitable for fast-moving federal systems in the lower 3 GHz band. It also relies on costly, interference-prone Environmental Sensing Capability (ESC) sensors, lacks context-awareness (e.g., weather, traffic priorities), lacks bi-directional communication, and employs worst-case interference assumptions due to the absence of intelligent algorithms [3], [4]. TVWS, though effective for rural long-range connectivity, struggles in urban areas due to less robust interference models, outdated geolocation databases, slow setup times, and limited capacity, restricting its use in high-density environments [5]. These challenges underscore the need for adaptive, real-time spectrum-sharing solutions.

Open Radio Access Network (O-RAN) and Digital Twin (DT) technologies offer complementary advantages, enhancing network efficiency and adaptability [6]. O-RAN enables network virtualization and disaggregation, supporting AI/ML-driven optimization and real-time RAN control, while DT provides accurate digital replicas of the RAN, enabling predictive analytics, AI/ML training, and performance assurance without disrupting live networks. Integrating DT with O-RAN enhances spectrum management, optimizes resource allocation, and enables safe policy testing before deployment. This synergy can overcome several limitations of legacy spectrum-sharing systems, such as high latency and static interference models. O-RAN's AI-driven control, combined with DT's real-time simulations, enables dynamic spectrum allocation and interference mitigation, offering a scalable and efficient alternative to traditional frameworks.

In this paper, we propose an advanced dynamic spectrum sharing framework, dubbed ***POST*: Programmable Open Spectrum Twin**, that features a novel, fundamentally new spectrum sensing and spectrum management infrastructure, based on O-RAN and DT. POST will monitor spectrum-sharing scenarios, predict future actions, and create new spectrum opportunities for 6G cellular infrastructure without compromising incumbent users in the shared mid-bands. The contributions of this paper are threefold. First, a detailed O-RAN-compliant architecture of POST

This work was supported by NSF under Award 2443035 and Award 2128584.

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Digital Object Identifier: 10.1109/MCOMSTD.2025.3645000

is proposed, defining its core components — DT, Intelligent Spectrum Sensing Unit (ISSU), and Intelligent Spectrum Management Unit (ISMU), along with an end-to-end workflow illustrating how these modules leverage O-RAN's RAN Intelligent Controllers (RICs) and standardized interfaces to enable closed-loop, context-aware spectrum decision-making. Second, the paper highlights the unique capabilities of POST over existing DSS frameworks, stemming from the seamless integration of O-RAN and DT. Finally, a proof-of-concept implementation of POST demonstrates its effectiveness in achieving near–real-time spectrum management in a realistic suburban 12 GHz coexistence scenario.

State-of-the-Art Spectrum Sharing Systems

Dynamic Spectrum Sharing (DSS) is a technique that enables efficient utilization of spectrum by dynamically allocating it based on real-time demand and availability. DSS ensures optimal spectrum usage while minimizing interference by allowing multiple users to share the same frequency bands under coordinated management.

DSS Overview: Fig. 1 gives a pictorial representation of DSS scenario. Broadly classified, traditionally, a DSS system is either database based or sensor based. Database-based DSS is a method that relies on a centralized database to manage and allocate spectrum resources [10]. In this system, the database maintains detailed records of spectrum availability, usage patterns, and restrictions based on regulatory and operational policies. Devices or users query the database to determine which frequency bands are available for use at a given time and location. On the other hand, sensor based DSS relies on real-time environmental sensing to detect spectrum occupancy and manage its allocation dynamically [11]. Devices or infrastructure equipped with spectrum sensors monitor the radio environment to identify available frequency bands, detect interference, and adapt usage accordingly. 6G wireless infrastructure will leverage both approaches, integrating database-based systems for broad-spectrum policy guidance and sensing-based systems for real-time adjustments. This hybrid strategy will ensure a balance between scalability and responsiveness, addressing the diverse demands of next generation wireless networks.

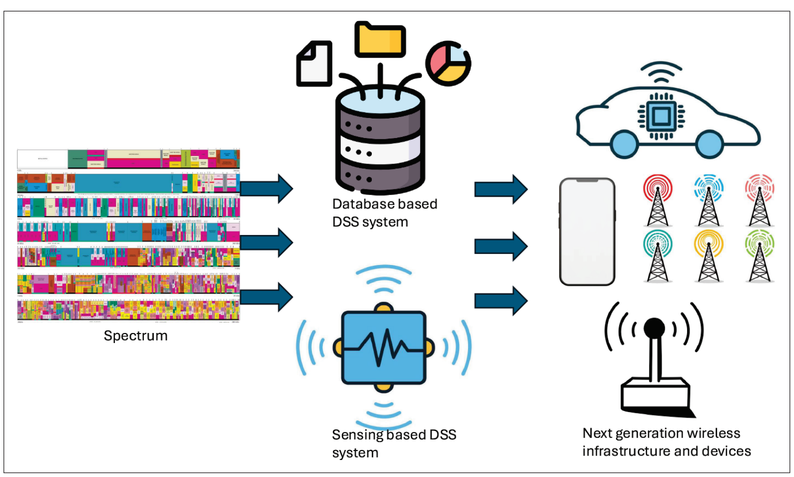

FIGURE 1. Database and Sensing Based DSS.

State-of-the-Art DSS Systems

Citizens Broadband Radio Service-Spectrum Access System (CBRS-SAS): The increasing demand for delay-sensitive applications, such as voice, video, and data services, has made efficient spectrum utilization a pressing challenge. To mitigate spectrum scarcity, the Federal Communications Commission (FCC) has enabled commercial use of the federally held CBRS band, also known as the 3.5 GHz spectrum band [12]. A centralized SAS manages the allocation of this band among incumbent users (i.e., federal radars), Priority Access License (PAL) users, and General Authorized Access (GAA) users, who utilize the spectrum opportunistically in descending priority order.

Challenges of SAS: SAS faces challenges that affect its effectiveness, particularly in dynamic and high-demand environments like the FR3 band. Protecting incumbent users can disrupt access for PAL and GAA users, especially in coastal areas, adding complexity and delays in reallocating spectrum, particularly for time-sensitive applications. The system's centralized coordination introduces further delays, reducing its ability to handle fast-moving scenarios. Strict power limitations within the CBRS band restrict coverage and signal strength, especially in wide-area deployments like rural applications. SAS also struggles with interference management in densely populated areas, where co-channel conflicts may degrade service quality. Mobility adds complexity, as handovers in shared spectrum environments can disrupt mobile service. Security and privacy risks arise from sharing operational data with SAS, and reliance on external sensor networks like ESC increases susceptibility to interference and inaccuracies in detecting incumbent signals. These limitations highlight the need for more agile, context-aware spectrum-sharing solutions to better handle fast dynamics and mitigate interference in high-demand scenarios.

Television White Space (TVWS): A significant portion of the lower-band spectrum initially allocated for TV broadcasting remains unused. This band includes frequencies within the Very High Frequency (VHF) and Ultra High frequency (UHF) spectrum, specifically between 470 and 790 MHz (in the United States). In the TVWS system, these frequencies are repurposed to deliver wireless internet services

Challenges of TVWS: TVWS faces operational challenges that limit its effectiveness, particularly in high-demand or urban areas. Its reliance on interference calculation models, which are less robust than other systems, can lead to inaccuracies and interference with incumbent services. Due to the slow setup time, rapid spectrum allocation is non-trivial in TVWS. Besides, TVWS is more suited for rural areas with spectrum underutilization but may struggle with capacity and interference in urban settings. Furthermore, its dependence on geolocation databases for managing exclusion zones (EZs) can result in inaccuracies, especially in areas with frequent environmental changes. These limitations affect scalability, real-time accuracy, and interference management in dynamic environments [5].

Recent Progress

Zone Management System: Recently, the authors in [13] have proposed a DSS system called Zone Management System (ZMS). The authors present a scalable, reactive framework for spectrum sharing between Radio Dynamic Zone (RDZ) transmitters and a sensitive receiver. The framework coordinates spectrum access using the ZMS, which relies on interference detection by the sensitive receiver. Utilizing energy detector-based sensing, the sensitive receiver monitors interference and alerts the ZMS, which dynamically revokes or restores spectrum access to RDZ transmitters to mitigate interference. ZMS aims to minimize interference duration at the sensitive receiver while maximizing spectrum utilization within the RDZ and focusing on aggregate impacts rather than individual signals. However, ZMS does not mitigate interference among RDZ users.

Proactive Spectrum Adaptation Scheme: Another recent progress is [7], where the authors have proposed a DSS system called the Proactive Spectrum Adaptation Scheme (ProSAS). The authors present an intelligent, data-driven framework for spectrum sharing between Long Term Evolution (LTE) and New Radio (NR) networks within an O-RAN architecture. The framework leverages AI/ML-based decision-making to predict radio resource demand and dynamically allocate spectrum, ensuring efficient utilization. Utilizing intent-driven spectrum management, ProSAS minimizes surplus or deficit spectrum allocation for both LTE and NR networks. By proactively adapting spectrum usage based on network demand patterns, ProSAS enhances spectrum efficiency while maintaining compatibility with incumbent systems. ProSAS optimizes spectrum access across multiple bands, ensuring scalability and adaptability in complex environments.

Unique Capabilities of POST

State-of-the-art spectrum sharing systems lack smart decision-making capabilities and support of modular RAN frameworks that act as enablers of next generation smart spectrum sensing and management solutions in the real time or near real time situations. POST overcomes such limitations by creating real-time digital replicas of network elements, enabling dynamic resource optimization through real-time simulation of network behaviors, traffic patterns, and interference without impacting live operations. As shown in Table 1, POST outperforms TVWS, SAS, ProSAS and ZMS in key functionalities, making it a more advanced spectrum management solution. Unlike SAS and TVWS, POST integrates AI/ML-based decision-making for proactive interference management. It also enables real-time interference prediction and dynamic resource optimization, ensuring faster and more efficient spectrum allocation. While ZMS and SAS rely on database-based access control and geolocation-based interference avoidance, POST enhances these with greater scalability and multi-band adaptability. Unlike SAS, TVWS, and ZMS, which react to spectrum changes, ProSAS offers limited proactive decision-making through demand prediction. In contrast, POST employs AI/ML for a more advanced proactive approach to spectrum deconfliction. POST's DT component further enhances its proactive capabilities by enabling "what-if" simulations for policy testing. Designed natively for near and non-RT RAN Intelligent Controllers (RICs) in the O-RAN architecture, POST ensures intelligent spectrum management through standardized open interfaces, making it a versatile, beyond-5G spectrum-sharing framework.

Remark 1: The integration of O-RAN and DT technologies makes POST uniquely capable of incorporating AI/ML algorithms. In particular, POST eliminates the need for external AI/ML training systems, as O-RAN natively supports the full AI/ML lifecycle—training, validation, and fine-tuning directly within the RAN. This capability is critical for continual model adaptation to dynamic RF environments while mitigating latency and privacy risks associated with data transfer to external servers. Moreover, POST addresses data scarcity in AI/ML training by leveraging O-RAN's extensive Key Performance Measurement (KPM) data collected via the O1 interface and augmenting it with large-scale, site-specific datasets generated by the DT. Since the DT is hosted within the SMO, these synthetic datasets can be seamlessly integrated with O-RAN-collected data to enhance AI/ML model robustness and generalization.

POST: Architecture, Walkthrough, and Building Blocks

This section first discusses architecture of POST and its workflow. Afterwards, it details the building blocks of POST.

Architecture and Workflow of POST

Architecture Overview: We present POST as a system of systems, broadly comprised of three

Functionality	TVWS	SAS	ProSAS	ZMS	POST
Real-time interference prediction	No	No	No	Yes	Yes
Dynamic resource optimization	No	No	Yes	Yes	Yes
Proactive interference management	No	No	No	No	Yes
Database-based access control	Yes	Yes	No	Yes	Yes
Geoloc.-based interference avoidance	Yes	Yes	No	Yes	Yes
AI/ML-based decision-making	No	No	Yes	No	Yes
In-band spectrum sensing	No	Yes	No	Yes	Yes
Scalability to complex environments	No	No	No	Yes	Yes
Compatibility with incumbents	Yes	Yes	Yes	Yes	Yes
Multi-band adaptability	No	Yes	No	Yes	Yes
What-if simulation for policy testing	No	No	No	No	Yes

TABLE 1. Comparison of functionalities among TVWS, SAS, PROSAS, ZMS, and POST [7], [8], [9].

modules: 1. *Digital Twin (DT)*, 2. *Intelligent Spectrum Sensing Unit (ISSU)*, and 3. *Intelligent Spectrum Management Unit (ISMU)*. Fig. 2(a) gives an overview of the building blocks and architecture of POST including the information flow. The local and global DTs are located in the near and non-RT RICs respectively. The spectrum sensing and management algorithms are integrated into the RICs as rApps and xApps. Specifically, ISSU hosts spectrum sensing rApp in the non-RT RIC, and spectrum sensing xApp in the near-RT RIC. Likewise, ISMU hosts spectrum management xApp and rApp at near and non-RT RICs, respectively. ISMU contributes to the spectrum management decision-making by transferring control decisions to the open-distributed unit/radio unit (O-DU/CU) of the RAN over the E2-interface. Ultimately, POST presents a closed-loop spectrum sensing, control, and analysis framework. Note that a reduced version of POST can be employed without a dedicated ISSU mechanism, particularly for 6G bands with incumbents that share their interference reports [14]. For such 6G bands, it can rely on RF sensing/interference report shared by incumbents (or sensors co-located with the incumbents), also as considered in the "Post Use Case: Spectrum Sharing IN 12 GHz" section.

Walkthrough: Next, we present a walkthrough of the information flow of POST. Note that the numbered hexagonal bullets correspond to the red hexagonal labels in Fig. 2(a).

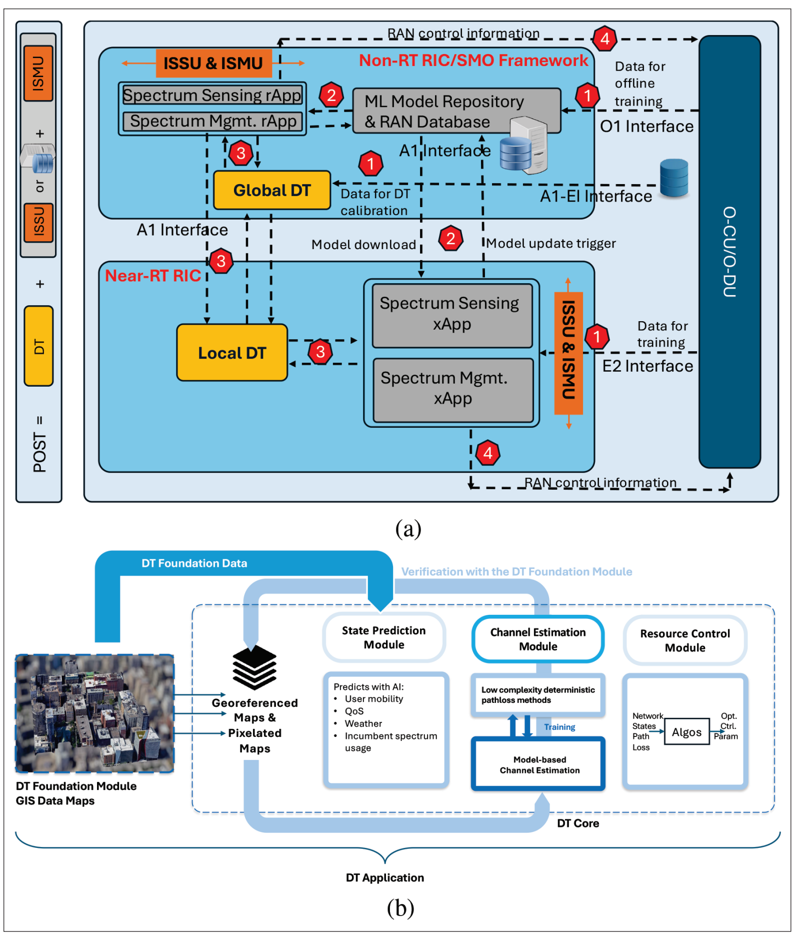

FIGURE 2. Detailed architecture of POST and its digital twin component. a) POST architecture. b) Digital twin in POST.

1. Network telemetry data (i.e., key performance measurements (KPMs)) are exported from the O-CU/O-DU to the spectrum sensing and management xApps in the near-RT RIC over the E2 interface. At the same time, for offline training in the Service and Management Orchestration (SMO) framework in the non-RT RIC, the same data is exported over the O1 interface. In case of the absence of ISSU, the sensing report/data can be shared by the incumbent (or co-located sensors) via A1-EI interface to near-RT RIC or non-RT RIC. DT calibration data in the form of georeferenced information as well as context information of the spectrum environment are fed to the DT via external open interfaces like A1-EI. DT calibration data is shareable since the DTs in the near and non-RT RICs are accessible to each other.
2. Both ISSU and ISMU xApps (and their corresponding rApps) access the ML Model Repository in the SMO framework to retrieve up-to-date inference models. These models are trained, validated, and fine-tuned at the non-RT RIC using telemetry data collected via the O1 interface, augmented with site-specific synthetic datasets generated by the global DT. Once validated, the models are published to the repository and periodically retrieved by near-RT RIC xApps via the A1 interface for real-time inference and decision-making.
3. The local and global DTs in the near-RT RIC and the non-RT RIC respectively get their inputs from the xApps and the rApps, respectively and enrich their representations of the spectrum environment to effectively model and predict the wireless system behaviors in near and non-real time, respectively.
4. The updated control parameters are sent back to the O-CU/O-DU by the corresponding xApps and rApps for optimal RAN functionality.

Building Blocks of POST

A key capability that distinguishes POST from prior spectrum-sharing systems is the tight integration of the DT with the O-RAN architecture. This integration allows POST to support the entire DT workflow: high-fidelity emulation and synchronization of the spectrum environment, "what-if" policy analysis, proactive optimization, control-decision feedback, and closed-loop operation across the near-RT and non-RT RICs. Through standardized O-RAN interfaces, the DT continuously exchanges telemetry, model updates, and optimization results, forming the core intelligence layer of POST.

1) First Key Component of POST: *DT*: The DT is a virtual representation of the physical spectrum environment, dynamically synchronized with real-world conditions. This synchronization is achieved through near-real time and non-real time updates, enabling the DT to model and predict the behavior of complex wireless systems accurately. By incorporating a wide array of data, including device locations, spectrum utilization, and environmental factors, the DT provides a comprehensive and adaptive view of the spectrum landscape. The DT can be used to train the rApps in the non-RT RIC and it can also be used to train the xApps in the near-RT RIC. In POST, we have local and global DTs housed in the near and non-RT RICs, respectively, as shown in 2a. They exchange data like device location and spectrum utilization with the spectrum sensing xApp and rApp , also housed within the near real-time RIC and non-RT RIC respectively. With this data, they guide spectrum management xApp and rApp to optimize resource allocation dynamically and predict potential interference scenarios before they occur. More specifically, the local DT is a lightweight, local and faster system in general, and its scope in terms of geographical data maps is limited. Hence, it is good for modeling and predicting a smaller span of geographical area and for training the xApps. On the other hand, the global DT has access to a much larger geographical area and captures a holistic picture of the radio environment and context information and trains the rApps over a longer period of time. For example, the GIS data maps shown in Fig. 2(b) can be divided into smaller geographical areas and each local geographical area is actually captured by the local DT while the global DT aggregates these smaller maps and captures the whole data map for large-scale policy design. Thus, a DT proactively ensures efficient and conflict-free spectrum usage in highly congested and diverse environments. Additionally, the local DT gathers varied time-scale granular spectrum awareness through the spectrum sensing xApp and rApp (over the A1 interface for the latter), while the global DT does the same locally within the SMO framework. Such spectrum awareness enables DTs supporting both short-term operational decisions and long-term policy development. Below are the key modularized components of POST's DTs [refer to Fig. 2(b)].

DT Foundation: DT foundation module consists of geographical information service (GIS) data maps, including digital elevation maps (DEMs), land-use or clutter maps, road orientations, and building footprints or heights, providing essential geographic and environmental information for RF modeling. Note that the size and complexity of these maps vary for local and global DTs.

DT Core: The core of the digital twin is the georeferenced map, a pixelated map with spatially precise data along with network state prediction module, channel prediction module, and resource control module. The DT follows a modular and extensible architecture, comprising multiple core modules and sub-modules that can be selectively activated or simplified depending on the operator's objectives and available computational resources. In practice, each module functions as an independent engine, such as data-ingestion, channel-estimation, network-state-prediction, and resource-control engines that can be configured or replaced using off-the-shelf datasets and models. This engine-based realization enables plug-and-play customization of DT fidelity and computational complexity while maintaining full interoperability through standardized O-RAN interfaces. This flexibility enables deployment of low-fidelity twins for lightweight inference or high-fidelity twins for detailed optimization without altering the system framework.

- Maps use propagation picture elements, or "proxels," [15] instead of simple image pixels, and operate across two levels of georeferenced mapping. Transmitter maps in a DT include known transmitter maps for existing transmitters and inferred transmitter maps based on measurements and inferred data. These maps, featuring associated or unassociated measurements, provide local ground-truth propagation information for the region.
- Network state prediction module, with the help of various AI algorithms predicts various network states like user mobility, quality-of-service (QoS), weather, and the incumbent's spectrum usage in time-spatial domain. It takes the DT foundation data like 3D maps of the environment and building footprints, weather etc. as inputs to various AI algorithms for prediction.
- Leveraging site-specific information from the maps, the channel prediction module provides accurate predictions of the electromagnetic propagation pathloss between the transmitter and the receiver and transmitter and the incumbent. Instead of using ray tracing methods which are computationally expensive, POST's DT relies on low-complexity deterministic pathloss estimation methods [16]. This module leverages maps data (proxels) from within the DT core and updates the ground truth.
- Resource control module implements resource control algorithms that takes network states, path loss etc. as inputs and provides the optimal control parameters (like transmit power, beamforming weights, channel allocation, user association etc.) for 6G networks like transmit power, beamforming etc. This module is exploited by DT to find the best DSS policy through what-if analysis. For example, before applying a new transmit-power reduction or beam re-orientation policy, the DT can evaluate its effect on both aggregate interference at the incumbent receiver and expected user throughput, allowing POST to enforce only policies that improve coexistence performance.

AI Refinement: Because the DT resides within the O-RAN environment, it continuously generates site-specific, labeled datasets that can be utilized by the rApps and xApps for AI model training and refinement. The non-RT RIC leverages these datasets to retrain long-term models, while the near-RT RIC uses the same contextual information to fine-tune inference networks in real time. This closed-loop data flow ensures that the AI components within POST remain adaptive to local spectrum dynamics and hardware conditions without requiring external data collection.

2) Second Key Component of POST: *Intelligent Spectrum Sensing Unit (ISSU):* The ISSU consists of mainly the spectrum sensing xApp in the near-RT RIC and the spectrum sensing rApp in the non-RT RIC along with the ML model repository. The spectrum sensing xApp obtains O-RAN KPMs such as received signal strength indicator (RSSI), user traffic types and volume, channel quality indicator (CQI), interference level etc. over the E2 interface. Over the O1 interface the rApp gets similar KPMs. The xApp performs intelligent sensing in 10 ms-1 s time frame whereas the rApp is geared towards spectrum sensing policy design. More specifically, the rApp has access to a longer-term time-scale data of incumbent activity, and hence it is possible for it to learn their patterns. For example, if an active incumbent is operational at particular times throughout a day (or even longer time frames), the task of predicting when to sense the spectrum becomes easier by learning patterns of the incumbent activities. This in turn adds tremendously to the sensing accuracy of the ISSU. Besides, by analyzing data collected via the O1 interface, ISSU rApps also orchestrate training of the ML model used by spectrum sensing xApp by selecting appropriate datasets, optimizing hyperparameters, and enabling continual model adaptation in dynamic environments.

How ISSU Leverages O-RAN Specific Capabilities: The ISSU basically comprises of the intelligent and accurate spectrum sensing capabilities enabled by the xApp and the rApp, and combined, they contribute to smart spectrum sensing and form the second key enabling technology of POST. To enable fast spectrum sensing, POST leverages O-RAN compliant KPMs like user throughput and CQI as input data for training and testing the spectrum sensing xApp in the near-RT RIC. This approach surpasses traditional methods using I/Q data and spectrograms by leveraging KPMs, which require minimal data collection — only kilobytes compared to the megabytes or gigabytes needed for spectrograms. This efficiency enables significantly faster sensing operations. ISSU xApp can also leverage spectrogram data collected via the E2 interface to enable more fine-grained spectrum sensing within a specific zone. Moreover, ISSU leverages diverse longer time-scale data from external servers about incumbent activity (such as frequency usage pattern data, weather data etc.) received over the A1-EI interface to improve the spectrum sensing accuracy of the ISSU.

3) Third Key Component of POST: *Intelligent Spectrum Management Unit (ISMU):* The ISMU of POST consists of intelligent spectrum resource control and management algorithms (xApp and rApp) working in tandem with the ML model repository in the non-RT RIC and eventually appropriately controlling RAN parameters in either near-real time or non-real time. Based on the results of spectrum sensing performed by ISSU, ISMU maximizes resource utilization, minimizes/nullifies interference among users, and enhances overall network throughput of coexisting networks by optimizing multiple control variables including activity of the cellular base stations (BSs), allocation of transmit power and physical resource blocks (PRBs). In other words, given policy and real-time network context information, ISMU enhances spectrum coexistence among the secondary users and incumbents in both near and non-real time scales and hence it largely dictates the control activity of POST.

The main function of ISMU is context aware RAN resource optimization in collaboration with DT for effective spectrum sharing in near-real time or non-real time. Here, contexts refer to a broad set of factors that impact DSS performance, including spectrum information obtained by ISSU and environmental factors such as buildings, weather, and user density, to name a few [2, Table 2]. For example, if ISSU senses a drop in RSSI or CQI then accordingly, the DT is updated with the sensed information. Likewise, if ISSU senses interference in a particular sector, then the ISMU can suggest updated sector control information to the O-DU or O-CU. Given the CQI and/or interference information within a cell, ISMU leverages its ML algorithms to send updated RAN control knobs to the DT. The DT validates these decision variables and informs ISMU of their impact. ISMU (i.e., the spectrum management xApp) then sends the optimal control decisions back to the O-CU and O-DU in near real time.

An Example of Near-Real time Context-Aware Resource Optimization via ISMU: A context-aware resource optimization problem can be maximizing network throughput for a given number of BSs and users while keeping the aggregated interference-over-noise (I/N) ratio at the incumbent receiver smaller than the predefined threshold (e.g., -8.5 dBm). This can accomplished by optimally tuning the control knobs, such as the activity of coexisting BSs, sectors of each BS, codebook vectors, antenna transmit powers and PRBs. As the optimization problem is computationally intractable, ISMU can exploit AI/ML framework, such as a trained Recurrent Deep Reinforcement Learning (R-DRL) agent to efficiently solve the optimization problem within near-RT RIC's sub-10 ms time frame. Leveraging O-RAN, ISMU operates as a spectrum management xApp for near real-time control. The DRL model utilizes KPMs, DT-driven dynamic contexts, and spectrum sensing results to learn optimal control variables. This integration ensures continual learning and adaptation to network changes. It is worth noting that a wide range of spectrum sensing and management algorithms can be implemented as xApps in POST, provided they comply with the latency and data availability constraints of the near-RT RIC. Thus, ISSU and ISMU are not limited to specific algorithms.

POST Use Case: Spectrum Sharing in 12 GHz

Frequency Band and DSS Environment

This section presents a use case evaluation of POST for spectrum sharing between 5G/beyond -5G downlink terrestrial cellular networks and earth-to-ground fixed satellite service (FSS) over the upper 12 GHz band (12.2 GHz-12.7 GHz). This use case is implemented by considering a simulated DSS environment as a coexisting

Evaluation Criteria	Value	Unit
Data sending and receiving time	5.639	ms
Model runtime	33.267	ms
Overall end-to-end delay	38.909	ms
Number of active BSs	19	count

TABLE 2. Performance Evaluation of Test Case of POST.

cellular network and consider the real geolocation of BS, FSS, 3D buildings and contextual factors such as weather, beam configurations, user mobility transmit power and site-specific channel.

PoC Architecture Details

1) Development of PoC Architecture of POST: We present the Proof of Concept (PoC) architecture of POST, which integrates its several sub-components, including the RIC Database, DT, ISSU, and ISMU. The implementation details and interconnections among these sub-components for the test case are described below.

The POST framework comprises four core components: **(1) the RIC Database**, which collects and manages both static and dynamic contextual data such as weather conditions, user mobility, beam directions, and BS configurations, thereby enabling adaptive and context-aware decision-making; **(2) the Digital Twin (DT),** developed on top of the ASCENT tool [17], which performs what-if analyses for optimal dynamic spectrum-sharing (DSS) policy evaluation and models real-world networks through a modular architecture and closed-loop feedback system. The DT leverages deterministic and site-specific path-loss modeling, rather than probabilistic methods, to achieve accurate interference estimation under varying conditions including weather, BS geolocation, 3D building layouts, FSS receiver placement, and regulatory constraints; **(3) the Intelligent Spectrum Sensing Unit (ISSU)**, which aggregates longer time-scale contextual information from external sources such as incumbent activity, frequency, and weather data to enhance environmental awareness. In this specific proof-of-concept (PoC) implementation, consistent with [14], the FSS receiver directly shares interference reports with the O-RAN–based POST framework, and therefore the ISSU is not explicitly instantiated; and **(4) the Intelligent Spectrum Management Unit (ISMU),** which implements intelligent spectrum control and management algorithms via xApp and rApp modules operating across the Near-RT and Non-RT RIC layers. The ISMU, developed on top of CAT3S (Context-Aware Terrestrial-Satellite Spectrum Sharing) algorithm [18, Algorithm 1], optimizes RAN parameters in real time to ensure efficient coexistence between terrestrial 5G networks and FSS receivers in the 12.2—12.7GHz band. By dynamically adapting sharing decisions to site-specific conditions, the ISMU outperforms conventional worst-case-based methods, significantly enhancing context awareness, adaptability, and spectral efficiency within the POST framework [18].

2) Development of Spectrum Management xApp: The Spectrum Management xApp is developed within POST as a central piece of the ISMU. This xApp leverages O-RAN's capability to integrate contextual information, host system models, and provide RAN control mechanisms through open interfaces. As illustrated in Fig. 3, the DT processes weather, BS, building, and FSS data, transmitting insights to the Near-RT RIC via an E2-like HTTP interface. The Near-RT RIC hosts the ISMU containing the spectrum management xApp that performs real-time sensing, spectrum allocation, and BS control optimization (On/Off status, transmit power, and beam selection). In this implementation, a simplified version of POST is considered where the ISSU is replaced with an RIC database that captures the necessary KPIs, including frequency channels occupied by FSS receivers. Hence, the ISSU is omitted, and the xApp directly analyzes the RIC database to detect interference events, while weather and FSS data are provided to the DT through an external interface. The implementation and communication workflow of the xApp are as follows: • **Step 1:** Deploy the spectrum management xApp in the Near-RT RIC to enable external communication and control exchanges with the simulated DSS environment via the E2 interface. • **Step 2:** The DT utilizes 5G network data from the RIC database and contextual and interference information from the simulated DSS environment through the Y1 interface, providing feedback and contextual insights to the xApp via HTTP communication. • **Step 3:** The xApp receives 5G RAN metrics and interference information from the DT and retrieves relevant contextual data from the RIC database for decision-making. • **Step 4:** The RIC database collects 5G network data from the simulated DSS environment via the E2 interface, including BS locations, transmit power, interference thresholds, and beamforming details. • **Step 5:** Using contextual and network data, the xApp executes the BS control algorithm to determine optimal transmit power and beam direction for given weather and interference conditions. • **Step 6:** The xApp finalizes active BS configurations and transmit parameters, sends them to the DT for what-if analysis, and delivers the optimized control actions to the simulated DSS environment through the E2 interface for implementation.

Baseline and Validation

For baseline comparison, the conventional EZ policy, widely adopted for incumbent protection in regulatory and industrial frameworks was used in our evaluation [19]. As no standardized DSS algorithm currently exists for the 12 GHz band, the EZ policy provides a meaningful reference point for assessing improvements. The reported results were generated and validated within a DT that accurately emulates the 12 GHz terrestrial-satellite coexistence scenario using realistic propagation, terrain, and environmental parameters, thereby ensuring practical fidelity.

Preliminary Results for Considered POST Use Case

For the performance evaluation of POST, we utilize a DT built on a realistic simulated DSS environment from [18]. The DT replicates real-world network conditions to support the CAT3S algorithm by incorporating 33 BSs and a FSS receiver in a suburban area in Blacksburg, VA, USA. As shown in Figs. 4 and 5, POST maintains the aggregate I/N ratio at the FSS receiver below the thresholds of − 8.5 dBm and — 12 dBm during sunny and rainy conditions, respectively. It also activates 19 BSs and achieves a spectral efficiency of $75K$ bps/Hz with a 4×4 antenna array. These results consistently outperform the conventional exclusion-zone (EZ)-based static DSS policy across different antenna configurations, thanks to POST's capability to optimize RAN control parameters with context-awareness. POST's performance is further evaluated in terms of its runtime. This includes the time overhead of

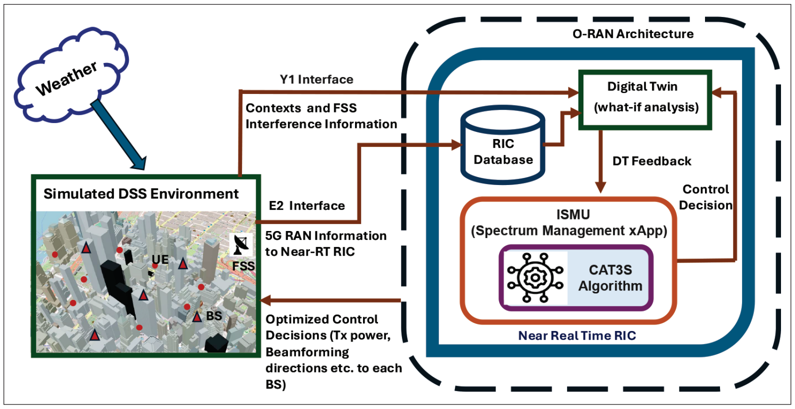

FIGURE 3. POST Implementation with ISMU and DT employing CAT3S as Spectrum Management xApp for 12 GHz spectrum sharing scenario. Note that ISSU aspect of POST is not considered in this use case.

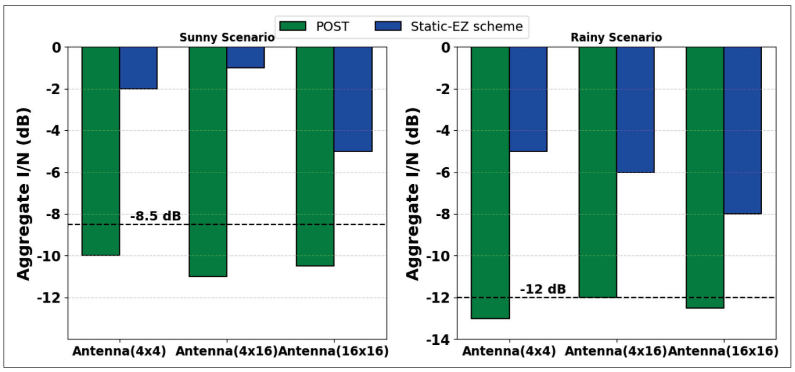

FIGURE 4. Aggregate I/N ratio at incumbent FSS receiver vs. antenna array sizes.

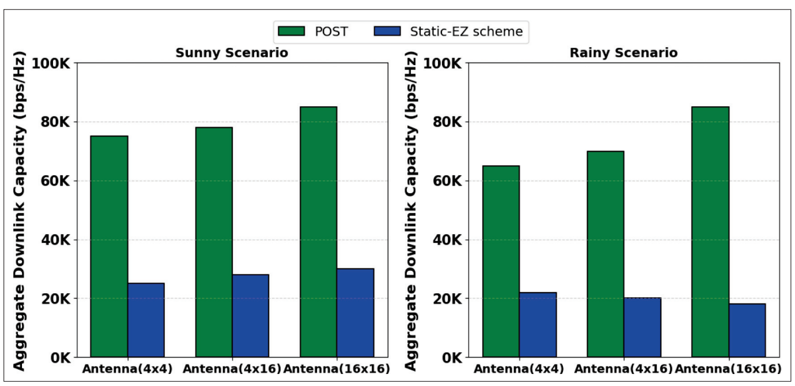

FIGURE 5. Achievable downlink capacity of coexisting cellular network versus antenna array sizes.

collecting contextual data and sending it to the near-RT RIC via the E2 and Y1 interface. The processing time and confirmation message back to the simulated DSS environment are also measured. Data exchange takes about 5 ms in total (2.5 ms each way). The overall decision-making delay is approximately 38.9 ms, supporting the feasibility of using POST for second-level decision making in DSS networks that maintain the near-real time RIC time constraints (10 ms - 1s).

Future Research Direction

Improving Scalability of POST via Federated Learning

While the current version of POST replicates the 3D environment of a single area within its DT, large-scale implementation requires mimicking multiple geographic areas, resulting in significant computation and data collection overhead. To address this, the POST framework can be expanded to include multiple geographically distributed DTs, each focusing on a specific zone. Each local POST DT trains its own machine learning model using local GIS data, which is then aggregated via federated learning (FL). Notably, both data collection and DT mapping from the collected data occur at the local level, while only model updates (e.g., gradients or parameters) are exchanged with a central server. This approach significantly reduces DT construction and synchronization costs for large-scale (i.e., city-scale) POST deployment. The federation of multiple DTs also supports combining high-and low-fidelity DTs for decision-making and enables model transfer from one setting (e.g., spectrum management in a warehouse) to others, aiding citywide or nationwide improvements. Optimal client selection strategy and innovative resource allocation for local data collection and DT federation are essential for effective large-scale POST implementation.

Enhancing POST's Local DT Fidelity

To address the bandwidth constraints of O-RAN interfaces and reduce computational complexity, POST's local DT usually relies on low-complexity deterministic path loss models. Such a DT's fidelity can be enhanced using low-fidelity georeferenced maps, collected over O-RAN interfaces and upscaling them to high fidelity with AI-based corrections. An AI model refines low-resolution maps by incorporating high-resolution patterns learned from high-quality imagery datasets. AI systems trained on high-resolution geospatial data can also be integrated to enhance accuracy while adding features like height attribution and land cover classification.

Securing POST

Given POST's DSS capabilities with sensitive incumbents, securing incumbent information is crucial. Said differently, POST must ensure sensitive data to be accessed by malicious and unknown third parties. In this context, a promising direction is to explore interference mitigation techniques such as beamforming and power control to protect incumbents from harmful interference while ensuring privacy of data shared by incumbents. Secure authentication and encryption mechanisms need to be developed to ensure data protection and compliance with regulatory frameworks while ensuring real-time operational constraints of POST.

Conclusion

This paper presents POST, a novel spectrum sensing and management framework for DSS in 6G, specifically targeting the mid-bands while ensuring incumbent protection. Compared to existing systems, POST excels by leveraging O-RAN interfaces, real-time and non-real-time spectrum sensing, and policy testing through what-if analyses. It integrates DT, ISSUs, and ISMUs within non-RT and near-RT RICs for efficient management. A simplified POST implementation for spectrum coexistence between downlink 5G cellular and FSS in the 12 GHz band demonstrates that POST enables fast, context-aware spectrum management decisions. Innovations in federated learning for scalability, AI-powered high-fidelity DT mapping, and enhanced security represent promising directions to further improve POST's effectiveness in 6G networks.

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