All-domain Spectrum Command and Control via Hierarchical Dynamic Spectrum Sharing with Implemented Dynamic Spectrum Access Toolchain

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***Abstract*— The proliferation of spectrum-dependent systems and the reduction in Federally-owned spectrum has challenged Radio Access Networks (RANs) to keep pace with requirements for increased data demands. Particularly, Department of Defense (DoD) bandwidth-intensive applications, such as the Internet of Military Things (IoMT), Command and Control (C2), and decentralized or distributed networks all share the need for ubiquitous wireless connectivity with limited spectrum resources. The paper presents a novel concept of Hierarchical Dynamic Spectrum Sharing (H-DSS) architecture standardization that leverages novel mission policy-based Dynamic Spectrum Access (DSA) and agnostic implementation within the DoD spectrum management tools lifecycle to meet bandwidth challenges. H-DSS and mission policy-based DSA are enablers for RANs to cooperate, coordinate, and dynamically share resources in decentralized or distributed Federal and non-Federal spectrum applications.**

Keywords*— *Cooperative Networks, Command and Control, Hierarchical, Dynamic Spectrum Sharing, Dynamic Spectrum Access, Policy, Spectrum Management, Spectrum Management Tools, Networks

I. Introduction

With the increased usage of smartphones, Internet of Things (IoT) devices, and bandwidth-intensive applications, the amount of data traffic on wireless networks is rapidly increasing. For example, a recent report [1] forecasts the total global mobile data traffic to grow from 58 exabytes (EB) per month to 300 EB per month in 2026. A primary challenge for wireless networks to meet the requirements associated with increased data demands is the management of spectrum resources. Most of the spectrum management is based on static frequency assignments, which grant exclusive use of a spectrum band to a single system. Studies [2] have shown that much of the spectrum is underutilized, making such static allocation policies inefficient. Dynamic Spectrum Access (DSA), Dynamic Spectrum Sharing (DSS), and cognitive radio (CR) are viewed as key enabling technologies for wireless networks to provide more efficient spectrum use and meet growing data requirements. DSA technologies also enable networks to be adaptable and resilient to dynamic environments with congested or contested spectrum.

The necessity for improving spectrum utilization and efficiency is recognized by policymakers and evidenced in a long history of regulatory pursuits towards adopting new spectrum-sharing paradigms. In June 2010, the Office of the President enacted regulatory policies that directed the Commerce Department's National Telecommunications and Information Administration (NTIA) to collaborate with the Federal Communications Commission (FCC) to find 500 MHz of spectrum that could be shared by Federal and non-Federal users. The 2012 President's Council of Advisors on Science and Technology (PCAST) Report [3] facilitated the use of a new spectrum band under the Advanced Wireless Services (AWS) auction. A more recent example is the Spectrum IT Modernization Act of 2020 [4]. This act calls explicitly for technological advancements in spectrum utilization across DoD spectrum-dependent systems. The FCC is also adopting a strategy for DSA using Spectrum Access Systems (SAS) in the Citizens Broadband Radio Service (CBRS) 3.5 GHz bands. A three-tiered sharing structure is used in the CBRS bands as described in the FCC's report to Congress [5] regarding the Spectrum Pipeline Act of 2015 enacted under the Bipartisan Budget Act of 2015 [6].

The standards communities are also heavily involved in the shift to spectrum sharing. For example, the 3rd Generation Partnership Project (3GPP) and fifth-generation (5G) standards include spectrum sharing, and the Institute of Electrical and Electronics Engineers (IEEE) Dynamic Spectrum Access Networks (DySPAN) is actively invested in developing standards in the areas of DSA and policy languages for next-

Funding Agency: Air Force Research Laboratory (AFRL) via National Spectrum Consortium (NSC).
This paper is cleared for public release (reference number: AFRL-2021-2391)

generation new radio (NR) systems. The result is a robust regulatory agenda to adopt dynamic spectrum sharing.

Despite the significant regulatory and technical initiatives to develop, standardize, and integrate DSS, DSA has yet to be fully adopted within the DoD. H-DSS architecture proposes novel policy creation, a standardized architecture, and an end-to-end toolchain that can facilitate DSA.

In the next section, related works and past efforts are explored to address the challenges of ubiquitous connectivity through DSS and DSA frameworks and architectures. Specific interest is aimed at policy deployment and policy conformance components to enable RANs to demonstrate policy-based DSA performance in real-time within the current DoD spectrum life cycle. Section III introduces the reference architecture developed to support the standardization of DSS and identifies target areas for the inclusion of DSA for current and future networks. Section IV describes in detail a prototype implementation to validate and verify the applicability of the works described. Section V validates the ubiquitous connectivity benefits of applying H-DSS to current and future DoD and commercial networks in both Federal and non-Federal spectrum bands via a series of use cases. Lastly, Section VI discusses how standardization enables DoD operational networks and commercial networks.

II. RELATED WORKS

Prior research provides insights into advancements of policy-based spectrum access conducted under the DARPA NeXt Generation (XG) program. The design, implementation, and experimentation of a policy-based spectrum access control framework are detailed in [7]. The framework consisted of a set of policy-based conformance and enforcement components that ensure that the radio abides by machine-understandable policies that are expressed in a declarative language. Policy authoring, analysis, and validation administration applications were developed to control the XG-enabled radio devices. The XG program proved the feasibility of policy-based spectrum access by demonstrating policy conformance components performing real-time policy reasoning and decision-making on embedded software-defined radio (SDR) hardware. The XG policy conformance reasoner and W3C Web Ontology Language (OWL) based policy were integrated into the DARPA Wireless Network after Next (WNaN) architecture [8]. As discussed earlier, the FCC has proposed the use of a SAS to facilitate spectrum sharing between incumbents, priority access licensees (PAL), and general authorized access (GAA) users in the 3550-3750 MHz CBRS bands [9]. The SAS is responsible for the creation and management of spectrum assignments for users in each tier and ensures higher-tier users are protected from interference due to lower-tier users.

This work considers several additional policy types that regulate more complex higher-level, hierarchical network-level behaviors beyond permissive/restrictive frequency usage. Additionally, it considers policy generation mechanisms that easily integrate into existing spectrum management tools, paradigms, and processes that automate spectrum management. Also proposed is a standardizable, hierarchical policy architecture to support dynamic policy optimization and sharing while leveraging the current IEEE Std. 1900.5 for DSA. Lastly, these proposed policies are demonstrated in an end-to-end toolchain to validate and verify the efficacy of the system.

III. HIERARCHICAL DYNAMIC SPECTRUM SHARING POLICIES

H-DSS is realized by two main components: (1) the H-DSS policy hierarchy and (2) the architecture that supports the real-time generation, dissemination, conformance, and optimization of DSS policies. Within the H-DSS policy structure, a new concept of DSA mission policies is introduced below. DSA mission policies allow for the encoding of higher-level behaviors and constraints to satisfy the objectives of a given scenario. A prototype H-DSS system is implemented that defines schemas for machine-readable DSA policies, performs policy generation using spectrum management tools, disseminates policies to DSA-capable radio networks using open interface policy deployment schema, and governs spectrum access at radio nodes using an implementation of IEEE Std. 1900.5-2011 [10].

A. H-DSS Policy Schema

Spectrum policy schemas naturally fit a hierarchical structure, as illustrated in Figure 1. The H-DSS policy schema affords four policy tiers that have the ability to bi-directionally assign priorities based on the use case, mission need, network state, and radio capability. H-DSS generically defines the architecture interfaces and interactions.

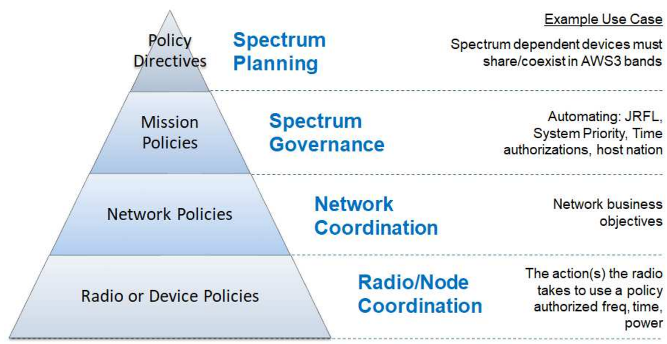

Fig. 1. H-DSS policy schema.

The highest first tier of the schema is titled "policy directives." Policy directives are defined by regulatory bodies, such as NTIA, FCC, or host nation regulations. These policies are inherently linked to DoD mission planning and resident spectrum-dependent systems in the band. A policy directive example is the enacted regulation of DoD spectrum-dependent systems that must share, relocate, or compress in the 1755 MHz – 1780 MHz band. A commercial example of a policy directive is spectrum access that must follow a three-tier sharing structure and be regulated using a SAS, as in the case of the 3550 MHz – 3700 MHz CBRS bands. These directives are established by regulators and, in most cases, do not specify the low-level technical aspects of how the systems must be implemented or behave.

The second tier in the policy schema is the mission policies and is the missing link to the immediate adoption of DSA for DSS in DoD radio networks. These policies allow the spectrum planners, communications planners, and Electronic Warfare Officers (EWOs) to have control and governance authority over the deployed spectrum-dependent systems, including those that dynamically share and access spectrum bands. These policies set the bounds for the deployed systems and inherently control them through both non-runtime and runtime policy updates providing network control and governance. This work defines multiple mission policy types that fall into three broad focus areas: Communication-Enabling, Communication-Restrictive, and Communication-Disruptive. Table 1 shows H-DSS mission policies for C2 in military networks.

TABLE 1. Mission Policies

Policy	Description
Communication Enabling	
Frequency Assignment	Sets the initial conditions or default state of a spectrum-dependent system
Coordination	Allows separate nets the ability to share and ensure spectrum access when the nets have the technological capability to communicate with each other through radio channels
Non-Coordination	Allows separate nets the ability to share and ensure spectrum access when the nets do not have the technological capability to communicate with each other through radio channels (such as legacy spectrum dependent systems)
Radio Health and Status	Stores and reports radio health and status thresholds
Host Nation	Provides authorized use requirements for the geographical location
Communication Check	Automates the current manual process of performing a communications check on a radio
Lost Communications	Triggered event based on a communication thresholding
Commander Override	Triggered event based on Commander actions
Retransmit	Assigns the communication requirements with a timing element (start, stop, interval) to attempt to connect to a known radio repeater
Single Channel DSA	Configures the radio back to a non-DSA enabled system
Forensics	Establishes the requirements necessary for radio audit
Communication Restricting	
Joint Restricted Frequency List (JRFL)	Issues taboo, protected, and guarded frequency restrictions and ensures that they are locally and autonomously enforced at the radio level
Radiation Hazard (RadHaz)	Selectively shuts down emissions from radios based on the hazards of electromagnetic radiation. For example, Hazards of Electromagnetic Radiation to Ordnance (HERO), Personnel (HERP), and Fuel (HERF)
Emission Control (EMCON)	Selectively shuts down emissions from radios
Communication Disrupting	
Cease Buzzer	Stops an entire radio network's spectrum access
Zeroize	Triggers a tool to clear all local information on the radio
Electronic Support	Triggers a radio to operate as an intentional interferer
Signal Gathering	Assigns a radio to listen to a specified spectrum band and collect spectrum and signal data

The communication-enabling mission policies are used to facilitate communication. The most basic communication-enabling policies specify the constraints on frequency usage, for example, permitted and restricted frequency bands, maximum power, and sensing thresholds subject to geographical bounds and temporal limits. Communication-enabling policies can also specify parameters for specific DSA protocols like coordinated or non-coordinated spectrum sharing. Data management policies that specify data to be collected, stored, and transmitted are also considered communication-enabling policies. These policies may instruct the radio to report performance metrics to a spectrum manager tool. Communication-restrictive policies restrict communication.

The third tier in the policy pyramid represents the network policies. These policies define how networks are required to coordinate through a global orchestrator or enact clustering protocols in ad-hoc or mesh networks. The protocols for dynamic policy dissemination and coordination of network access strategies exist in this tier.

The fourth tier represents the radio policies, which are the rules on the actual radio or spectrum-dependent system. These are the radio protocols, including fundamental DSA algorithms, implemented at the device that defines how the radio accesses spectrum. Note that in fully distributed networks, the third and fourth-tiers are blended or intersect. Much work has already gone into creating spectrum sharing through DSA at the network and radio coordination tiers. This approach has provided the benefits of DSA, such as improved spectrum efficiency and spectrum utilization. This method refers to the traditional DSA that uses TV whitespaces, sense and avoid, or thresholding schemes.

The tiered policy schema is one of the key technological developments that clearly describes how DSS can be governed and automated. The H-DSS concept takes advantage of a mature DSA ecosystem with many different DSA implementations at the network and radio levels. H-DSS facilitates this ecosystem of technologies, connecting actual DoD mission requirements via a governance chain to the regulatory committees.

IV. TOOLCHAIN IMPLEMENTATION

The H-DSS toolchain consists of software engines enabled with runtime radio operations that enhance a radio's capability to perform governed DSA and mission-based actions. The software engines connect over standardized interfaces and common DoD data formats to create a mission plan, generate both human and machine-readable DSA policies, auto-deploy them on the radio devices, and interoperate with the policy radio controller. This H-DSS toolchain is shown in Figure 2.

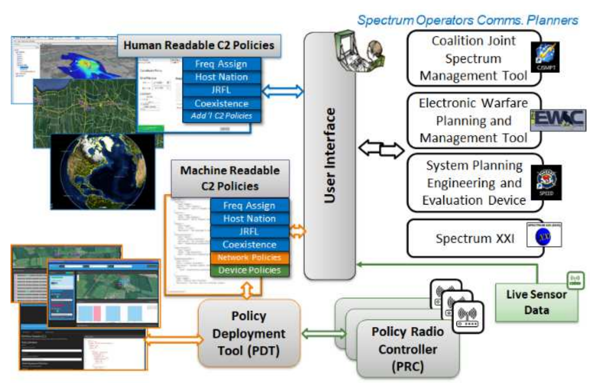

Fig. 2. H-DSS toolchain implementation.

The implementation of a H-DSS toolchain inspired by the IEEE Std. 1900.5-2011 is further discussed in this section. The prototype system provides mechanisms for generating, disseminating, and enforcing policies on DSA radio networks.

A. *Policy Generation (Hierarchical Second Tier)*

The H-DSS implementation utilizes established spectrum management modeling tools to model the electromagnetic operating environment (EMOE) and process regulatory spectrum information to generate machine-readable policies for DSA-capable radios. The analysis of the EMOE is used to determine how DSA systems should operate by specifying policy constraints like allowed frequencies and transmit power. The spectrum management tools provide the H-DSS implementation with a baseline understanding and visualization of the EMOE by managing deployment information, equipment operational characteristics, and spectrum assignment records within a specified area of interest (AOI). Using the baseline EMOE model, the system/user can search for existing spectrum resource records to determine frequencies that can be assigned to DSA networks. In many scenarios, existing spectrum assignments are reused for DSA policies which allow the DSA systems to operate as secondary users on a "Non-Interference Basis (NIB)." An important aspect of DSA adoption is the adherence to DoD regulations. The DoD expects each spectrum-dependent system to operate with a valid Spectrum XXI (SXXI) assignment. The approach allows for the reuse of SXXI assignments for DSA. Furthermore, spectrum management tools can be utilized to simulate the EMOE and potential interference scenarios between non-DSA and DSA systems to determine policy parameters. To facilitate the generation of the proposed DSA mission policies, the authors developed a software middleware that allows the aggregation of data from multiple spectrum management tools and databases.

B. *Policy Deployment Process (Hierarchical Third Tier)*

In Figure 3, the policy deployment subsystem consists of a Policy Distribution Tool (PDT), Policy Distribution Point (PDP), Policy Distribution Broker/Network (PDBN), and Policy Validation System (PVS). The PDT is a GUI application to assist in network configuration and policy distribution to DSA radio systems. The PDP is a database component hosting human-readable policies prior to being distributed to policy radio controllers. The PDBN is a control network allowing the distribution of machine-readable policies to policy-based radios.

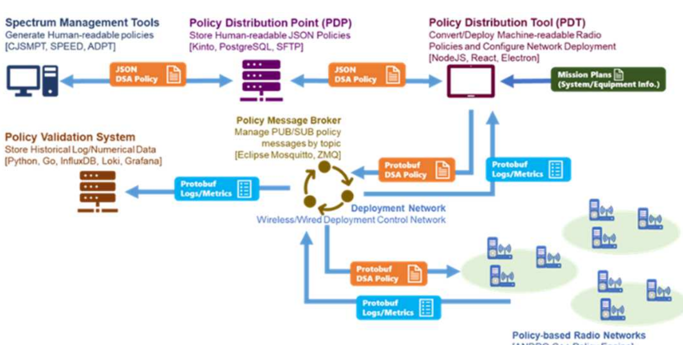

Fig. 3. Policy deployment.

The distribution network is physical layer agnostic and can be implemented either using wired or wireless technologies. The policy-based radios interface with the PDT over the distribution control network and are responsible for authenticating policies and implementing the radio configuration changes to adhere to the installed policy. The PVS is another database component with the ability to collect and store time-series metric data and logs from the distributed set of policy radio controllers allowing operators to monitor performance parameters in real-time.

C. *Policy Radio Controller (Hierarchical Third and Fourth Tier)*

The policy radio controller facilitates the inclusion of DSA by providing a non-vendor locked software that allows DSA capable radios to become policy-based radios by enforcing compliance to mission policies. Currently, the DoD has no standardized way of accepting machine-readable policies to the spectrum-dependent systems due to proprietary radio interfaces, vendor-locked software, and no standardization. Likewise, for commercial systems, the CBRS Alliance has specifications for interfaces between CBSD and SAS to obtain frequency policies; however, there is no specification on how to enforce policies on the actual radio device. Therefore, the policy radio controller is a technology solution that utilizes the IEEE Std. 1900.5-2011 to build a modular application. The policy radio controller is developed to be radio system agnostic and can integrate with any radio platform with the capability of implementing Application Programming Interface (API) calls to change frequency settings. Furthermore, if a radio platform allows additional configuration flexibility, the APIs and rulesets can be extended to implement more complex spectral usage optimizations. Figure 4 highlights the main components of the policy radio controller, which are the Policy Enforcer (PE), Policy Conformance Reasoner (PCR), System Strategy Reasoning Capability (SSRC), and a generic interface to the radio, known as a Radio Control (RC) API.

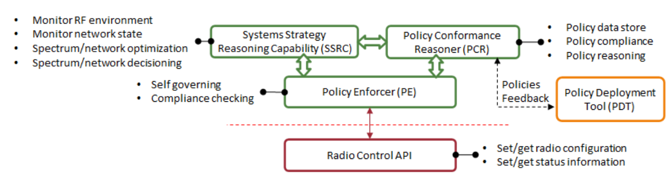

Fig. 4. Policy radio controller.

The PCR is responsible for interfacing with a policy source, such as the PDT, to receive and manage policy sets and for determining the policy compliance of current and proposed radio configurations. The PCR evaluates policy compliance by logically comparing radio configuration parameters and state information against constraints in the active policy set. As an example, the PCR determines if a proposed configuration that specifies center frequency, bandwidth, and transmit power abides by the policy, given the radio's current location, sensing information, and current time.

The SSRC monitors the state of the radio and the RF environment to seek new spectrum transmission opportunities intelligently. As opportunities are identified, the SSRC makes transmission requests to the PE and PCR. Any decisions made by the SSRC are vetted by the PCR for policy compliance before receiving permission to transmit. Additional responsibilities of the SSRC include handling the radio's capabilities, users, and collaborative network information (such as the status of the network or local neighbor DSA radios). Using rulesets, the SSRC makes use of all collaborative data to make informed decisions on transmission strategies to optimize performance and meet mission objectives. The goal is for the SSRC component to be capable of fully utilizing all permitted transmission parameters. For a DSA radio, this may include agile frequency hopping, power control, modulation changes, time constraints, and other policy-oriented parameters. The ruleset algorithms can vary from conformance rulesets that derive transmission parameters directly from the policy, to complex rulesets designed to optimize network functions like throughput or power consumption.

The primary function of the PE is to ensure that the radio platform is compliant with the policy set. To this end, the PE verifies the policy compliance of the current radio configuration and all SSRC transmission requests with the PCR. In addition, the PE interfaces to the radio system using the RC API to issue and track radio operations. Like the IEEE Std. 1900.5-2011, the PE is the only component within the policy radio controller with authority to interface to the radio system directly. Because of this, the PE is tasked with managing all associated transmission requests, replies, and status updates from the radio's hardware control system. Additionally, the PE interfaces to the SSRC to process transmission requests (radio configuration updates), radio information requests, and policy updates requests. Upon receiving a radio configuration update from the SSRC, the PE requests a policy compliance check from the PCR module. If the radio configuration is policy compliant, the PE reconfigures the radio system. Regardless of whether the radio configuration is policy compliant, the PE provides the results from the PCR to the SSRC. Radio information requests from the SSRC include requests for spectrum sensing information, performance metrics, or state statistics from the radio system. The PE handles radio information requests using the RC API and returns results to the SSRC. The PE can request a policy update from the PDT or spectrum management tool if the radio is not meeting performance objectives under the current policy set. The PE also periodically interfaces to the PCR to request policy compliance checks for the current radio configuration.

The Radio Control (RC) module is a component of the policy radio controller that enables the PE to manage the DSA-capable radio system via a generic interface. Since the policy radio controller is designed to be radio agnostic, the RC modules follow a common API, and the implementation is hardware-specific. For deployment onto a DSA radio system, the policy radio controller is compiled with an RC module implemented for the target radio platform. The RC API contains functions to set and query the various radio parameters. Generally, the radio parameters include frequency, power, bandwidth, waveform, sensing periods, and other parameters specific to a given radio system. Radio queries include radio type/capabilities, metrics and statistics, and sensing information, among others. The RC API translates generic radio configuration commands generated within the policy radio controller into commands specific to the controlled radio system.

The policy radio controller is a modular and extensible application that can seamlessly integrate with DSA-capable radio systems. The policy radio controller is implemented as a user-space application in C++. The application is object-oriented, and each of the core components, the PE, PCR, SSRC, and RC API is implemented as separate classes. To facilitate modularity, the RC API and SSRC are defined as interfaces (abstract base classes) and utilize the factory design pattern to allow for easy integration of the radio interfaces and rulesets specific to the radio system and operational objectives.

V. RESULTS

The toolchain and mission policies have been evaluated by conducting a series of experiments at a DoD outdoor test site. The experiments are intended to validate the toolchain under several mission-relevant scenarios, as summarized in Table 2.

TABLE 2. Scenarios and Descriptions

Scenario	Description
Coexistence of Multiple Policy-based DSA Networks	Two policy-based DSA networks are assigned both overlapping and non-overlapping frequency bands. If interference occurs, the lower priority network is issued a new policy forcing it to evacuate the band.
Cease Buzzer Condition	A command is issued to stop all transmissions after a report of unauthorized interference.
Point-to-Point Single Channel System	A power-based policy is applied to facilitate coexistence between a DSA network and a point-to-point single-channel system.
DSA Network on a Known Convoy	A mobile DSA network traveling on a known route has a policy with three frequency bands with associated geographical and time bounds.
Radio Goes Out of Range	A mobile radio moves out of normal communication range, causing the lost communications policy and procedures to activate (incremental power increase)
DSA and Cellular Sharing	A DSA and commercial cellular network (4G LTE) coexist using non-coordinated sharing and pre-planned deconfliction frequencies.
Automated Bi-directional Sharing	A DSA and non-DSA coordinate spectrum usage with an automated bi-directional sharing policy.
Automated Range Operations	A mobile DSA network abides by multiple test range policies: Host Nation, RadHaz, JRFL, and Radio Health and Status Reporting.

A. *Automated Bi-directional Sharing Experiment*

This experiment demonstrates the use of the policy toolchain to facilitate automated spectrum sharing between two networks, as shown in Figure 5. A 2-node incumbent network is used to represent a DoD-managed air-to-ground link, and a secondary-user 4-node DSA network coordinates spectrum usage over a shared network (via test site's fiber network). Both networks process multiple mission policies that specify allowed frequencies and coordination requirements. The DSA network's default frequency assignment policy allows it to operate between 902-903.6 MHz and the coordination policy allows usage of the 902-903.6 MHz, 906-907.6 MHz, and 910-911.6 MHz bands. The incumbent system switches randomly between 903 MHz and 906 MHz every 5 seconds and coordinates by announcing its frequency usage on the shared network.

The DSA squad net is the slightly lower power network, while the incumbent is the higher power network. The latter is highlighted by the DSA squad net in light yellow and the ground to air incumbent in dark red in Figure 6. The DSA network does not have a coordination policy which results in interference events shown in Figure 6 (left). The PDT disseminates the coordination policy, which instructs the DSA network to coordinate with the incumbent, as Figure 6 (right) shows.

Fig. 5. Automated bi-directional sharing.

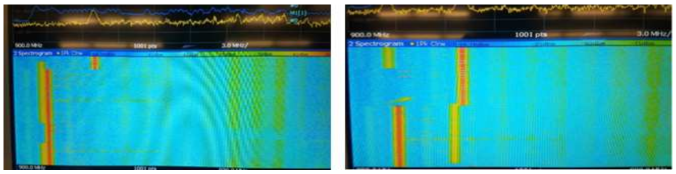

Fig. 6. Bi-directional frequency sharing.

The coordination policy's performance is quantified by measuring the throughput of data transmissions on both the DSA and incumbent network with and without the coordination policy enabled. As shown in Table 3, the throughput on both networks increases when the coordination policy is enabled due to decreased interference events.

TABLE 3. Network Throughput for Bi-Directional Sharing Policy

Network (in *kbps*)	**Throughput Without Coordination Policy**	**Throughput With Coordination Policy**
DSA	49.9892	59.6583
Incumbent	49.7664	64.512

B. Automated Spectrum Operations Experiment

This experiment demonstrates the policy toolchain automating common test range procedures and operations on a mobile network, as shown in Figure 7. The mobile DSA network uses WNaN radios and includes Host Nation, RadHaz, JRFL, and Radio Status policies. The Host Nation policy allows the network to operate in the 1755-1850 MHz band within the test range's geographical area. The RadHaz policy restricts all emissions within a 50-meter radius of a specified location. The Radio Status policy requires the radios to send status messages to the PDT at a specified interval. During the execution of the scenario, the nodes are carried on vehicles and travel a path on the test range that enters and exits the RadHaz geographical zone.

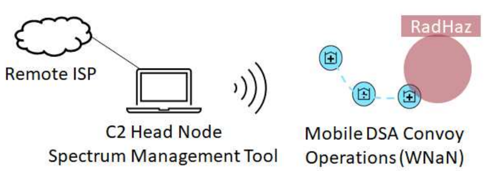

Fig. 7. Automated range operation scenario overview.

Figure 8 presents snapshots from a spectrum analyzer taken at different times during the scenario showing the WNaN abiding by the policy set. The WNaN spectrum is highlighted in yellow in Figure 8 (left) at the beginning of convoy operations. As the WNaN convoy enters the RadHaz geographical region, transmission autonomously halts at the radio device, as shown in Figure 8 (middle). Normal operation continues as the WNaN convoy leaves the RadHaz region, as shown in Figure 8 (right).

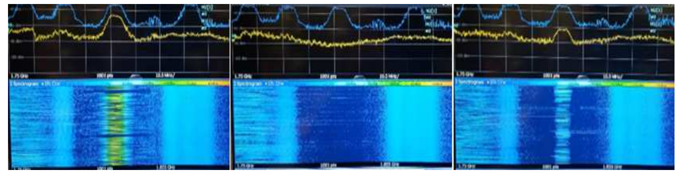

Fig. 8. Spectrum analyzer view of automated spectrum operations.

VI. Conclusions

This paper presented a concept of H-DSS and DSA mission policies to facilitate enhanced spectrum management required to serve bandwidth-intensive applications with finite spectrum resources. A prototype H-DSS system and schema were described for machine-readable DSA policies that generate policies using spectrum management tools, disseminate policies to DSA-capable radio networks, and govern spectrum access at radio nodes, all using open interfaces. Results from experimental evaluations of the prototype establish the feasibility of H-DSS and demonstrate a potential order of magnitude or more performance improvement when DSA mission policies are enabled. Future work will examine standardizing a H-DSS system architecture. A system is envisioned that employs the proposed architecture for dynamic and optimized policy generation and governance at each layer of the schema to meet mission requirements as spectral conditions change.

Acknowledgment of Support and Disclaimer

The work was funded in part by the Spectrum Access Research and Development Program (SARDP) under award number NSC-17-7031 and under an IRAD project funded by ANDRO. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the U.S. Government.

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