Radio Dynamic Zone Management System for Urban Environments

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***Abstract*—The growing demand for wireless communications and the emergence of 5G and beyond-5G networks have made dynamic spectrum sharing and efficient radio frequency (RF) spectrum management critical challenges for both researchers and regulators. This paper presents the COSMOS Zone Management System (ZMS), a cloud-native, web-based spectrum coordination platform designed to enable dynamic electromagnetic spectrum sharing in dense urban environments. Developed as part of a multi-university NSF SII-NRDZ collaboration, the ZMS operates within the COSMOS PAWR testbed in West Harlem, New York City, inside an FCC-designated Innovation Zone. The system leverages Spectrum Consumption Models (SCMs) standardized under IEEE 1900.5.2 to formally characterize RF device spectrum use and execute Compatibility Test (CT) computations for interference analysis and spectrum use authorization. Built on a Kubernetes-based microservices architecture, the ZMS integrates real-time spectrum monitoring, automated compatibility testing, interference alarm management, and external tool integrations — including NG-Scope for LTE network telemetry and Geo2SigMap for 3D radio propagation modeling. Two representative use cases demonstrate the system's planning and coordination capabilities. The results illustrate the ZMS's ability to serve as both an operational spectrum management tool and a research platform for studying spectrum coexistence in complex urban RF environments.**

***Index Terms*—Spectrum sharing, Spectrum Management, Wireless communications, Interference management**

I. INTRODUCTION

The efficient use of Radio Frequency spectrum resources represents an important technological and regulatory objective given the rapid growth in mobile data services and the emergence of 5G and beyond-5G networks. Spectrum sharing and dynamic spectrum access (DSA) technologies have become increasingly critical for these networks as the demand for wireless communications continues to surge. Traditional spectrum management and assignment methods - where specific bands are exclusively assigned to particular users or services - have led to significant inefficiencies. By enabling multiple users or systems to share the same spectrum bands, either simultaneously or by opportunistically filling unused gaps, spectrum sharing maximizes the utility of this resource. Dynamic spectrum access techniques allow RF devices to autonomously identify and exploit underutilized spectrum in real time and/or to intelligently coordinate and achieve efficient use of spectrum with capable spectrum management systems.

The COSMOS Zone Management System (ZMS) is a cloud-native, web-based spectrum coordination platform developed as part of an NSF SII-NRDZ multi-university collaboration (Columbia, Rutgers, Syracuse, Duke, Princeton, CCNY) to enable dynamic electromagnetic spectrum sharing in dense urban environments. The system operates in the NSF sponsored COSMOS PAWR (Platforms for Advanced Wireless Research) which is an open-access urban testbed for wireless research operating in West Harlem, NYC [1], [2]. The FCC Innovation Zone associated to the COSMOS testbed for RF coexistence experiments between multiple wireless services and systems provides the boundaries for the Radio Dynamic Zone (RDZ) of COSMOS ZMS (See Figure 1).

The COSMOS ZMS core operations for managing RF spectrum resources follow a declarative spectrum management model supported by the use of Spectrum Consumption Models (SCMs) specified in IEEE standard 1900.5.2. SCMs are information models that can capture the spectrum use boundaries by RF devices and systems so that their compatibility (i.e., non-interference) can be arbitrated by efficient and standard-

Fig. 1. RDZ Area in NYC

This work was supported in part by NSF grants CNS-2128638, CNS-2211944, AST-2232455, AST-2232456, AST-2232457, AST-2232458, AST-2232459, AST-2232460, CNS-2433974, CNS-2433975, ECCS-2434131, CNS-2223556, OAC-2429485, and CNS-2450567.

ized computational methods [3]–[5]. With the SCMs for the RF systems present in the COSMOS RDZ, the ZMS can continuously evaluate spectrum use compatibility between the systems, generate alerts when interference events are detected, and serve as a planning tool for spectrum use authorizations and/or experiment execution within the RDZ. Experimentation with the ZMS in the COSMOS RDZ is currently ongoing with particular interest in enabling spectrum sharing and incumbent protection across multiple frequency bands — notably the 28 GHz mmWave band — with a primary use case being the protection of NOAA-CESSRST passive receivers (microwave radiometers used for weather monitoring) from interference caused by co-located 5G and experimental wireless systems and also the protection of satellite receivers operating at 1.7 GHz and 7.7–8.2 GHz, used for polar orbiting weather satellite data reception.

II. INTRODUCTION TO SCMS

Spectrum Consumption Models are information models that provide a formal declarative way to describe how RF systems use spectrum resources and/or their interference protection requirements. Their primary purpose is to enable standardized, computational methods for determining whether multiple devices can coexist without causing harmful interference to one another. SCMs can account for complex real-world factors like antenna directionality, device placement, and varying propagation conditions, and they scale effectively to environments with large numbers of RF devices [5]. The IEEE 1900.5.2 standard defines eleven data elements called constructs (four of them are optional and not used on most cases) to describe the characteristics of spectrum use by an RF device:

- *Reference Power:* A baseline power level representing either a transmitter's emission strength or the maximum interference a receiver can tolerate.
- *Spectrum Mask:* Describes how a transmitter's emitted power is distributed across frequencies. This is exclusive to transmitter models.
- *Underlay Mask:* The receiver-side counterpart of a spectrum mask. It defines the maximum allowable interference power across frequencies. This is exclusive to receiver models.
- *Intermodulation Mask (optional):* Captures how signals present at the same location interact to produce unwanted interference products in transmitters or receivers.
- *Power Map:* Represents how electromagnetic energy is distributed across different directions, reflecting the behavior of transmitter and receiver antennas.
- *Propagation Map:* Describes how signal strength attenuates in different directions as it travels through the environment.
- *Location:* Specifies where a device may operate, ranging from a fixed point to an area, a volume, or even a trajectory. Area and volume definitions can also include device density values.
- *Platform name (optional):* Associates a device or group of devices with a named platform such as a ship or aircraft, helping identify when multiple systems share the same physical location.
- *Schedule:* Defines the time window during which the model is valid, including support for recurring or periodic activity patterns.
- *Policy or Protocol (optional):* Describes any spectrum access rules or coexistence protocols the system follows, such as listen-before-talk or CSMA/CD.
- *Minimum Power Spectral Flux Density (optional):* Used in transmitter models to help establish the geographic region within which associated receivers are entitled to protection.

Several constructs can carry a confidence value, allowing spectrum use boundaries to be expressed with some flexibility rather than being locked to worst-case assumptions. The IEEE 1900.5.2 standard also defines a hierarchy of models that provide different levels of granularity which can be used to create agile spectrum assignment mechanisms and service level agreements. At the first level of the hierarchy, *Transmitter Models* capture the full spatial, spectral, and temporal footprint of an active radio device's emissions. *Receiver Models* define the conditions under which a device would experience harmful interference. At higher levels in the hierarchy *System Models* combine transmitter and receiver models to represent a complete RF system. SCM *Sets* are collections of system, transmitter, and receiver models and can be structured to represent available spectrum (authorization sets), applicable restrictions (constraint sets), or desired spectrum use requests and configurations.

The spectrum use characteristics and boundaries of an RF device captured by an SCM can be used to execute a *Compatibility Test (CT)* computation also defined in the IEEE 1900.5.2 standard. This computation determines whether multiple systems can operate simultaneously in the same spectral environment without causing unacceptable interference. The CT calculation factors in transmitter power, receiver sensitivity, antenna pattern, propagation, and location information (among other items) to produce a *power margin value*. When evaluating the compatibility between a single transmitter potentially interfering with the operations of a particular receiver, a negative power margin indicates that the interfering signal falls below the receiver's interference threshold — meaning the systems are compatible. A positive margin signals that the receiver's interference threshold has been exceeded, indicating a conflict. This analytical framework extends to complex, densely populated RF environments where cumulative interference from many sources must be evaluated to support dynamic and adaptive spectrum sharing strategies.

III. COSMOS ZMS ARCHITECTURE

The ZMS serves as an end-to-end spectrum sharing solution whose primary mission is to coordinate spectrum use among multiple wireless systems operating within the COSMOS RDZ, while protecting sensitive incumbent passive receivers from harmful interference. The ZMS accomplishes this through a combination of SCM-based coordination, real-time spectrum monitoring and telemetry, automated interference analysis, and a web-based management interface.

The ZMS is built as a cloud-native system following microservices and containerization principles. It is deployed as a Kubernetes cluster along with several supporting services as shown in Figure 2. The current Kubernetes cluster has one master node and two worker nodes but can be easily scaled for higher resiliency and to support larger CT loads. An NFS (Network File System) storage server provides shared persistent storage for SCM based operations, compatibility test results, and status logs. A PostgreSQL database server with integrated GIS (Geographic Information System) extensions serves as the SCM database for the system. An Azure Container Registry for storing container images facilitates and supports quick updates to ZMS container-based logic and automations.

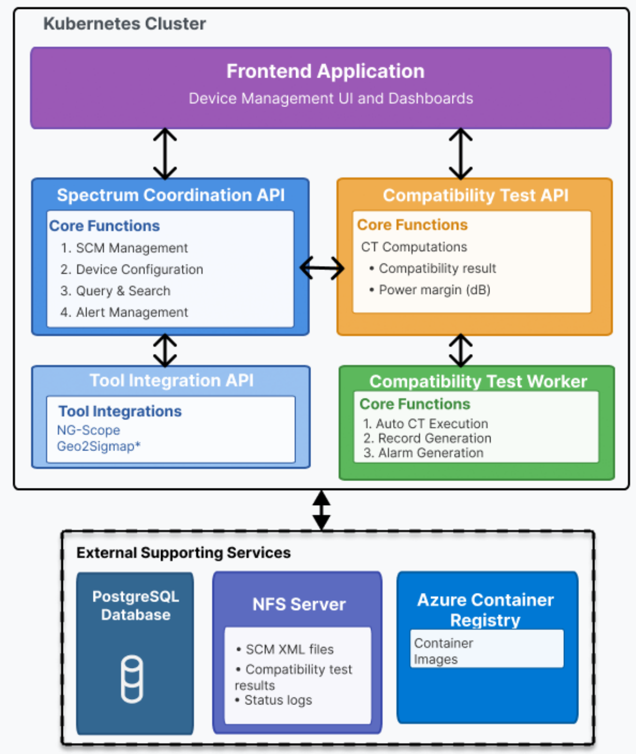


Fig. 2. COSMOS ZMS Architecture

The Kubernetes cluster hosts several distinct microservices:

- **Spectrum Coordination**: Provides the primary spectrum management operations including SCM management, device configuration, record generation, query and search, and alert management.
- **Frontend Application**: The user-facing web interface for all ZMS operations, including SCM configuration, device management UI, and alert dashboards including dashboards built with Apache Superset [6].
- **Compatibility Test (Computation Engine)**: Handles CT computations, produces compatibility results including power margin calculations, and exposes these results via API endpoints.
- **Compatibility Test Worker**: Executes the automated and scheduled compatibility tests (CTs), records results and generates alarms.
- **Tool Integration**: Handles ingestion of data from external spectrum monitoring tools such as NG-Scope [7] and Geo2SigMap [8], translating their outputs into SCM-compatible formats for storage in the ZMS database.

IV. CORE COSMOS ZMS CAPABILITIES

A. *RF Device Registration and Management*

The ZMS provides a comprehensive web-based interface for adding and managing RF devices enabling the following registration, search and query capabilities:

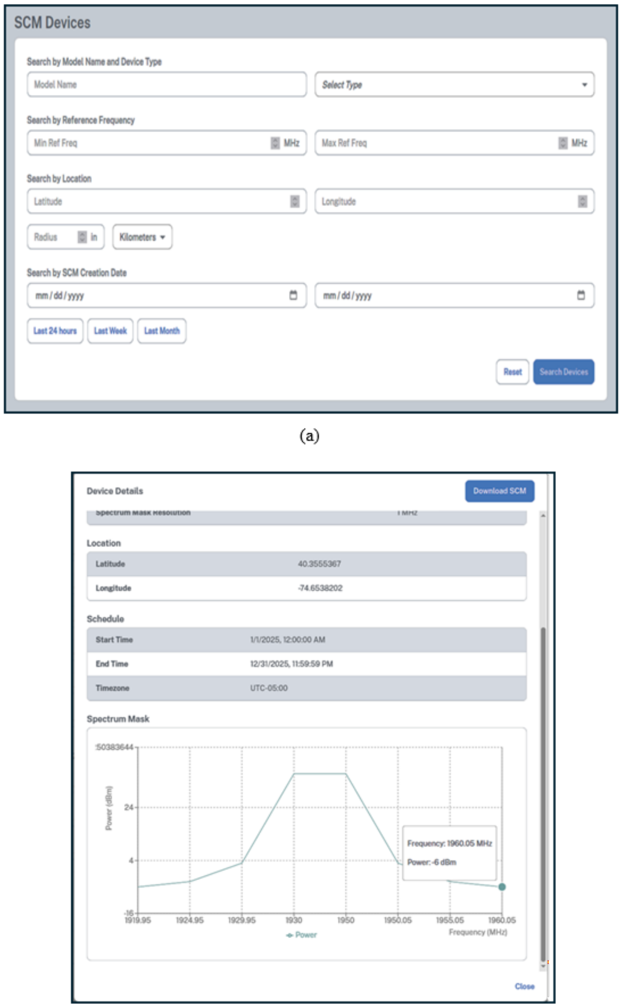
- Multiple RF device registration methods: Four methods are supported for registering a new device: (i) Upload of an SCM for the device in XML format, (ii) Clone an existing device and use it as a template for creating a new device, (iii) External tool/sensor input that triggers a new SCM registration (e.g. LTE base station detected with NG-Scope), (iv) create an SCM for the device via a guided web-based workflow where the user specifies model name and device type (Receiver or Transmitter), then configures detailed parameters including spectrum mask, propagation map, antenna characteristics, location coordinates, and schedule (start time, end time, timezone). The completed SCM can be saved directly to the ZMS database.
- Search devices by model name and device type
- Search devices by frequency range (min/max MHz)
- Search by geographic location (latitude, longitude and radius in kilometers)
- Search by device/system registration date or time period.

When using search capabilities, the search results are displayed in a tabular format showing device name, type, reference frequency, location coordinates, and creation date, with action buttons to View, Update, or Delete each device. Viewing a device's full details reveals all SCM parameters and the option to export the SCM in XML format. Examples of these capabilities are shown in Figure 3.

B. *Spectrum Coordination and Compatibility Testing*

Spectrum coordination capabilities are central to the operation of the ZMS and are heavily reliant on the execution of CT computations based on the SCMs of registered devices. Manual CT computations can take place when users search for and select specific transmitters and receivers using the a multi-criteria search interface (model name, frequency range, location, etc.). Once a transmitter-receiver pair is selected and confirmed, the system executes the CT.

Additionally, the ZMS runs an automated daily CT process that assesses spectrum use compatibility between all applicable device pairs in the ZMS database. The assessment skips CT tests between systems that have not been updated in the last 30 days (to avoid redundant computation on static devices). CT tests returning a Non-Compatible (NC) result automatically update the interference alarm database and the alarms dashboard. Devices on an exclusion list (e.g., test/demo devices) are not considered for automated CTs. An example of a CT computation is shown in Figure 4



(a)

Device Details

Spectrum Mask Resolution	1 MHz

Location

Latitude	40.3555367
Longitude	-74.6538202

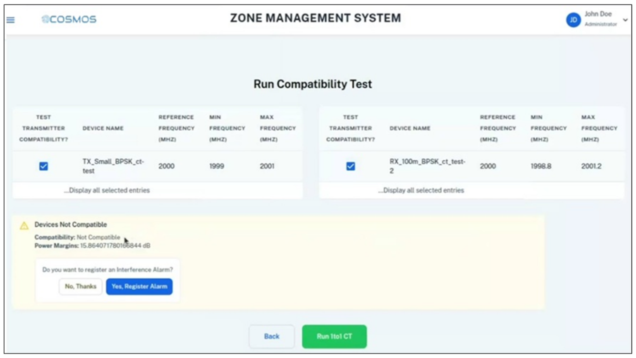
Schedule

Start Time	1/1/2025, 12:00:00 AM
End Time	12/31/2025, 11:59:59 PM
Timezone	UTC-05:00

Spectrum Mask

(b)

Fig. 3. RF Device Management



TEST TRANSMITTER COMPATIBILITY?	DEVICE NAME	REFERENCE FREQUENCY (MHZ)	MIN FREQUENCY (MHZ)	MAX FREQUENCY (MHZ)
☑	TX_Small_BPSK_ct-test	2000	1999	2001

...Display all selected entries

TEST TRANSMITTER COMPATIBILITY?	DEVICE NAME	REFERENCE FREQUENCY (MHZ)	MIN FREQUENCY (MHZ)	MAX FREQUENCY (MHZ)
☑	RX_100m_BPSK_ct_test-2	2000	1998.8	2001.2

...Display all selected entries

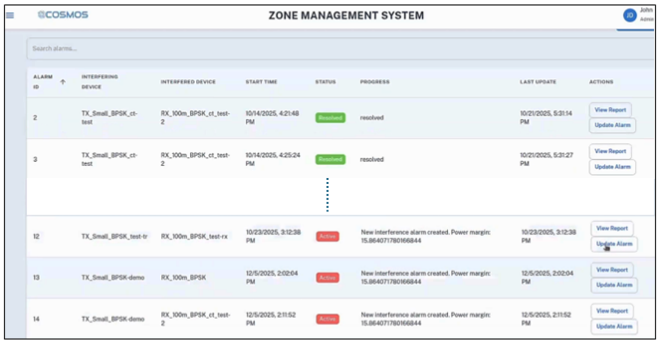
Devices Not Compatible
Compatibility: Not Compatible
Power Margins: 15.864071780166844 dB

Do you want to register an Interference Alarm?

Fig. 4. Example of a CT computation

C. Monitoring and Reporting

The COSMOS ZMS has several monitoring and reporting tools that give users full visibility into how spectrum is being used in the RDZ, where interference is occurring, and the overall status of RF devices registered with the system. These capabilities are accessible through several dashboard interfaces and query tools. One key feature is a searchable dashboard for RF devices registered in the ZMS, which includes map-based visualizations showing where devices are located, and their spectrum use details. Users can narrow down results by filtering on criteria such as frequency range, geographic location with an adjustable search radius, and device type. These map views make it straightforward to grasp the spatial dynamics of the RF environment and identify systems that may interact or interfere with one another.



ALARM ID	INTERFERING DEVICE	INTERFERED DEVICE	START TIME	STATUS	PROGRESS	LAST UPDATE	ACTIONS
2	TX_Small_BPSK_ct-test	RX_100m_BPSK_ct_test-2	10/14/2025, 4:21:48 PM	Resolved	resolved	10/21/2025, 5:31:14 PM	View Report Update Alarm
3	TX_Small_BPSK_ct-test	RX_100m_BPSK_ct_test-2	10/14/2025, 4:25:24 PM	Resolved	resolved	10/21/2025, 5:31:27 PM	View Report Update Alarm
12	TX_Small_BPSK_test-tr	RX_100m_BPSK_test-rx	10/23/2025, 3:12:38 PM	Active	New interference alarm created. Power margin: 15.864071780166844	10/23/2025, 3:12:38 PM	View Report Update Alarm
13	TX_Small_BPSK-demo	RX_100m_BPSK	12/5/2025, 2:02:04 PM	Active	New interference alarm created. Power margin: 15.864071780166844	12/5/2025, 2:02:04 PM	View Report Update Alarm
14	TX_Small_BPSK-demo	RX_100m_BPSK_ct_test-2	12/5/2025, 2:11:52 PM	Active	New interference alarm created. Power margin: 15.864071780166844	12/5/2025, 2:11:52 PM	View Report Update Alarm

Fig. 5. Interference alarm management dashboard (List view)

A dedicated interference alarm dashboard presents a list of interference events and alerts, along with information about the devices involved and the current status of the event (See Figure 5). Users can review historical alarm logs and monitor how compatibility and interference issues are being resolved over time. A map-based view of interference alarms is also available. Taken together, the logs generated by the ZMS serve as a valuable resource for guiding operational decisions and meeting documentation needs for both research experiments and regulatory compliance within the RDZ.

D. External tool integration

The COSMOS ZMS supports connections with external spectrum management/monitoring related tools through a Tool Integration API, which allows outside measurement and modeling systems to automatically feed data into the ZMS's spectrum consumption model (SCM) framework.

One completed integration is with NG-Scope [7], a cellular network monitoring tool that scans LTE signals to extract cell-level parameters — including tower location, carrier identity, transmit power, received signal strength, and resource block usage. NG-Scope packages this data as JSON and sends it to the ZMS, which then constructs an SCM for each detected base station. These SCMs feed into the RF management processes giving the ZMS ongoing visibility into cellular spectrum activity. Plans are in place to extend this capability to 5G NR using NR-Scope [9].

A second integration, still in development, connects the ZMS with Geo2SigMap [8], a 3D scene and radio propagation modeling tool. This will allow the ZMS to generate more realistic propagation and path loss estimates by incorporating building geometry, terrain data, and site-specific ray tracing — moving beyond simplified analytical models. In future work, the ZMS is also planned to connect directly to COSMOS's distributed software-defined radio nodes, which will act as real-time spectrum sensors across the testbed.

All of these integrations are designed with scheduling and coordination in mind, allowing external tools to deliver data on defined intervals while the ZMS controls how that data is validated and incorporated into its operational database.

V. ZMS USE CASES

Since the COSMOS RDZ is located in a heavily populated urban area of NYC with many RF systems in operation, including passive RF devices, we have been progressively adapting the operations of the ZMS to account for the diversity of devices and potential co-existence and interference issues that may arise. The main bottleneck for generating effective SCMs that can be used in the ZMS is collecting details of antenna patterns, gains and receiver sensitivity levels. Characterization of realistic propagation conditions at different frequencies and locations has also been a challenge but via the collection of measurements (see [10]), the integration of NG-Scope and the future integration of Geo2Sigmap we hope to address this limitation.

In this section, we present two use cases where the COSMOS ZMS can be used as a planning tool for experiments to be conducted in the COSMOS RDZ or for actual commercial operation of RF devices. As more SDR nodes from the COSMOS testbed get scheduled and configured to report to the ZMS, its spectrum use monitoring capabilities will be active in a more continuous manner.

A. 28 GHz transmission planning

Several coverage and propagation measurement campaigns have taken place in COSMOS since its inception. Detailed measurements of propagation conditions for operations at mmWave frequencies (28 GHz +) in the COSMOS RDZ area have been reported in [10], [11]. In this ZMS use case example, the measured path gain values for a subset of the measured locations have been used in the creation of SCMs that model the operations of FR2 base stations and UEs in the 28 GHz band. Detailed path gain measurements provide a high degree of accuracy to the characterization of propagation effects and are used in the Propagation Map construct of the SCMs we created. Since this construct captures the rate of RF power attenuation by direction, it provides higher path loss estimation accuracy than using traditional fitted line models that obscure directional details of the attenuation of RF power.

We will consider that a 5G FR2 base station (BS) transmitter and a 5G FR2 UE receiver, labeled Tx1 and Rx1 respectively, have an established communications link and that the FR2 base station is providing coverage in the direction of Rx1 (see Figuree 6). The base station is using a directional antenna with a 24dBi gain and 10° HPBW, the transmit power is 13 dBm (small local area BS) and the channel bandwidth is 50 MHz. The UE is a handheld UE (Power class 3) with a 3dBi omnidirectional antenna. The emission and reception limits of the BS and the UE follow the 3GPP technical specifications for FR2 operations stated in ITU-T recommendations TS 38.104 and TS 38.101 respectively.

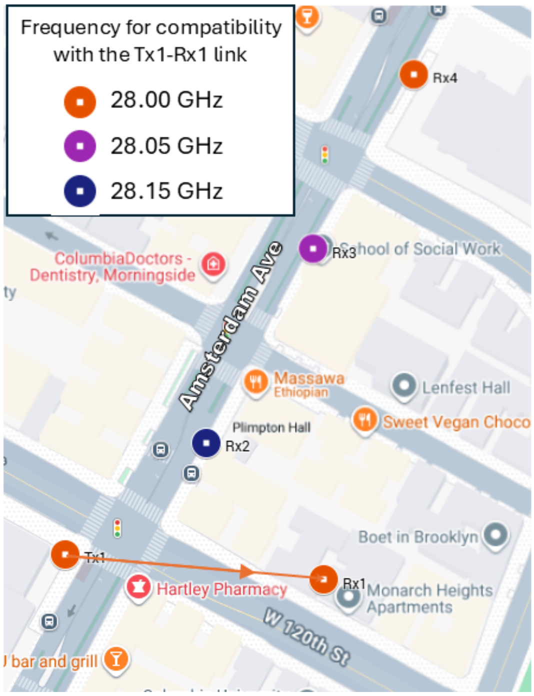


Fig. 6. 28 GHz spectrum use planning

Assume that 28.0 GHz operations (over a 50 MHz channel) are ongoing between TX1 and RX1 we want to find out the channel center frequency closest to 28.0 GHz at which UE RXs at locations RX2 – Rx4 can operate given the presence of interference from the operations of the TX1 to RX1 link. Note that RX2 – RX4 are the locations of UE devices associated with a different base station(s). By providing to the ZMS the SCMs of the BS, and the UEs, the location information for each device and carrying out a compatibility analysis, we determine that for compatibility with the Tx1-Rx1 link: A UE at RX2 would have to operate at 28.15 GHz or above, UE at RX3 can operate at 28.05 GHz or above and a UE at RX4 can operate at 28.0 GHz – thus reusing the same frequency being used in the TX1 to RX1 link. Figure 6 summarizes the results. Similar spectrum use planning and/or resource deconfliction cases can be done at other RDZ locations. Additional examples can be found in [11].

B. 6 GHz operations

Since 2020, the FCC has opened up 1,200 MHz of spectrum in the 6 GHz band (5.1925–7.125 GHz) for unlicensed use. To manage shared access in this band by unlicensed devices while safeguarding existing licensed operations — such as microwave backhaul links, fixed satellite services, and broadcast auxiliary services — the FCC requires the use of an Automated Frequency Coordination (AFC) system. Unlicensed outdoor devices classified as Standard-Power Access Points (SPAPs), which may provide Wi-Fi 6E or Wi-Fi 7 connectivity, must obtain AFC authorization before transmitting.

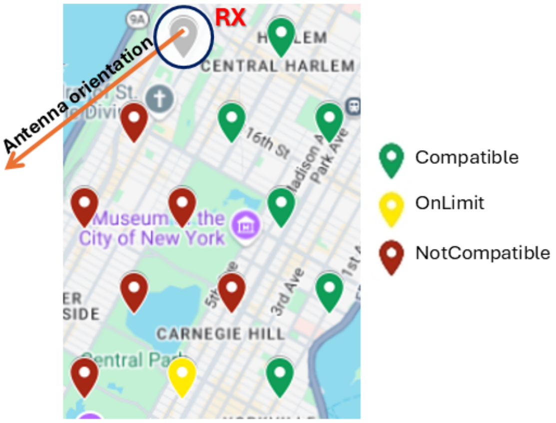


Fig. 7. 6 GHz spectrum use planning

The AFC system maintains awareness of incumbent operations by querying the FCC's Universal Licensing System (ULS) database on a daily basis. This database contains detailed records for each licensed receiver, including geographic coordinates, antenna height and radiation pattern, operating frequency and bandwidth, and noise figure. Using these parameters, the AFC calculates a protected area — referred to as an exclusion zone — around each incumbent receiver. Any SPAP located within that zone is prohibited from transmitting on the corresponding frequency at the power level in question.

The exclusion zone is computed based on the condition that if I is the interference seen at the receiving antenna from the emissions of an SPAP and N is the noise level affecting the protected receiver, the I/N ratio should not exceed -6 dB. In other words the interference-to-noise ratio $I/N \leq -6$ dB. Additional details on how an AFC performs this computation are stated in [12]. More details on the use of SCMs for operations in the 6 GHz band are in [13].

For our analysis, in this section, we will study the feasibility of using an SPAP in our RDZ near an area where a 6 GHz microwave receiver is present. In reality, we have to register the SPAP with an AFC but we can determine feasible locations for our SPAP beforehand using the ZMS. The SPAP operates over a 20 MHz channel centered at 6585 MHz and uses an omnidirectional antenna with a gain of 8 dBi at a height of 5 meters. We seek operation at the highest allowed SPAP transmit power of 36 dBm. For illustrative purposes, we consider that the area of operation (see Figure 7) has a microwave receiver that operates at 6585 MHz with a 10 MHz channel bandwidth, using 64 QAM modulation, a directional antenna gain of 35.5 dBi with a 1.6 degree beamwidth and an antenna height of 25 meters (above terrain).

With the scenario setup and conditions mentioned above, we generated SCMs representing the operations of the SPAP (interfering transmitter) and microwave receiver (protected incumbent) and used them in the ZMS to determine feasible locations for the SPAP. Figure 7 captures the results, where the "NonCompatible" locations are locations where the SPAP would violate the 6 GHz interference protection criteria. The "OnLimit" location is just above (0.2 dB) the protection criteria and should not be used for SPAP placement. The "Compatible" locations are feasible for our SPAP setup.

VI. CONCLUSIONS

This paper has presented the COSMOS Zone Management System (ZMS), a cloud-native, SCM-based spectrum coordination platform for managing dynamic RF spectrum sharing within the COSMOS RDZ in an urban area. The system's declarative approach, grounded in the IEEE 1900.5.2 standard, provides a flexible and scalable foundation for automated interference analysis, real-time monitoring, and proactive spectrum use planning across diverse co-located wireless systems. The two use cases presented — 28 GHz mmWave transmission planning and 6 GHz unlicensed device placement — demonstrate the ZMS's practical utility as both a research tool and a spectrum authorization aid for complex urban RF environments.

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