A Spectrum Consumption Model-based Framework for DSA Experimentation on the COSMOS Testbed

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ABSTRACT

This paper describes a wireless experimentation framework for studying dynamic spectrum access mechanisms and an experiment that showcases its capabilities. The framework was built on COSMOS, an advanced wireless testbed designed to support real-world experimentation of next generation wireless technologies and applications. Our deployed framework supports experimentation over a large number of wireless networks, with a PUB-SUB based network interaction structure, based on the Collaborative Intelligent Radio Networks (CIRN) Interaction Language (CIL) developed by DARPA for the Spectrum Collaboration Challenge (SC2). As such, it enables interaction and message exchanges between the networks for the purposes of coordinating spectrum use. For our experiment, the message exchanges are aimed primarily for, but not limited to, Spectrum Consumption Model (SCM) messages. RF devices/systems use SCM messages which contain detailed information about their wireless transmission characteristics (i.e., spectrum mask, frequency, bandwidth, power and location) to determine their operational compatibility (non-interference) with prior transmitters and receivers, and to dynamically determine spectrum use characteristics for their own transmissions.

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CCS CONCEPTS

• **Networks** → **Network architectures**; **Network experimentation**; • **Hardware** → **Wireless devices**.

KEYWORDS

Dynamic spectrum access, Spectrum consumption model, GNU Radio, Wireless experimentation, Open-access wireless testbeds

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1 INTRODUCTION

Spectrum scarcity has been a well known and growing problem for decades, and has motivated researchers across the globe to continuously innovate and find ways to increase spectrum use efficiency. For years, the research was focused on improving the achievable data rate for a given bandwidth. However, with the increasing number of wireless protocols, the focus has shifted towards developing methods that would enable multiple heterogeneous wireless networks to coexist in the same spectrum. More recently, attention has been given to cooperation and mutual coordination regarding access to shared spectrum by such heterogeneous wireless networks.

The described shift in the research focus is apparent from recent competitions and research initiatives organized to support the scientific community in its efforts to develop efficient ways to coordinate and synchronize spectrum access. In 2016, DARPA started the Spectrum Collaboration Challenge (SC2), which engaged multiple teams, each with their own wireless network, to interact with each other, where the mutual goal was increasing the combined throughput. The competitor networks were encouraged to use Artificial Intelligence (AI) approaches to build intelligent networks, which are able to adapt their spectral behavior. The networks were called Collaborative Intelligent Radio Networks (CIRN), and the interaction language developed by DARPA was named CIRN Interaction Language (CIL). In the spirit of the competition, the language itself was also developed collaboratively, by DARPA and all the participating teams. In its simplest form, CIL provides the networks with information exchange functionality and supports various types of messages [14].

More recently, the National Science Foundation (NSF) has started the Spectrum Innovation Initiative (SII). The goal of the initiative is to build an ecosystem for research related to dynamic and agile spectrum utilization. As part of our efforts to address the challenges that have been identified by this initiative, we *built a framework which supports and facilitates experimentation and research of architectures and mechanisms for coordinated use of spectrum resources between collaborative wireless networks*. The framework was built on COSMOS [3, 10], an advanced wireless testbed designed to support real-world experimentation of next-generation wireless technologies and applications. To showcase the framework's capabilities, we also designed and carried out an experiment where the framework components were used to allow three different wireless networks to coordinate their spectrum usage via the exchange of messages carrying Spectrum Consumption Models (SCMs). The SCMs describe the characteristics and boundaries of spectrum usage of the devices in each network and facilitate the autonomous and dynamic selection of spectrum resources for each network in order to establish non-interfering communication links between the devices of each network. This kind of use of SCMs is a first of its kind in a civilian communications environment.

To provide a description of the Dynamic Spectrum Access (DSA) research framework and experiment, the rest of the paper is organized as follows: Section 2 provides a brief description of related work on the implementation of dynamic spectrum access and sharing mechanisms. Section 3 provides an introduction to SCMs. Section 4 describes the spectrum management architecture underlying our framework and experimentation. Section 5 describes the design and implementation of several framework components, including the way the SCMs for our experiments were generated, a description of the infrastructure used in our experiments and our experimental results. Section 6 provides some directions for future experimentation and Section 7 concludes the paper.

2 RELATED WORK

Over the course of several decades, with various wireless communication protocols emerging, it has long been understood that heterogeneous networks using these protocols would end up competing for wireless spectrum. Accordingly, more and more effort was focused on manners to improve coexistence of heterogeneous networks in the same spectrum, some of which use collaboration methods and additional protocols for networks to coordinate their spectrum usage. Indeed, DARPA's CIL was not the first instance of a proposed spectrum access coordination protocol. Several similar ideas were discussed in [6, 8, 11, 14, 16]. Spectrum sharing has been extensively studied for over a decade and, recently, there has been special interest in the coexistence of LTE and WiFi, with several proposed solutions for LTE in unlicensed spectrum. Next, we describe some related work.

The work described in [7] presents an opportunistic protocol for spectrum access coordination between independent networks operating with different wireless protocols. This opportunistic protocol included a central Cognitive Radio (CR) terminal which assigned spectrum aiming to establish fairness based on data flows. In [5], a simple message exchange protocol (in many ways similar to CIL) is presented. This message exchange protocol, named Common Spectrum Coordination Channel, operated in a separate narrow frequency band to allow networks to exchange simple messages to announce their spectrum usage. The evaluation of its performance was based on ns-2 simulations. The work in [15] showed a semantic-based algorithm which used FFT analysis and energy detection with semantic reasoning to determine available frequency bands for transmission. A distinctive feature of this paper is that it included a real-world implementation of its algorithm using OpenAirInterface (OAI). Another semantic approach is shown in [2]. Spectrum coordination in 5G is considered in [12], where the authors introduced a virtual currency-based non-cooperative negotiation protocol for spectrum access.

With a significant amount of research efforts aimed at enabling coexistence of heterogeneous networks in the same spectrum bands, it is important to note that the bulk of the work has been theoretical, occasionally backed by simulations (often in MATLAB or a network simulation framework such as ns-3), with few scientific papers that evaluate their findings using practical implementations. This paper aims in part to fill that gap. We build a wireless experimentation framework on the COSMOS testbed [3, 10] for studying dynamic spectrum access. Then, we implement a coordination protocol based on CIL, a prime example of a protocol that was already successfully utilized for spectrum access coordination during DARPA SC2, which in our case is used to exchange SCM messages to enable spectrum resource use coordination.

3 SPECTRUM CONSUMPTION MODELS

SCMs provide an information model that can capture the boundaries of the use of spectrum by RF systems so that their compatibility (i.e., non-interference) can be arbitrated by efficient and standardized computational methods [1, 4, 13]. The information captured in SCMs allows for efficient determination of aggregate interference levels and of aggregate compatibility interference between many devices.

The IEEE 1900.5.2 standard[4] for modeling spectrum consumption specifies 11 constructs for an SCM:

(1) Reference power: This value provides a reference power level for the emission of a transmitter or for the allowed interference in a receiver. It is used as the reference power value for several other SCM constructs (i.e., spectrum mask, underlay mask, and power map).
(2) Spectrum mask: Data structure that defines the relative spectral power density of emissions by frequency.
(3) Underlay mask: Data structure that defines the relative spectral power density of allowed interference by frequency.
(4) Power map: Data structure that defines a relative power flux density per solid angle.
(5) Propagation map: Data structure that defines a path loss model per solid angle.
(6) Intermodulation mask: Data structure that defines how co-located signals generate intermodulation products in a transmitter or receiver.
(7) Platform name: A name or list of names of platforms that are attributed to a particular site (i.e., ship, airplane, etc.). They are useful in identifying when multiple systems are co-located.
(8) Schedule: Construct that specifies the time in which the model applies (start time, end time). Periodic activity can also be defined.
(9) Location: The location where an RF device may be used. Several types of locations and trajectory/orbit descriptions are supported.
(10) Minimum power spectral flux density: A power spectral flux density that when used as part of a transmitter model, implies the geographical extent in which receivers in the system are protected.
(11) Policy or protocol: A named protocol or policy with parameters that define behaviors supported by a device or systems that allow different systems to be co-located and to coexist in the same spectrum.

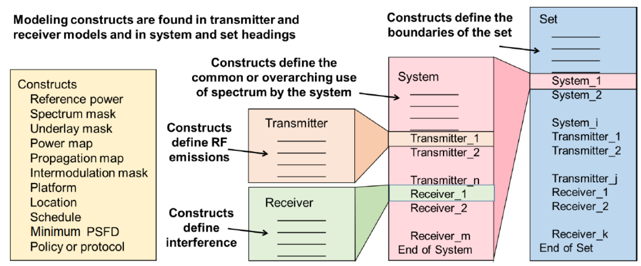


Figure 1: Spectrum Consumption Model (SCM) types

These constructs can be used to build different types of SCMs that follow an aggregation hierarchy as shown in Figure 1. It is worth noting that depending on the type of model and its purpose, not all constructs are required. Figure 1 shows the relationships between different types of SCMs as defined in the IEEE 1900.5.2 standard [4]. A transmitter model captures the extent of RF emissions of an active radio device, including but not limited to: spectral emission mask, propagation map, antenna radiation pattern, possible locations of the device, and times of operation. A receiver model conveys what is harmful interference to an RF device, providing a limit to the aggregate interference that transmitter devices can cause to a receiver in the temporal, spatial, and spectrum dimensions. System models are a collection of transmitter and receiver models that collectively capture the spectrum use of an RF system. An SCM set is a collection of system, transmitter, and receiver SCMs. SCM sets can be used to structure lists that describe spectrum that is available for use (Spectrum authorization sets), identify constraints to spectrum use (Spectrum constraint sets), and to list the spectrum being consumed (used) by a group of systems and devices (Collective consumption set)

In addition to a definition of the constructs for SCMs, the IEEE 1900.5.2 standard specifies a method for computing the compatibility of spectrum use between devices and/or systems that have expressed the boundaries of their spectrum use via SCMs [1, 4]. Depending on the locations of the devices for which compatibility is to be assessed and if there is overlap in their spectrum use operations (in time and in frequency), the information conveyed by their SCMs related to transmitter spectrum masks, receiver underlay mask, reference power, power map, and propagation map, among other constructs, determine the details of a link budget computation. In the case of a single transmitter-receiver pair, if the RF signal power from the transmitter is determined to be below the interference limit value specified in the receiver model, the pair is determined to be compatible (i.e., they can share spectrum). This computation can extended to multiple transmitter and receiver pairs making use of the information in the SCMs to compute aggregate interference values. Other spectrum use characteristics such as intermodulation and frequency hopping behavior can also be taken into account. For additional details, we refer the reader to [4]. Next, we discuss the architecture which employs SCMs to enable spectrum sharing between multiple wireless networks.

4 ARCHITECTURE FOR DYNAMIC SPECTRUM MANAGEMENT

The spectrum management architecture illustrated in Figure 2 is composed of four functional planes:

- cloud based spectrum service plane,
- wireless domain control plane,
- wireless data plane, and
- monitoring and measurement plane.

The sensors, radio devices, and networks on the data plane are represented by Wireless Domain (WD) controllers in the control plane. In particular, a WD controller can represent one or more wireless networks operating in a single administrative domain. SCMs from individual RF devices in each of the wireless networks are aggregated at the corresponding WD controller. The WD control plane is heavily based on DARPA's CIL, allowing for the exchange messages containing SCMs between the domains as well as to control radio nodes in the data plane. In addition to peering of SCM exchanges enabled by the control plane, a cloud based spectrum service layer is introduced to accommodate hierarchical control with the benefits of centralized optimization involving complex AI/ML algorithms. The cloud service layer provides spectrum management, monitoring, and marketplace capabilities to which WD's can subscribe. The data, control, and cloud service planes are further supported by an independent spectrum monitoring infrastructure intended to provide accountability for actual spectrum use. The monitoring plane collects and aggregates sensor data which is then passed up to a spectrum analytic service in cloud layer for further processing. The analytic/monitoring application in the cloud disseminate this information to WD controllers using information centric PUB/SUB techniques.

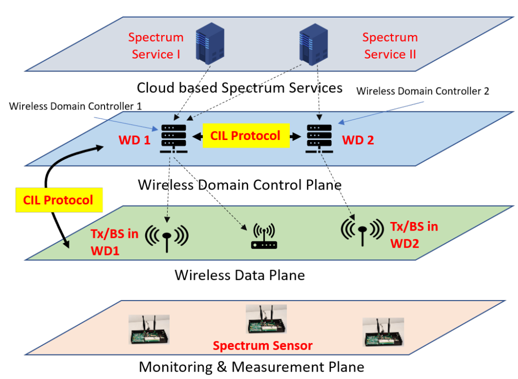


Figure 2: Overview of decentralized spectrum management architecture

The CIL protocol between the domain controllers and radio nodes supports several types of messages as listed below. More details on protocol exchange can be found in Section 5.

1. ***Register ()*** : Generated by WD to register with collaboration server/system
2. ***Inform ()*** : Informs newly joined peer about existing peers
3. ***Notify ()*** : Notifies existing peers about the new joined peer
4. ***SCM Request ()*** : Message to request SCMs from peers
5. ***SCM ()*** : Message to send SCM to the requester
6. ***CT Report ()*** : Sends compatibility test report to peers
7. ***Calibrate Radios ()*** : Message to calibrate SDRs with respective gain, frequency, modulation, etc.
8. ***Leave ()*** : Generated by WD to exit the system

5 FRAMEWORK AND EXPERIMENT DESIGN AND IMPLEMENTATION

Our experimentation framework for dynamic spectrum access interactions was built on top of the COSMOS wireless testbed [3, 10]. As described earlier, the framework aims to enable wireless networks to exchange messages in order to coordinate and synchronize their spectrum access, it also facilitates the execution of the computations necessary to determine available spectrum resources and avoid interference events with other networks present in the same spectrum.

The network interaction language for our framework was built on top of DARPA's implementation of CIL. CIL was originally designed as a PUB-SUB message queuing system, with several types of messages being broadcast, and all networks

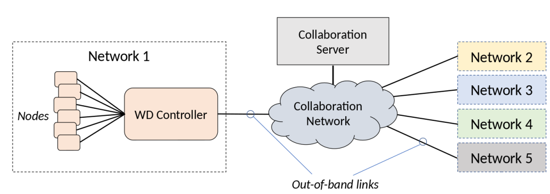


Figure 3: Network Interaction Language overview. The domain controller of a network can exchange messages with other networks' domain controllers via independent, out-of-band links.

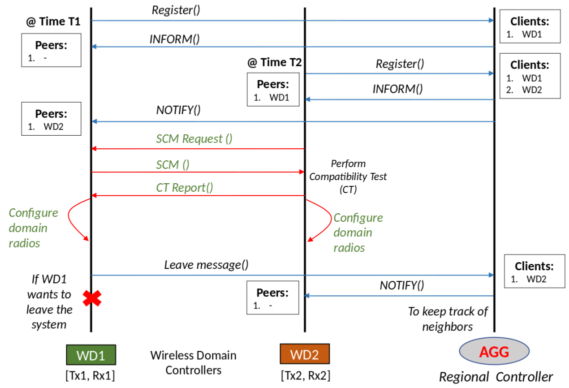


Figure 4: Network Interaction Language protocol details, showing the message types exchanged when a wireless network joins, interacts with other networks, and leaves the domain.

able to receive them. The new interaction language developed for our experiments has introduced several adaptations and improvements. Figure 3 shows the design schematic of the language. Similarly to CIL, each network has a designated node, a WD controller, which can use the interaction language to communicate with other networks' WDs. To maintain the high performance and efficiency of the message queuing service, Google's Protocol Buffers are still used to convert all supported messages into binary blobs. However, the message types were adapted to accommodate newer spectrum usage description standards. The networks are now able to exchange SCM messages which provide a standardized and detailed description of spectrum usage [1].

Another advantage gained by using SCM based messages, in addition to the level of detail the messages provide, is that the standard on which they are based also includes the algorithms for the computations necessary to determine spectral compatibility between different transmitters or receivers. The framework heavily utilizes these computations. Compatibility computations are included as a component of the interaction language. First, with each new network joining the framework, the interaction server performs the compatibility computations, and only sends its SCM information to the networks in the same interference domain. Additionally, the networks themselves can invoke compatibility computations for any pair of nodes, and use the obtained information to determine the optimal bands for their transmissions. The details of the protocol used by the interaction language are shown in Figure 4.

5.1 SCM Generation and Processing

The interactions in our WD control plane will rely on the exchange of SCM messages that characterize the transmitters and receivers of each WD. The required constructs for the transmitter models are: reference power, spectrum mask, power map, propagation map, schedule, and location. For the receivers, the spectrum mask is not required but an underlay mask is. For our experiments, we used a set of NI USRPs as transmitters and another set as receivers. The schedule and location of each transmitter and receiver device was well known. For simplicity, all transmissions used BPSK modulation with a channel bandwidth of 1 MHz. Additional details on the characterization of the devices and the processing of their SCMs are mentioned in the following subsections.

5.1.1 Transmitter characterization. In order to characterize and build the SCM for a transmitter (Tx) USRP, we first obtain the Power Spectral Density (PSD) plot that will help us build the spectrum mask for the device. This is performed by setting Tx gain to 10dB, resolution bandwidth to 100 KHz or lower and amplitude 500mV. The received samples are captured at a distant receiver (Rx) setup to operate at the same central frequency as the Tx and the distance between Tx and Rx is reported. Next, we change the amplitude values at the Tx to understand how well it translates to radiated power. The separation distance between the devices should always be at least 1 meter. Finally, we repeat the same experiment again but with a different receiver and report the distances between Tx and Rx. Capturing the Tx's radiated power at receivers located at different distances provides details to elaborate the propagation map construct needed in the SCMs.

5.1.2 Receiver characterization. To characterize the receiver USRP, determining the shape of its underlay mask is key. For this purpose, we fix the Tx amplitude to 500mV, Rx and Tx gain to 10dB and the center frequency at receiver to 2 GHz. From the Tx, transmit a BPSK modulated signal while varying the central frequency and capture the PSD image and SNR value at each frequency value at the receiver. The central frequency of the transmission is varied in steps of 200 KHz from 1997 MHz to 2003 MHz. Next, we gather data to determine the allowable interference on the receiver considering Figure 5 as an example topology. From Tx1, we transmit a BPSK modulated signal with a center frequency of 2 GHz and gain 10dB. At the receiver, we make sure that we can demodulate Tx1's BPSK signal and capture the signal at the receiver while Tx1 is ON and Tx2 is OFF. Continuing with the same setup as before, while Tx1 is still transmitting, Tx2 is turned on and transmits a QPSK modulated signal (interfering signal) with a center frequency of 2 GHz. The initial Tx2 gain should be 10dB, and later we change Tx2's gain until we get to a value which we will call X where Rx1 will stop demodulating Tx1's transmissions and if Tx2's gain is later lowered by 0.5dB (i.e., Tx2's gain becomes $X - 0.5$dB), Rx1 will be able to demodulate some of Tx1 transmissions. We report the value of X and generate a signal capture on Rx1 when Tx2 is operating with gain X and Tx1 is ON. Finally

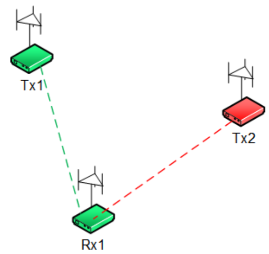


Figure 5: Topology used for receiver characterization

we also determine the available interference on the receiver considering a displaced frequency of 1999.6 MHz. The above described procedure is repeated using this frequency and the value of X and signal is captured.

5.1.3 Compatibility computations. An overview of the structure of the transmitter spectrum mask and receiver underlay mask obtained after our characterization process is shown in Figure 6. Using the data contained in the SCMs, calculations are performed to determine a bound that specifies by how much power can the spectrum mask of a transmitter be adjusted to be at the threshold of compatibility (i.e., non-interference) with the underlay mask of a receiver. This computation is known as the power margin computation, and its result can be used to evaluate how spectrum reuse and/or sharing opportunities can be leveraged. Two types of power margin computations are specified in the IEEE 1900.5.2 standard: (i) maximum power density and (ii) total power. The maximum power density method determines if the maximum power spectral density of a transmitter's spectrum mask (after propagation and antenna gains) exceeds any threshold level of the receiver's underlay mask. The total power method uses the underlay mask to determine the total power from the transmitter that enters the receiver and check, if it is less than some threshold that would otherwise be characterized as unacceptable interference. We used the total power method in our experiments.

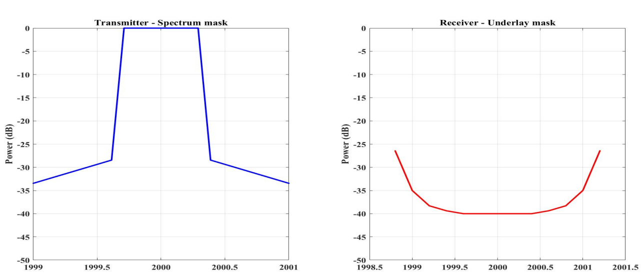


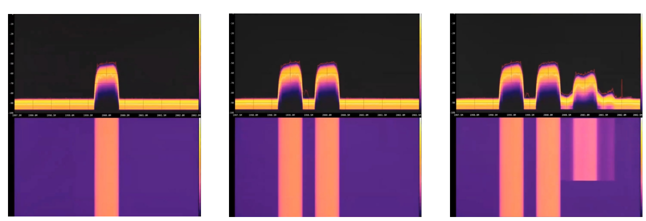
Figure 6: Transmitter spectrum mask and receiver underlay mask

Table 1: Experimentation Settings

Parameter	Value
Central Freq	2.0 GHz
No. of Channels	3
Bandwidth	1 MHz
Modulation	BPSK
Bitrate	0.5M
Gnuradio	v3.7
USRPs	x310s and b210s

5.2 DSA Experimentation in COSMOS

This subsection describes an experiment designed to demonstrate the capabilities of the developed framework. In the experiment, there are three wireless networks that have transmitters and receivers near each other's local area. The goal is for the networks to dynamically configure their wireless transmission characteristics, in this case, their central frequency of operation so that there is no harmful interference between the devices of different networks. Each network contains only a single transmitter and a single receiver. Transmitters and receivers are implemented using NI USRP X310 and B210 devices, while on the control plane, WD controllers operate on separate nodes with CIL message exchanges conducted via out of band links between the WD controller nodes. Additionally, all transmitters use the same spectrum mask and attempt transmission using a 1 MHz wide channel. The radio node acting as spectrum sensor/monitor and used for visualization is sampling captured signals at 10 Msps. The decision-making logic (whether to transmit and which frequency and power to use) of the network is implemented as part of the WD node, and GNU Radio scripts are utilized to implement the physical layer functionality, including packetization and USRP over-the-air transmission.



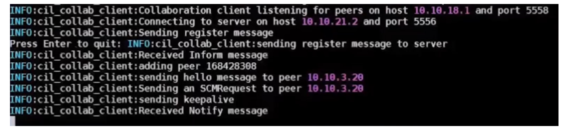
(a) One TX **(b) Two TX** **(c) Three TX**

Figure 7: Fosphor visualization showing the spectrum occupancy as the first, second and third network start operating

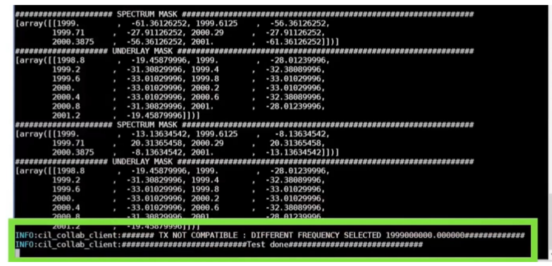
The experiment showcases a simple scenario. At the beginning, there are no networks present in the spectrum. At time t_1, Network 1 joins, and since the entire spectrum is available, it is free to select any channel. A 1 MHz channel centered around 2 GHz is selected. Figure 7a shows a

GNU Radio Fosphor visualization of the spectrum with only a single transmitter. After that, at time t_2 Network 2 joins the domain. Its default frequency setting is 2 GHz, the same central frequency used by Network 1. The interaction language server (Regional Topology Manager) determines that the networks are in the same wireless collision domain, and notifies Network 1 that a peer is now present. Networks 1 and 2 establish a peering relationship as shown in Figure 8a, and immediately exchange their SCMs. After performing the compatibility checks, the results of which are shown on Figure 8b, Network 2 determines that it can not use the intended frequency, and finds an alternative optimal center frequency – 1999 MHz. Similarly, at time t_3, Network 3 joins, with the assistance of the Regional Topology Manager establishes connections with Networks 1 and 2, and after exchanging a set of SCM messages and performing its spectrum compatibility calculations determines that the optimal center frequency to use is 2001 MHz. Figure 7c shows all three transmitters at three orthogonal central frequencies. Figure 8c shows a summary of the SCM information that the controller node at Wireless Domain 3 (WD3) had to process to carry out the compatibility tests necessary to locate a central frequency where its Transmitter (Tx3) could operate without causing interference to receivers already present in the environment and where its receiver (Rx3) could also operate without being interfered by existing transmitters.

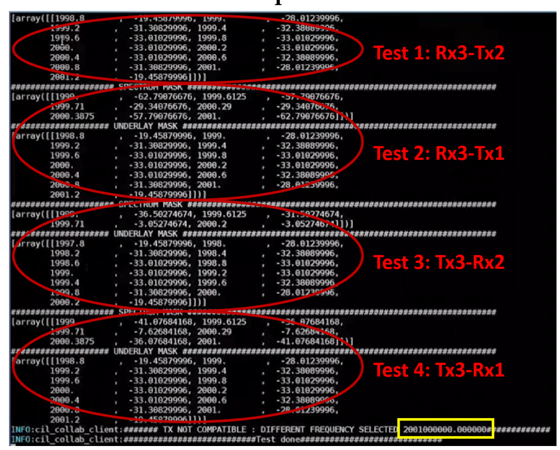
Figure 9 shows the scheme of the experiment – the networks with their WDs, node IDs of the USRPs utilized, and the established interaction links. Figure 10 shows the physical topology of the USRP nodes used within the COSMOS Sandbox, as well as the location of the Sensor node (used for GNU Radio Fosphor visualization). It also provides the location of the columns in the room, which are built out of concrete and metal and may affect the wireless signal propagation within the room.



(a) Exchange of 'Inform' and 'Register' messages between domain controllers



(b) Compatibility test result, reporting that the newly added transmitter would not be compatible with existing receivers with its intended parameters



(c) List of compatibility tests between WD3's devices (Tx3 and Rx3) and existing Tx/Rx devices

Figure 8: Screenshots of specific message types supported by the system

6 FUTURE EXPERIMENTATION

The experiment described in Section 5.2 has three networks, all using a relatively simple algorithm to coordinate their spectrum usage. Our future work will focus on developing and implementing advanced algorithms that are able to dynamically optimize the configuration of the networks. In particular, we will develop traditional and ML-based algorithms with different computational complexities and different performance metrics in terms of spectrum utilization, power consumption, data throughput, reconfiguration delay, and transient congestion due to reconfigurations. Notice that, in practice, network reconfiguration is not instantaneous and may lead to transient congestion. Depending on the duration and magnitude of the congestion, data packets may be severely delayed or even lost, which may degrade the performance of delay-sensitive ultra low-latency applications. We plan to take into account both the transient and steady-state effects of algorithms that reconfigure the network. Two examples of algorithms are: (i) a centralized global reconfiguration algorithm in which a central server/node receives information from every associated network and solves an optimization problem to compute a near-optimal resource allocation; and (ii) a distributed local reconfiguration algorithm in which a local disturbance triggers neighboring networks to start negotiating, aiming to agree on a new improved resource allocation. In the case of decentralized algorithms, it is important to evaluate the time that the algorithm takes to converge. In general, to evaluate and compare these and other algorithms with the state-of-the-art in the literature we will leverage the framework described in this paper.

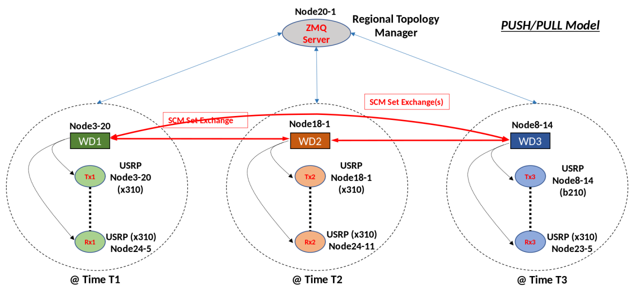


Figure 9: Experiment scheme – Timeline of networks joining the coordinated spectrum use environment

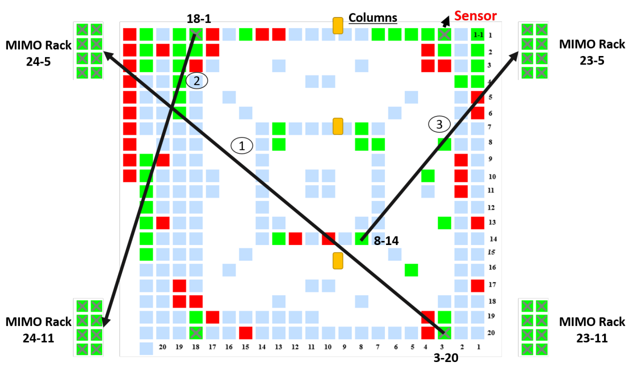


Figure 10: Distribution of transmitters and receivers from the COSMOS Sandbox (ORBIT Grid [9])

7 CONCLUSION

We designed and implemented a framework on the COSMOS testbed that enables experimentation and research of dynamic spectrum access mechanisms and coordination of the use of spectrum resources across different wireless networks. The framework utilizes a modified version of the interaction language CIL developed by DARPA for the Spectrum Collaboration Challenge to enable the exchange of SCM messages between wireless networks. SCMs provide peer networks with detailed information about the spectrum use characteristics of RF devices and procedures to quickly and efficiently perform compatibility calculations to determine usable spectrum resources and avoid interference with other networks. Finally, to showcase the capabilities of the developed framework, we described an experiment with 3 networks, joining the wireless communication environment at different times and exchanging SCM messages to autonomously determine optimal frequencies for their communication links. The work we have conducted is the first step towards the exploration of more elaborate algorithms and their extensive experimentation that will leverage the same framework.

ACKNOWLEDGMENTS

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