Experimental Field Test Results on Feasibility of Declarative Spectrum Management

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***Abstract*— We describe the design and report on experience fielding an end-to-end framework for declarative spectrum management of frequency agile wireless communication devices. As part of the Defense Advanced Research Projects Agency NeXt Generation communication program, we developed a distributed, policy-driven system that restricts spectrum access based on spectral, temporal and geospatial context. We report on our field framework experimentation, illustrating the capability offered to wireless systems, their command & control management, and individual radios for enforcing spectrum access policies while enabling the radios to fully utilize available spectrum in comparison to traditional, static-assignment spectrum access methods.**

***Index Terms*— Spectrum Access Management Techniques; Experimental Prototypes and Results; Defining and Enforcing Rights and Responsibilities of Spectrum Licensees**

I. Introduction

Cognitive frequency-agile devices offer the vision of virtually unlimited data and voice throughput, thus promising to satisfy communication requirements for any application, anytime, anywhere. The technology bases the premise on the ability of frequency-agile devices to communicate on any available frequency channel and on the devices' cognitive ability to pick the right frequency channel from a finite pool of spectra that is currently deemed as available based on the devices' temporal, geospatial and spectral context.

Given the magnitude of opportunities cognitive frequency-agile devices would create – ranging from improved spectrum utilization to spectrum sharing to spectrum pooling – there has been a vast interest in both researching and developing mechanisms for enabling such devices. This interest focuses primarily on improving the frequency agility, the cognition and on improving the underlying hardware and software communication stack; however, the issue on selecting not just *any* available transmission channel but rather choosing a transmission configuration that *complies* with requirements of all potentially affected parties has received a lesser attention.

Whereas this may not be an issue for existing spectrum owners that wish to introduce additional radio devices that will operate within their spectrum assignments only; this is a fundamental challenge for introducing radio devices that may cross either in time, space or spectrum across boundaries of multiple spectrum owners.

To better understand the challenges and study the impact cognitive frequency-agile devices present to military and commercial applications, the U.S. Department of Defense Advanced Research Projects Agency (DARPA) executed the NeXt Generation (XG) Communication Program [1] and selected Shared Spectrum Company as the prime contractor.

As part of the XG program, we developed a real-time declarative spectrum management system for controlling and enforcing spectrum access rights [2, 3]. The system consists of authoring and management tools for expressing spectrum access requirements of each stakeholder in terms of policies. The policies are written using a declarative policy language. The system also defines enforcement architecture for run-time merging, de-conflicting and execution of multiple multi-source policies and for evaluating context of a device against its assigned policies for applying and enforcing transmission etiquettes.

In our preliminary work, we have shown that it is plausible to use declarative policies for enforcing access rights [2]. Additionally, we have preliminary tested that an implementing the declarative approach is also plausible [3]; however, it was never previously shown that the approach is, in fact, feasible in an operational environment.

In March 2008, as part of the XG demonstrations, we have presented, for the first time, a four-node network of XG-enabled cognitive frequency-agile radios with embedded policy-driven spectrum access control mechanisms. In this field demonstration, the radios continuously maintained a communication data network as they traveled through a military training test range, avoided interference to and from other signals, and responded to changing spectrum access requirements expressed as policies, which were remotely changed during scripted and also unscripted scenarios.

This article reports on the experimental field test results from the March demonstrations and our contributions to the overall XG program on the declarative spectrum management architecture. These contributions extend our prior work in the early phases of the XG program and, in part, are based on the collaboration efforts with our subcontractors [4] and work

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performed by other organizations involved in previous phases of the XG program [5].

The live demonstration illustrated several fundamental positive results for the declarative spectrum management:

– It is feasible to embedded policy-driven control into operational cognitive frequency-agile devices.
– Using a declarative language, it is feasible to specify radio-independent requirements for spectrum access control.
– It is feasible to employ a policy enforcement framework that is
    - Hardware-independent,
    - Operating-system-independent,
    - Software-independent, and
    - Stakeholder-independent.

The platform independence makes the declarative spectrum management resilient and relatively free of the development difficulties that can afflict systems that depend on proprietary equipment. If any hardware, operating system, or software is discontinued or ceases to be adequately supported, the system can migrate to newer or better-supported platforms without changing any policy. In this way, supply chain resilience is designed into the declarative spectrum management system from its inception.

In the present article, we describe the overall declarative system management and its relationship to the XG-enabled cognitive frequency-agile device. We then introduce test scenarios, test metrics and results. In the last two sections, we highlight relevant related work and draw conclusions.

II. Declarative Spectrum Management System

Frequency-agile radios radically challenge existing spectrum management principles, which are based on static frequency assignments. In current approach, spectrum management is performed using a preemptive interference-avoidance preplanning approach based on location, frequency, and time:

First, spectrum is divided vertically along geopolitical boundaries. Whereas this is a logical consequence of world's organization, it does not always follow the laws of physics.

Next, spectrum is divided horizontally into other seemingly random sections where each section is assigned fixed energy emission requirements for avoiding interference to devices operating in other spectrum sections or within the same section.

Finally, spectrum is also divided in time by assigning a specific spectrum section to a fixed amount of users.

While spectrum remained an underutilized resource, this approach was a great allocation method as it was based on models in other proven domains.

Consequently, now spectrum is, however, fully allocated across all three domains. Yet spectrum usage measurements show that spectrum remains underutilized [6].

Instead of relying on a static preplanning method, the spectrum ought to be assigned and revoked, dynamically in order to improve the usage of underutilized spectrum. Automation of spectrum management is essential to near-optimal spectrum usage similarly as it was essential to other application domains.

To better understand the challenges and further to study the impact frequency-agile devices, DARPA executed the XG Program, which resulted in the creation of frequency-agile radio devices capable of communicating in frequency ranges from 30MHz to 4GHz [7, 8].

These XG-enabled frequency-agile radios as well as other frequency-agile radios render the static frequency-assignment approach obsolete. This is because frequency-agile radios are, by design, capable of operating across many spectrum boundaries.

Therefore, an alternative method for spectrum management is needed to control spectrum either within a single frequency assignment, i.e. local spectrum management by the rightful spectrum owner, or across spectra within one geopolitical region, or even across spectra around the entire world.

Disregarding the amount of time, location or frequency the alternative approach should consider; the approach must be automated in order to utilize the most of the permitted scope.

Generally, there are two automated alternatives to static spectrum planning:

I. Spectrum plan is dynamically computed externally to a radio device and then the plan is transferred onto the device.

II. Spectrum plan is dynamically computed internally by the radio device itself.

The advantage of the former approach is that plans for multiple devices can be computed at the same time. As the plans are done for multiple devices, a better care can be done for sharing and balancing the spectrum usage. The disadvantage of this approach is that radio devices must report on the state of their environment back to the spectrum planning framework.

The advantage of the approach II is that a device makes a local decision. This approach results in faster response to changing environments, decreased management traffic overhead as well as removes infrastructure dependency. The disadvantage of this approach, however, is that spectrum access control requirements must be propagated to all devices and each device must perform its own spectrum planning.

Essentially, the difference is that in the approach I planning logic is external and execution logic internal while in the approach II both planning and execution is internal.

For the XG program, we chose to employ the approach II. For one, we chose an internal planning logic because XG-enabled devices should maintain operations even while disconnected from an infrastructure. Next, XG-enabled devices should provided maximum of their throughput to application data not management data. Moreover, the focus of the XG program was to avoid interference and thus the response speed is essential.

A. *Declarative Spectrum Access Control within XG*

The XG architecture is based on internal spectrum planning and execution logic. In order to allow XG-enabled frequency-

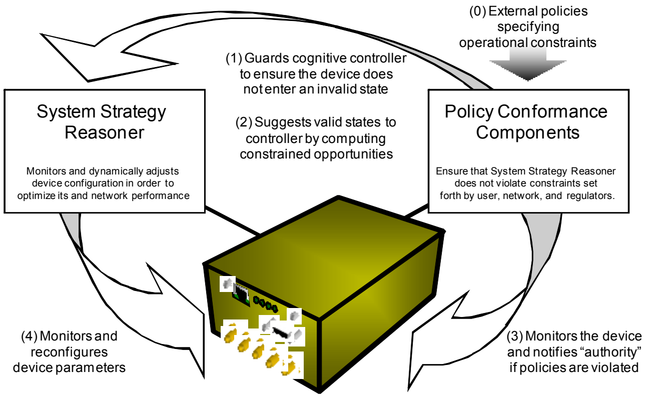

Fig. 1. XG-enabled cognitive frequency-agile device includes a cognitive System Strategy Reasoner for monitoring and adjusting the device for balancing its performance and Policy Conformance Components for providing operational spectrum access assurance to stakeholders.

agile devices to rapidly make correct decisions, we have designed declarative spectrum management architecture.

The architecture relies on declarative spectrum access control policies so that policies only specify conditions an XG-enabled device must meet before it can transmit. The policies may consider the radio's capability, current state, location, time, and spectral environment for allowing or denying a transmission. The policies do not specify actions an XG-enabled device must execute to meet the conditions. The policies are thus radio implementation independent. Moreover, the architecture supports merging policies from multiple stakeholders, which may be regulating, owning or using the same spectrum at that time and place.

It is insufficient to send configuration commands to the XG-enabled devices stating what transmission frequency, bandwidth, power, modulation, etc. the device is to use when transmitting data as the planning would have to be performed externally, thus resulting in the disadvantages listed above.

Instead the XG-enabled devices must be given the requirements imposed by each stakeholder in such a fashion so that the XG-enabled devices can merge together these requirements and compute the right plan based on their immediate current context.

One such approach is expressing spectrum access requirements as rules or policies using a declarative language. The advantage is interoperability and application independence. First, requirements expressed in the declarative approach can be used by any radio device as it is not written for any specific device in mind. Therefore, once a stakeholder writes a rule, the stakeholder is assured that all radios will be capable of processing it. Next, since the requirements are not written with a specific device in mind, the requirements apply to all radio devices equally. Therefore, a stakeholder is assured that its requirement applies to all and an owner is assured that its radio device will always be able to transmit if requirements are met.

To support this approach, we have designed the XG architecture as shown in Fig 1. We divide the XG-enabled frequency-agile device into three areas:

I. The communication stack and the underlying radio hardware.
II. The cognitive System Strategy Reasoner (SSR), and
III. The Policy Conformance Components (PCCs).

The SSR represents a cognitive module that controls the hardware, gathers data, forms strategies, and acts as an interface for transmitting and receiving data. The SSR is responsible for interacting with the PCCs for determining spectrum access opportunities that are currently available, e.g. frequencies, bandwidth, power level, or modulation techniques the SDR can use to transmit given its current environment. The SSR then executes applicable strategies needed for the radio's transmissions to conform to the policies. The SSR is also responsible for providing the PCCs with an access to its current state, evidential results obtained from other radio components, including detector's measurements, and data received from other radios.

The PCCs are responsible for planning and executing spectrum access plans. The PCCs assure the device operates correctly and does not cause harmful interference. When SSR attempts to modify the radio's state, the PCCs validate that the resulting state complies with current policies. Otherwise the PCCs intercept and deny illegal transmission requests.

Whereas any radio can implement custom SSRs, it is expected that the PCCs represent standardized, accredited components for conforming to the stakeholder requirements as they represent the core *trusted* components on the device.

The PCCs consist of the Policy Manager, Database, and Policy Conformance Reasoner and Policy Enforcer. Depending on the resources available to a SDR, the PCCs can be embedded on the SDR. Alternatively, the Policy Manager, Database, and Policy Conformance Reasoner can be moved to a remote proxy and accessed remotely by the Policy Enforcer on the SDR.

B. Interoperable Policy Conformance Components

The PCCs are essential to the declarative spectrum access control as much as the declarative policy language. In our approach, we chose to rely on the device to create and enforce its spectrum access plan. The Policy Conformance Reasoner is responsible for creating and maintaining such a plan, while the Policy Enforcer is enforcing the plan.

Without going into details of these components previously described [2, 3], the emphasis is that they must correctly merge requirements from multiple stakeholders. This is so that the spectrum access plan does not violate requirements from a single stakeholder. Moreover, the PCCs must create and enforce such a plan quickly with minimum processing requirements to maintain high data throughput while preserving battery life.

To study the correctness and performance of various approaches, we designed an extensible approach for embedding different PCCs. As shown in Fig. 2, the PCCs interact with SSR via Policy API, which defines protocols for sending and enforcing spectrum plan. Additionally, as shown in the figure, the Policy Reasoner itself is implemented using numerous approaches, which can be embedded within XG

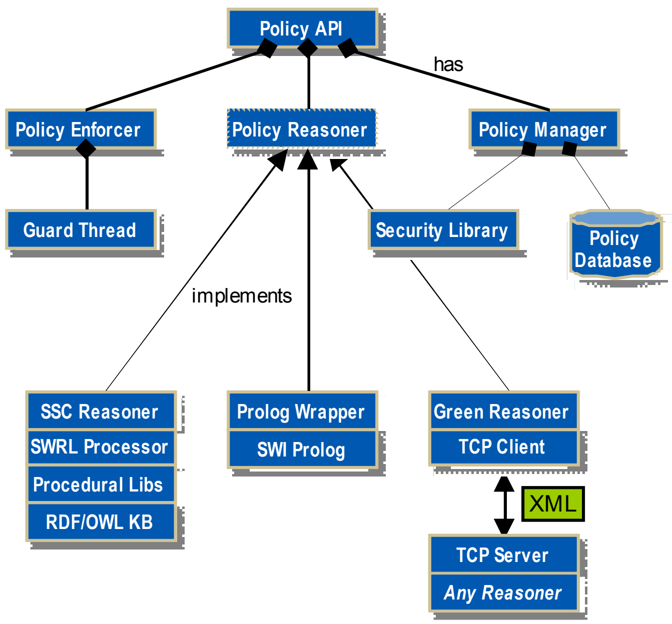

Fig. 2. XG Policy Conformance Components interact with the XG System Strategy Reasoner via Policy API, which allows for the development of additional PCCs either integrated within the XG software or as an external application communicating through an XML-based protocol.

software or which can execute externally and communicate via a *green* XML-based messaging API for computing spectrum access opportunities and for making decisions.

In the March 2008 demonstration, we studied the performance differences of our embedded reasoner vs. our reasoner communicating via the green API and a reasoner also developed as part of the XG Program by SRI International [4], also communicating through the green API.

C. *Provisioning System*

Our approach still requires some external management framework for managing and distributing the spectrum access requirements from all stakeholders.

As illustrated in Fig. 3, we have developed several tools and communication protocols for authoring, managing, and disseminating policies onto XG-enabled devices. These components are applicable to managing any devices that are capable of processing XG policies, i.e. capable of processing information encoded in XG declarative language.

III. Demonstration Setup

The March 2008 demonstrations as part of the XG program were designed to illustrate the capability and feasibility of the declarative spectrum management to control cognitive frequency-agile devices. Therefore, as part of the demonstrations, we focused on several objectives:

I. Declarative spectrum access control works – radios make correct and timely spectrum access decisions.
II. Declarative spectrum access control does no harm – radios do not cause harmful interference.
III. Declarative spectrum access adds value – the approach is scalable and agnostic to hardware, software, operating systems, etc.

A. *Equipment*

We employed a total of six SSC DSA 2100 radio devices, which are frequency-agile radio devices built partially as part of the XG program; we, however, varied the hardware in terms of generic purpose processor used to run the XG appliqué, the operating systems, and the PCCs software:

– One pair of devices was configured with AMD processor, running Microsoft Windows XP operating system and running SSC PCCs software load with SSC reasoner embedded within the SSC PCCs load.
– Another pair of devices was configured with PowerPC processor, running Linux as an operating system, and operating with the same embedded SSC PCCs software.

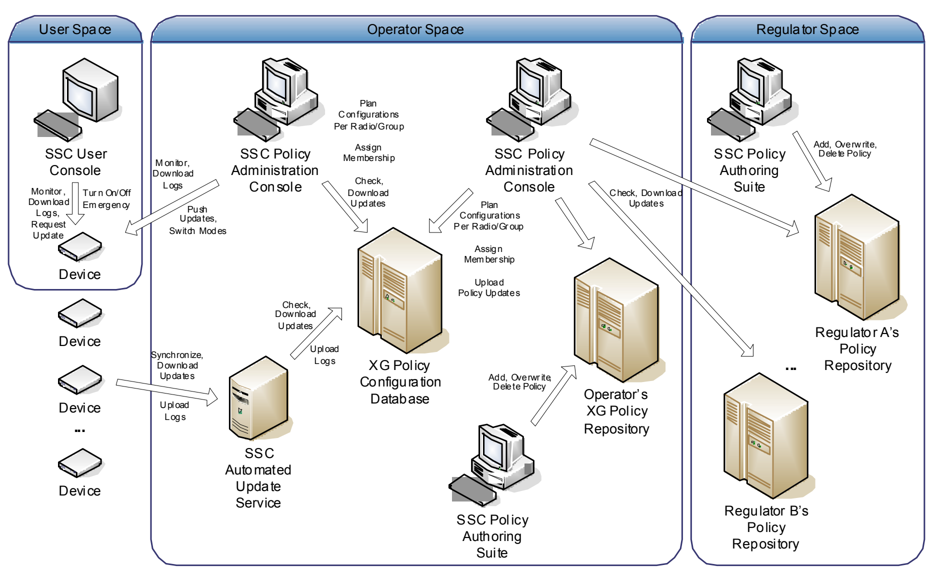

Fig. 3. For enabling each and all spectrum stakeholders to define and manage their spectrum access requirements, the system includes authoring and controlling tools used to manually and automatically assign spectrum access rights in terms of policies to XG-enabled cognitive frequency-agile radios.

Fig. 4. Map of the demonstration and the VIP presentation location.

– The last pair of devices was configured with PowerPC, Linux but used PCCs software with green messaging API in order to support external SSC reasoner on one radio and an external SRI International's reasoner on the other radio.

All radios were equipped with the SSC DSA EXP expansion box, which included a fast-scan, large-bandwidth signal detector developed by Rockwell Collins, a generic purpose GPS locating system, and a networking backhaul for communicating with the radios through an alternate network in order to visualize their current state in the demonstration room without interfering with the XG tests.

B. Configuration and Frequency Assignments

The radios were configured to operate with signal bandwidth 1.75 MHz, power of up to 20dBm, and using the native IEEE 802.16-based waveform and modulation. Additionally, the radios were assigned to operate at center frequencies of 231, 233, 242, 247, 273, and 281 MHz. While this was only a limited range of the radio's capability, this was sufficient for demonstrating the declarative spectrum management feasibility.

C. Experimentation Location

The location for our demonstration was chosen to be a rural area in Virginia, USA. As shown in Fig. 4, the demonstration area consisted of roads along heavily wooden area with a limited amount of living corridors. The experimentation location resulted in varied signal propagation coverage ranges. Moreover, the experimentation area included various other radio devices that were spread throughout the area and that operated at known (as expressed in policies) as well as unknown frequencies that the XG-enabled devices must avoid in order not to cause interference to them.

Fig. 5. An image from the XG VIP demonstration venue with the declarative spectrum management projection screens.

D. Demonstration Display System

Although the demonstration was performed in the field, the demonstration included a VIP presentation area for allowing hosts to oversee the experimentation and study the performance of the declarative spectrum management and the overall XG system. Fig. 5 shows an image from the VIP demonstration venue.

The focus of the demonstration venue was the display system, which provided real-time status of the location of each radio device and its current spectrum plan.

Fig. 6 shows a snapshot of the system. The tool consisted of a map pinpointing current location of each XG radio as yellow dots. When a pair of XG radio devices established a connection, a yellow line was drawn between the two radios. Additionally, the tool consisted of frequency map of each XG radio along the frequencies assigned to them for operation. Channels forbidden by the PCCs were drawn in brick red while channels made available by the PCCs were rendered in teal color. The channel currently in use by the corresponding XG radio was then drawn in bright green.

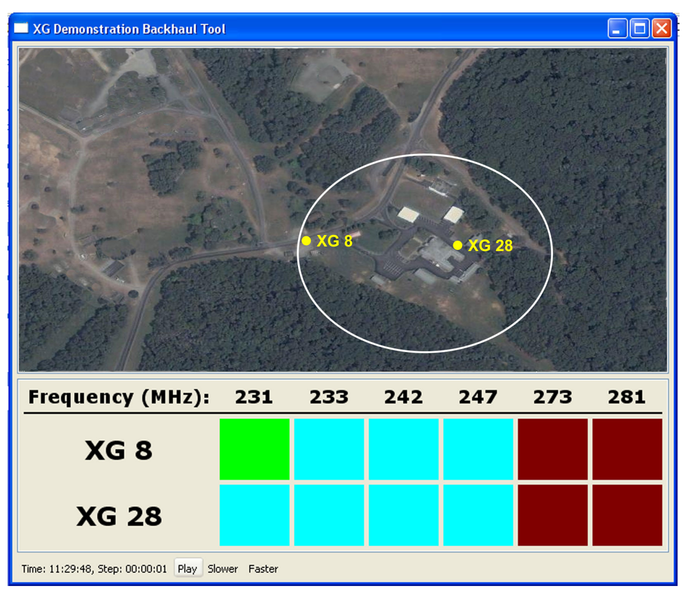

Fig. 6. A screen snapshot of the demonstration backhaul tool showing the current position and spectral map of a pair of XG-enabled devices. Permitted, unused channels are shown in teal; active channels in bright green; and prohibited channels in brick red. The perimeter used for the location-based policy demonstration is seen here in white.

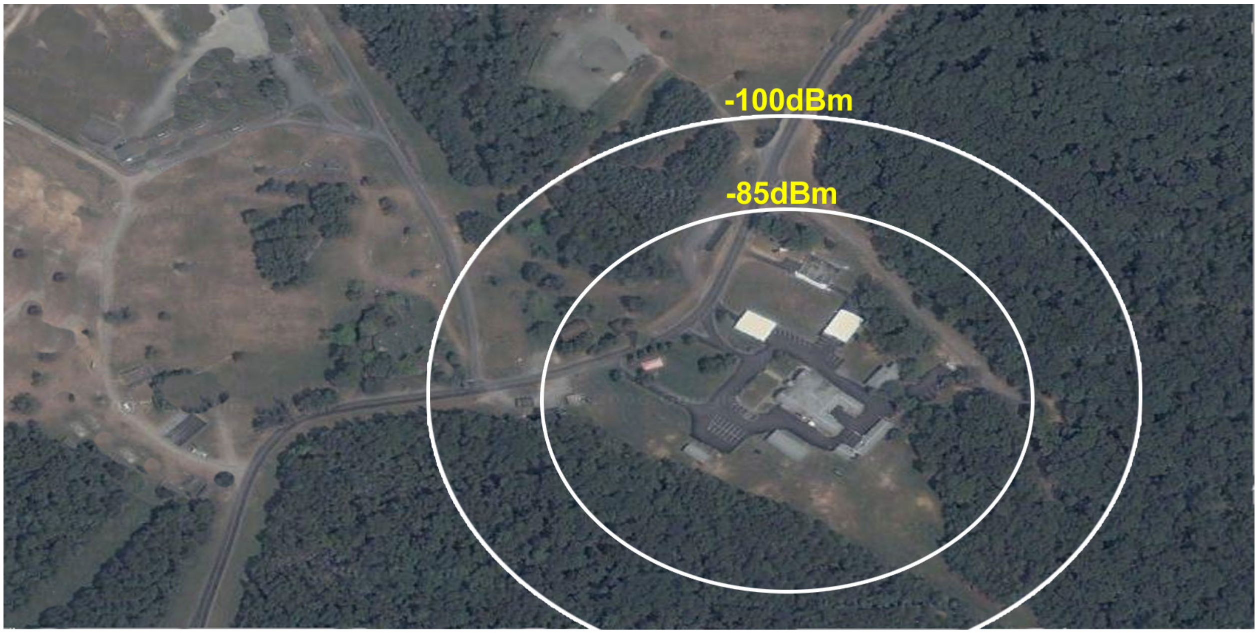

Fig. 7. In Scenario 3, policy dictates different detection thresholds for different channels, with implications for detection range as shown here. In the actual demonstration, thresholds were adjusted in advance to make the best use of the test range available (so -85 and -100 dBm are just given as examples).

While a channel may have been permitted by a policy, and thus rendered in teal, the XG radio was still required to employ listen-before-talk (LBT) method for vacating channels with foreign energy above a certain threshold, which was varied based on policies.

IV. Test Scenarios

Four scenarios were chosen to study the runtime declarative spectrum management system.

A. Scenario 1: No Policy

This scenario was enacted to demonstrate that uninitialized cognitive frequency-agile radios, which are equipped with PCCs but have no policies loaded, will cause no harm to other radios that may be present. That is, the radios in this scenario will not spontaneously chatter or seek to rendezvous with other radios of their type as the default action under is to deny any transmission since there are no known requirements.

B. Scenario 2: Baseline (Limited) Policy Operation

In the second scenario, a simple policy permitting transmission on any of the first three channels at center frequency 231, 233 and 242 MHz is loaded onto two pairs of radios, with the restriction that if a non-cooperative radio comes on the air, the XG network on its frequency must vacate it and take up station on another frequency. For the demonstration, a single interfering signal is broadcast from a signal generator with power equal to 20 dBm. When the signal is detected, there remains only one frequency where each pair can move.

This scenario was enacted to show the system works in two ways:

I. Two pairs of XG radios successfully avoided each other's frequencies and formed separate networks.
II. An explicit listen-before-talk policy was put in place, enabling the XG radio to vacate a non-cooperative radio's channel and re-rendezvous elsewhere. The system therefore avoided interfering with or causing interference to the non-cooperative radio.

C. Scenario 3: Enhanced Signal-based Policy

The next scenario was designed to illustrate enhanced signal-based spectrum access control beyond listen-before-talk mechanisms for non-interference to paired uplink-downlink channels as used in some communication systems.

Here there were two policies running conjointly:

I. "Permit transmission on Channel 1 (231 MHz)";
II. "Permit transmission on Channel 2 or 3 if the detected signal on Channel 2 is below -100 dBm and detected signal on Channel 3 is also below -100 dBm."

Policy II is more restrictive to the radios than the explicit LBT rule inside SSR, enabling a weaker or more distant signal to trigger abandonment of the channel as shown in Fig 7.

Each radio can use Channel 1 as long as the explicit LBT rule permits it to, but if it is on channel 2 or 3, it must abandon the channel and return to Channel 1 when a signal is detected there on either channel 2 or 3.

This type of policy enables a DSA radio to avoid occupying either of two paired uplink-downlink channels. In this way, the framework can intelligently avoid causing interference to communication systems that need such paired channels and where activity on one predicts activity on the other. One case of the "hidden node problem" — interference to receivers that offer no emissions to detect — can be mitigated in this way.

Here also, the XG-enabled radio can be seen putting multiple policies in play together, conjointly, and merging their requirements to run in a real situation.

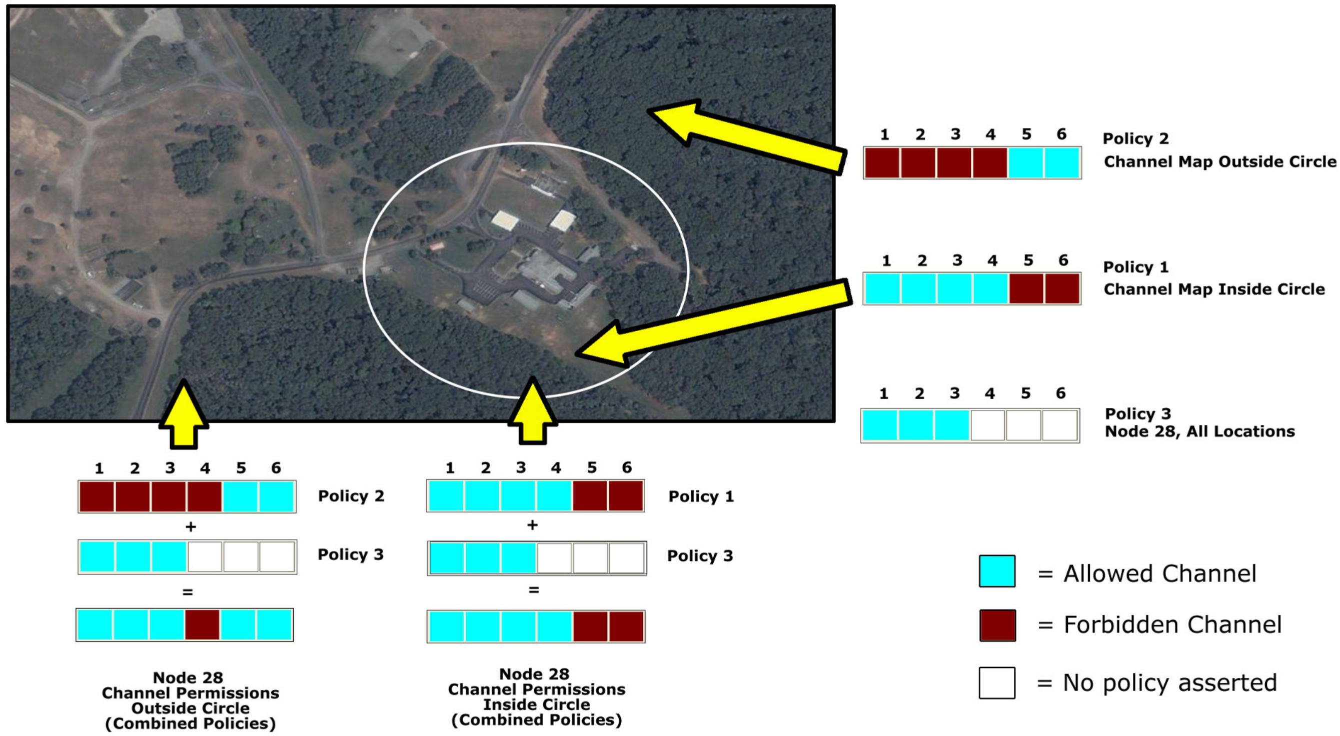

Fig. 8. In Scenario 4, policies dictate usage of different channels based on radio's current location. Within the circle, radios are permitted to use only channels 1 through 4 whereas outside of the circle radios are permitted to consider channels 5 and 6. Additionally, for this scenario we have re-introduced a third policy, which enables a radio to use channels 1 through 3 anywhere, anytime provided the radio does not interfere with other signals possibly present on those channels.

D. Scenario 4: Enhanced Location-based Policy

In the fourth scenario, for illustrating that spectrum access requirements are not based on spectrum environment only but in fact are often based on the time and location domain, here two policies run conjointly this time:

I. "Permit transmission on Channels 1 through 4 when inside a circle";

II. "Permit transmission on Channels 5 and 6 when outside of a circle."

Under these policies, each radio computes its relationship to a geographical circle identified by a point centered at a fixed latitude and longitude of the VIP demonstration building and a fixed radius of 250m from the building. Based on the relationship, then, each radio can use any of a given set of channels as long as the explicit LBT rule permits.

Therefore, this scenario illustrates that using policies, one can restrict spectrum access based on the radio's mobility, enabling different rules to be applied in different areas.

Moreover, in this scenario we optionally introduce a third policy of higher importance than the other two policies, which is loaded just on one radio:

III. "Permit transmissions on Channels 1, 2 and 3".

Using the combination of these three policies, one can study the impact of merging multiple requirements and multiple configurations where a radio may have different information than its pears and where a radio may receive conflicting requirements from multiple stakeholders.

Fig. 8 illustrates the effects of the three policies for a single radio as collected during the demonstrations. Although, by design the default XG de-confliction rule is to prohibit a spectrum transmission when one policy allows transmission and another policy simultaneously denies transmission, we define a prioritization scheme to allow stakeholders to assign higher priorities to their requirements and therefore allow PCCs to override the default policy ordering scheme.

In this figure, when policies 1 and 2 are loaded only, the results are clear. With the policy 3 loaded, the resulting plan is that a radio with all three policies present can use all but channel 4 outside of the circle while inside the circle it can still use just channels from 1 to 4.

V. Test Metrics and Results

The demonstration was intended to fulfill several goals, namely, to:

I. Establish that declarative spectrum access control works and is operationally feasible by demonstrating that DARPA XG radios are policy-enabled and make correct and timely spectrum access decisions.

II. Show that XG declarative policies specify cognitive-frequency-agile-radio-independent requirements for spectrum access control. Spectrum access can thus be predicated on characteristics of the radio (whether an original XG radio or not), of the network, of spectrum restrictions, on time of day, and on location. The emphasis in this demonstration is on radio-extrinsic parameters of spectrum activity, location, etc.

III. Show that XG declarative spectrum access control is scalable and implementation agnostic in hardware, software, operating system, and stakeholders.

A. Declarative Spectrum Access Control Works

During the March 2008 demonstrations, we employed the six SSC DSA 2100 radio devices for all four scenarios. As demonstrated to the VIP visitors, the radio devices made correct decisions while employing either reasoner from SSC or from SRI International and while using their embedded versions of standalone application versions communicating over the green messaging API.

In each scenario, the XG-enabled devices exhibited the correct, expected behavior. The PCCs on each radio correctly marked each channel as permitted or prohibited, and colored the channels in teal or brick red, correspondingly.

Primarily due to the green messaging API overhead, the various radio configurations, however, exhibited extensive processing delays:

- XG radio devices with an AMD processor, Windows XP operating system and an embedded SSC reasoner were clearing the six channels within 348ms on average, i.e. 58ms on average to clear one channel based on about 11500 decisions.
- XG radio devices with a PowerPC processor, Linux and again embedded SSC reasoner were clearing the six channels within 2618ms on average, i.e. 436ms to clear one channel.
- XG radio devices with a PowerPC processor, Linux and SSC reasoner operating via green messaging API took on average 4903ms to clear the six channels, i.e. 817ms to clear a single channel.
- XG radio devices with a PowerPC processor, Linux and SRI International's reasoner operating via green API took on average 76105ms to clear six channels, i.e. 12684ms to clear one channel.

The large time difference was due to using extra steps in the green messaging approach to encode the system state on the SSR side and decode the state on the PCCs site. Additionally, the large overhead in the last configuration was due to minimal memory and processor optimization of the PCCs reasoner code, which resulted in large memory overhead and processing delay due to frequent memory cache operations.

The demonstrations have illustrated, however, that regardless of the processing speed; the spectrum access requirements are agnostic to XG radio configuration and can be processed by heterogeneous PCCs.

Moreover, the demonstrations illustrated the processing is correct and stakeholder's requirements are enforced at all times.

The demonstrations also showed the declarative spectrum management is operationally feasible as the radios were making correct runtime decisions on restricting spectrum access based on stakeholder's requirements. Especially the embedded reasoning systems were able to make immediate decisions as the window to clear channels was experimentally set to 5 second boundaries.

Additionally, the demonstrations showed that using the policy provisioning system is feasible as users were able to draft and add random policies onto the device at run time using the administration tool shown in Fig. 9.

B. Declarative Spectrum Access Control Does No Harm

During the demonstrations, at no time did any of the six XG radio devices make an incorrect conclusion. Depending on the current policy load set, the radio's location, time of the day spectrum measurement history, the PCCs drew the correct conclusions on channels to be permitted and channels to be prohibited from using for transmission.

Therefore, in combination with the default LBT mechanism embedded inside the SSR, the framework showed that the declarative spectrum access control avoids significant harm to other radio signals present in the specific time, location and frequency ranges. That is the demonstration showed that spectrum stakeholder's requirements can be met effectively.

At the same time, based on the processing response time, some configurations would be unable to meet rapid spectrum evacuation as some decisions took significantly longer time than the XG-imposed limit on 500ms channel evacuation time from detection. This was, however, in all four configurations remedied by the embedded LBT mechanism inside SSR.

C. Declarative Spectrum Access Control Adds Value

The last objective was to demonstrate that the declarative spectrum access control also adds value by being scalable, implementation agnostic and by supporting requirements from any stakeholder.

The demonstrations showed the approach is implementation agnostic. Although, the demonstrations used SSC radio devices only, the devices used different general purpose processor with underlying hardware support. Additionally, the devices ran different operating systems – Microsoft Windows

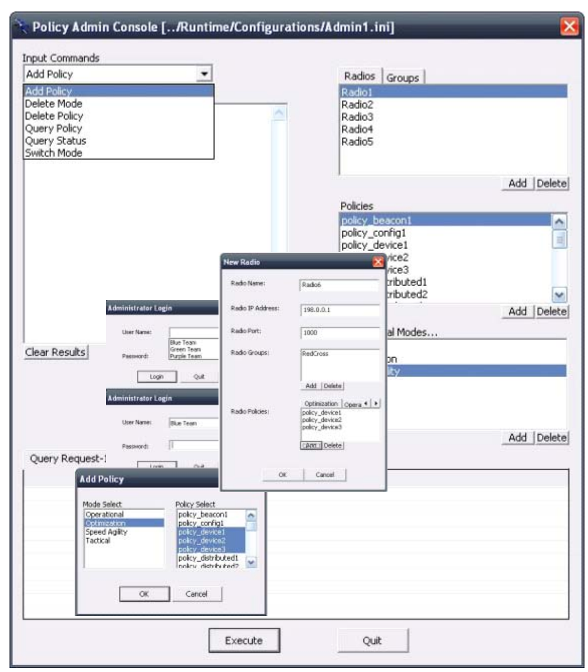

Fig. 9. A snapshot of the administration tool used to disseminate policies onto XG-enabled radios.

XP and Linux. Last, the demonstrations used two different policy reasoning systems from two different companies. Hence, the demonstrations showed that the approach is agnostic to implementation.

Additionally, the demonstrations illustrated that the approach supports multiple stakeholders with varying requirements, which can be expressed using the declarative language and which then can be merged, de-conflicted and enforced on the radios in real time. Therefore, stakeholders define restrictions on radio operation and radios automatically adjust their operation to meet requirements from *all* stakeholders.

Additionally, the demonstrations have shown – for the first time – that the framework is not only feasible in terms of simulations but also feasible operationally and can be used as a baseline for future spectrum access control models.

VI. Related Work

Cognitive software-defined radio technology and policy based control have recently received vast interest across many communities. This can be evidenced by the interest in the IEEE P1900 Standards Coordinating Committee for DSA networks [9] and in the IEEE Dynamic Spectrum Access Networks conferences [10]. While the XG program is one of the initial research efforts on developing cognitive radio devices, additional ongoing programs and efforts now exist for managing shared spectrum access [11] based on time, spectrum or location [12].

The Center for Wireless Telecommunications at Virginia Tech developed a cognitive software engine for dynamically adjusting configuration of a legacy Proxim Tsunami 5-GHz radio in response to changing interference and propagation environment [13]. The cognitive engine collects information about the radio's environment and uses the data for identifying a radio behavior that worked well in such environments in the past and instructs the radio to configure itself to adapt to such a behavior. The approach is similar to the XG architecture; however, we also define and implement the necessary policy-based control mechanism for enforcing regulatory compliance.

Additionally, the Centre for Telecommunications Value-Chain Research at Trinity College Dublin is exploring issues related to policy-based management mechanisms [14-17]. The group explores alternative organizational structures for defining and enforcing policies in order to allow frequency-agile radios to self-organize based on multiple groupings with differing goals and spectrum access policies. The approach is similar to the XG architecture in that it allows multiple stakeholders to define conflicting policies; however, the proposed architecture de-conflicts the policies based on the dynamic roles of organizations prior to deploying the pre-computed policy model onto the radios.

VII. Conclusions

We reported on experience of fielding the first end-to-end framework for declarative spectrum management of frequency agile wireless communication devices. As part of the DARPA XG communication program, we developed a distributed, policy-driven system that restricts spectrum access based on spectral, temporal and geospatial context. We reported on our field demonstration, illustrating the capability offered to wireless systems, their command & control management, and individual radios for enforcing spectrum access policies while enabling the radios to fully utilize available spectrum in comparison to traditional, static-assignment spectrum access methods.

The live demonstration illustrated several fundamental positive results for the declarative spectrum management: (i) it is feasible to embedded policy-driven control into operational cognitive frequency-agile devices; (ii) it is feasible to specify radio-independent requirements for spectrum access control; and (iii) it is feasible to employ a policy enforcement framework that is radio implementation agnostic.

Additionally, the demonstrations showed that the system is operationally feasible and can, thus, be used as a baseline for future spectrum access control research.

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