Demonstration of a Policy Engine for Spectrum Sharing

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***Abstract*— We argue for a policy-based approach to increase spectrum availability. We have designed a language to capture rules and regulations for opportunistic spectrum use. A Policy Reasoner that reasons about these spectrum-sharing policies can be used with cognitive radios to guarantee policy-specified behaviors. We demonstrate the reasoner on various policies, including those established for the dedicated spectrum from the Commisssion for Communication Regulations that has been acquired for DySPAN 2007. We show the effects of enforcing these policies and how a radio adapts to the conditions of dynamically changing environments. We will link our reasoner to a live sensor from Rockwell Collins that measures the state of the spectrum at the conference site and delivers input data for the reasoner. We will also illustrate the ease of changing policies and uploading new policies.**

I. Introduction

Currently, radio communication is impacted by the lack of access to unused spectrum. Existing spectrum-management procedures are inflexible and cannot react to dynamically changing operational needs. As a result, regulatory policies are static and spectrum is no longer sufficiently available, because it has been assigned to primary users who own the privileges to their assigned spectrum.

However, studies have shown that most of the spectrum is, in practice, unused most of the time. This observation was the staring point for DARPA's NeXt Generation (XG) Communications program, which proposes opportunistic spectrum use to increase spectrum availability. To achieve opportunistic spectrum use, radios must have the following capabilities.

- Sensing over a wide frequency band and identifying primaries
- Characterizing available opportunities
- Communicating among devices to coordinate the use of identified opportunities
- Expressing and applying interference-limiting policies (among others)
- Enforcing behaviors consistent with applicable policies while using identified opportunities

Because of the large number of operating dimensions to be considered (frequencies, waveforms, power levels, and so forth) and the ever-changing nature of regulatory environments and application requirements, it is not feasible to design and implement optimal algorithms that allow radios to flexibly make use of available spectrum over time. Instead, a flexible mechanism has to be provided that supports spectrum sharing while ensuring that radios will adhere to regulatory policies. The solution must be able to adapt to changes in policies, applications, and radio technology. The XG Program has embraced a solution based on policies. The significance of a policy-based approach is detailed in Section III.

We have implemented a device-independent Policy Reasoner (PR) that provides a software solution to opportunistic spectrum access. Our approach allows encoding of spectrum-sharing policies, ensures radio behavior that is compliant with policies, and allows policies to be dynamically changed. The PR either approves or disallows every transmission candidate proposed by a radio, based on compliance with currently active policies. Flexibility and spectrum sharing are achieved by expressing policies in a declarative language based on formal logic, and allowing devices to load and change policies at runtime.

Section II discusses the primary goals of the PR demonstration. We give an overview of the reasoner architecture and describe policies that we will demonstrate. We also present screenshots of the reasoner demonstration. In Section III, we address the technical significance of the demonstration and why the reasoner is an important milestone on the way to fully capable cognitive radios. The maturity of the reasoner is addressed in Section IV. Logistical needs for the demonstration at DySPAN are discussed in Section V.

II. Description and Technical Approach

The primary goal of this demonstration is to show the feasibility of a policy-based approach to opportunistic spectrum use. In current radios, policies are programmed or hardwired into the radio and form an inseparable part of the radio's firmware, which has obvious drawbacks given the profusion of radio designs [1]. In particular, new spectrum-sharing policies may initially change frequently as best practice is discovered or additional opportunities exploited.

The key difference in our approach is that declarative policies are expressed in terms of "what" should be protected or made available rather then "how" spectrum is protected or made available. Such policies are higher level than typical radio code and free from implementation details. A PR loads applicable policies and checks transmission requests of the radio for compliance.

The challenges are threefold: (1) design and implement a PR that is capable of loading complex and previously unknown policies and interpret them correctly, so that transmission requests from the radio result in behavior that is compatible with the policies, (2) process transmission requests and make decisions fast enough to support rapid frequency abandonment (usually a few hundred milliseconds), and (3) allow for dynamically changing policies without the need of recompiling any software, so that fielded radios can be uploaded with new policies to adapt to changes in mission goals, locations, or regulations.

We implemented a PR that can reason with policies written in the Cognitive (Policy) Radio Language CoRaL [1]. We designed CoRaL to express complex policies such as dynamic frequency selection [2], listen-before-talk (LBT), and other time, location, or radio capability dependent policies. Our efficient PR processes approximately 200 requests per second. The 5 ms reasoning time therefore supports rapid frequency abandonment. We will demonstrate our PR on nominal DySPAN policies as well as other LBT policies that require sensing. Before we go into the details of the policies that will be demonstrated, we give an overview of the demonstration architecture.

A. Policy Reasoner Architecture

For the proposed demonstration, we use an architecture (see Figure 1) that consists of the platform-independent PR, sensor hardware, and an interface module that reads real-time sensor data and other data from files (e.g., location and operational mode of the radio), forms transmission requests, and sends them to the PR. The interface module also forwards transmission requests and replies to the GUI for visualization.

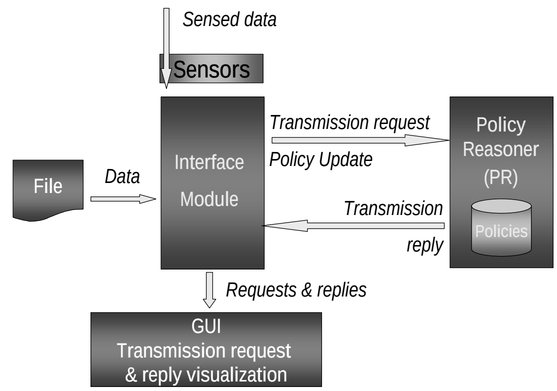

Fig. 1. XG policy reasoner demonstration architecture.

There are several types of messages between the interface module and the PR. **Transmission requests:** Before an XG radio can send a transmission, it needs approval from the PR. Normally, requests are formed by radios, but in our demonstration the interface module builds a transmission request, and sends it to the PR. The PR reasons about the request and the active policies, and responds by sending one of two replies: (1) The transmission is allowed. (2) The transmission is not allowed. **Policy updates:** The interface module can also send policy-update messages to the PR to add/activate or remove/deactivate policies.

B. Spectrum Policy Examples

For the experiments at DySPAN 2007, we wrote policies that capture the requirements for the frequencies that have been provisionally "booked" for the DySPAN conference as stated at its website `http://www.ieee-dyspan.org/Papers.html`. These policies do not require active sensing. However, active sensing over a wide frequency band to identify primaries is one key principle of opportunistic spectrum sharing. We therefore also defined LBT policies [3] over a broad range of frequencies. The policies illustrate some of the main features of CoRaL (but they do not exhibit all language features), and we aimed at making the policies somewhat realistic and thus potentially relevant for spectrum-sharing radio operations in the field. Further details on CoRaL can be found in [1].

a) Nominal DySPAN Policies: It is expected that 12 channels will be reserved for demonstration purposes at DySPAN. The channels are identified by center carrier frequencies given in the following table.

Channel	Center Freq. (MHz)	Max ERP	BW (MHz)	Mobile
1	231.2250	1 W (0dBW)	1.75	Yes
2	233.0250	1 W (0dBW)	1.75	Yes
3	234.8250	1 W (0dBW)	1.75	Yes
4	236.6250	1 W (0dBW)	1.75	Yes
5	238.4250	1 W (0dBW)	1.75	Yes
6	386.8750	1 W (0dBW)	1.75	Yes
7	396.8750	10 W (10dBW)	1.75	Yes
8	406.9750	1 W (0dBW)	1.75	Yes
9	408.7750	10 W (10dBW)	1.75	Yes
10	436.8750	1 W (0dBW)	1.75	Yes
11	2056.0000	1 W (0dBW)	50.0	No
12	2231.0000	1 W (0dBW)	50.0	No

The DySPAN website defines the following "usage policies" for these frequencies: "These frequencies are the centre carrier frequencies, with a channel bandwidth of 1.75 MHz in the 230-440 MHz band and 50 MHz in the 2-3 GHz band. Note that the maximum Effective Radiated Power (ERP) permitted is 1 W (0 dBW) apart from Channel 7 and Channel 9 where a maximum power of 10 W (10 dBW) is permitted. Omni-directional, vertically-polarised antennas are to be used, where the antenna height above ground should not exceed 2 metres. Mobile operation is permitted in Dublin city using channels 1-10, but use of channels 11 and 12 are ONLY permitted at the conference centre and at University of Dublin, Trinity College."

The requirements for using these twelve channels all describe *permissive policies*, that is, policies that allow the use of a channel under certain conditions. Sometimes one wants to define *restrictive policies*, that is, policies that define under what conditions channels *cannot* be used. We will give examples of restrictive policies for our LBT policies.

These permissive policies define the bandwidth for each channel, the maximum power emitted by the radios, where the channel can be used (Dublin city in general or only at the University of Dublin, Trinity College), whether the channel can be used for mobile devices, and what type of antenna must be used.

Before we can define these policies, we must define concepts used in the policies. These concepts are defined in ontologies in the CoRaL language. We have ontologies for basic types (such as bandwidth, frequency, power), radio capabilities, evidence, signals, time, powermasks, transmissions, and request parameters (among others). These ontologies give an extensible base for the parameters over which policies can be formulated. In particular, CoRaL expresses hierarchies of domain concepts using type and subtype declarations.

Our request-parameter ontology defines three variables that are typically contained in a transmission request. The variables are *req_radio : Radio*, which describes characteristics of the requesting radio; *req_transmission : Transmission*, which details parameters of the requested transmission, such as frequency and power; and *req_evidence : Evidence*, which contains one or more evidence objects, each of which generally pertains to location, signal, or time of sensed data that was collected by the radio.

As an example, we show more detail about the ontology for transmission. One operation on the *Transmission* type is a function that determines the center frequency of the requested transmission:

centerFrequency: Transmission $\longrightarrow$ *Frequency*

Other operations, such as mean EIRP (effective isotropic radiated power), are defined in a similar fashion. The formalization of the transmission ontology in CoRal is given below.

```
ontology transmission is
  use time,basic_types;

  public type Transmission;

  public const centerFrequency :
               Transmission -> Frequency;
  public const bandwidth :
               Transmission -> Bandwidth;
  public const maxOnTime :
               Transmission -> TimeDuration;
  public const minOffTime :
               Transmission -> TimeDuration;
  public const meanEIRP :
               Transmission -> Power;
  public const maxERP :
               Transmission -> Power;
  public const transmittedBy :
               Transmission -> Transmitter;
end
```

An ontology describing antenna properties is necessary for the DySPAN policies. We show only part of an antenna ontology that is used later.

```
ontology antenna is
  use transmission;

  public subtype Antenna < Transmitter;
  public subtype OmniDirectionalAntenna < Antenna;
  public subtype DirectionalAntenna < Antenna;

  public const verticalPolarization :
               Antenna -> Bool;
  public const height: Antenna -> Float;
  ...
end ontology
```

New requirements can be captured in user-defined ontologies, which may also build on the basic types. For our policies, we define a location ontology with Dublin

Center and Trinity College locations defined by latitude and longitude. This is done for convenience to abbreviate the policies shown later.

```
ontology location is
 use request_params;

 defconst DublinCenter : Location = loc(53.3374, -
6.2457, 0.0);
 defconst TrinityCollege : Location = loc(53.3438, -
6.2550, 0.0);
end
```

With these concepts, we can formulate nominal DySPAN policies in CoRaL. The policy imports the `request_param` ontology (and the ontologies imported by this ontology via transitivity of import), which defines concepts such as `centerFrequency`, `req_transmission`. The policy also imports the `antenna` ontology, so that the rules in the DySPAN policy can refer to concepts such as omni-directional antenna and polarization. Finally, the policy imports the `antenna` ontology in which we defined two particular regions.

```
policy dyspan is
  use request_params,antenna,region;

  allow if
    (centerFrequency(req_transmission) = 231.2250 or
     centerFrequency(req_transmission) = 233.0250 or
     centerFrequency(req_transmission) = 234.8250 or
     centerFrequency(req_transmission) = 236.6250 or
     centerFrequency(req_transmission) = 238.4250 or
     centerFrequency(req_transmission) = 386.8750 or
     centerFrequency(req_transmission) = 406.9750 or
     centerFrequency(req_transmission) = 436.8750)
    and bandwidth(req_transmission) <= 1.75
    and maxERP(req_transmission) <= 1
    and
    ((exists ?le : LocationEvidence)
        req_evidence(?le) and
        distance(location(?le),DublinCenter) =< 15000))
        // 15 km radius from center of city
    and
    ((forall ?tr : Transmitter)
        transmitter(req_radio,?tr) and
        height(?tr) <= 2 and
        verticalPolarization(?tr) = true));

 allow if
    (centerFrequency(req_transmission) = 396.8750 or
     centerFrequency(req_transmission) = 408.7750)
    and bandwidth(req_transmission) <=  1.75
    and maxERP(req_transmission) <= 10
    and
    ((exists ?le : LocationEvidence, ?l : Location)
        req_evidence(?le) and
        distance(location(?le),DublinCenter) =< 15000))
        // 15 km radius from center of city
    and
    ((forall ?tr : Transmitter)
        transmitter(req_radio,?tr) and
        height(?tr) <= 2 and
        verticalPolarization(?tr) = true));

  allow if
    (centerFrequency(req_transmission) = 2056.0000 or
     centerFrequency(req_transmission) = 2231.0000)
    and bandwidth(req_transmission) <=  50
    and maxERP(req_transmission) <= 1
    and
    ((exists ?le : LocationEvidence, ?l : Location)
        req_evidence(?le) and
        distance(location(?le),TrinityCollege) =< 400))
        // 400 m radius from center of college
    and
    ((forall ?tr : Transmitter)
        transmitter(req_radio,?tr) and
        height(?tr) <= 2 and
        verticalPolarization(?tr) = true));
```

We assigned the DySPAN frequencies to three groups: a group with 1.75 MHz bandwidth and maximum ERP of 1 W, a group with 1.75 MHz bandwidth and 10 W maximum ERP, and a group with 50 MHz bandwidth and maximum emitted power limited to 1 W. The DySPAN policy has three rules, one for each group of frequencies. Each rule starts with the keyword "allow". Therefore, all rules are interpreted as permissive.

Each rule lists the center frequencies of the bands (`centerFrequency(req_transmission)=...`), the maximum bandwidth (`bandwidth(req_transmission)<= ...`), and the maximum emitted power (`maxERP(req_transmission) <= ...`). The three groups also differ in the requirements for location. The radio must provide evidence of its location. Usually, radios can provide many evidence items, some pertaining to location, others pertaining to sensed data or any other information that is of importance. For the DySPAN policies we require that the radio submits location evidence data to the PR (`(exists ?le : LocationEvidence) req_evidence(?le)`) and that the location recorded in this evidence (`location(?le))`) is within a certain radius of the two following locations: For the first and second group of frequencies, the radio can be anywhere in Dublin city, which is defined to be a radius of 15 km from Dublin Center (`distance(location(?le),DublinCenter) =< 15000`), whereas for channels 11 and 12, the radio must be in the Unversity of Dublin, Trinity College (`distance(location(?le),TrinityCollege) =< 400)`). We use an "exists" statement for the location, meaning that there must be at least one evidence datum that indicates a location in the required area.

Finally, regardless of the channel, the policy requires that the radio uses vertically polarized antennas (`verticalPolarization(?tr) = true`, where `?tr)` is the transmitter (antenna) of the radio defined in the request `transmitter(req_radio,?tr)`). Moreover, the antenna cannot be higher than 2 m from the ground (`height(?tr) <= 2`). This is defined in the final "forall" clause of each allow rule. Using the universal quantifiers ensures that there are no antennas on the radio that do not satisfy this requirement.

b) Listen-Before-Talk Policies: The nominal DySPAN policies do not require active sensing, and therefore we will also demonstrate LBT policies that require a radio to actively sense its environment and submit data to the reasoner about what other signals were detected at what power levels. To add realism, we also included operational phases and geographical information as parameters.

We defined example operational phases, such as "Day-to-Day", "Natural Disaster", and "Training and Testing", each with policies that address the specific communication needs of that phase. To mimic two countries with different regulations, we defined two adjacent regions that would be traversed by the radios. The radio must submit information about location and phase to the PR to get transmission requests approved by policies that require those parameters. The PR will apply the policies appropriate to the location and phase of a request.

Figure 2 depicts three (of many possible) categories of policies used in our experiments. While our work has not formalized any such higher-level classifications, these could provide utility and aid understanding. For example, the categories in Figure 2 could correspond to increasingly higher-level regulatory agencies.

The policies in the inner circles generally require increasingly more information in transmission requests. Thus, a policy belonging to the innermost circle often requires information about operational phases, location, frequencies, and sensed state of the spectrum. The policies in the middle circle only check for operational phases, frequencies and state of the spectrum, while policies in the outermost circle might only constrain the frequencies to be used.

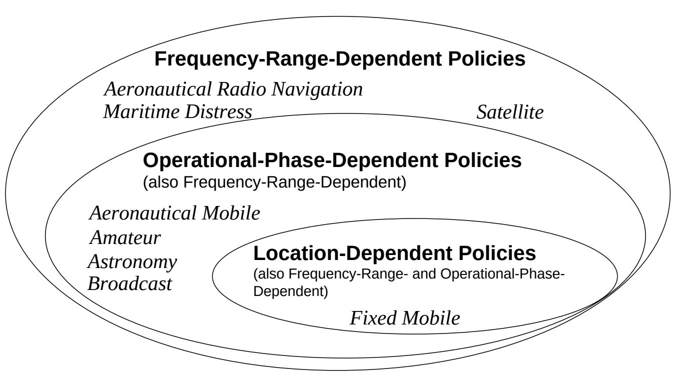

Fig. 2. Classification of encoded policies used in our experiments.

Some of the policies are *permissive* and allow use of spectrum under given conditions. Other policies are *restrictive* and forbid or restrict the use of bands. Figure 3 summarizes some of the policies used in our experiments. The restrictive policies in the second row forbid access to the Satellite, Aeronautical Radio Navigation, and Maritime Distress bands, as indicated by the *Protected* keyword. (We show details of such a policy below.)

Threshold in MHz for Band and Operational Phase in Region 1 (Different Threshold for Region 2, if applicable)	Day-To-Day	Special Event	Natural Disaster	Testing and Training
Satellite Aeraonautical Radio Navigation Maritime Distress	Protected	Protected	Protected	Protected
Amateur	No Policy	-100	-80	No Policy
Astronomy	No Policy	-100	-80	No Policy
Broadcast	No Policy	-90	-80	No Policy
Aeronautical Mobile	No Policy	No Policy	-100	No Policy
Fixed Mobile 1	-100 (-90)	-100 (-90)	-80	-100 (-90)
Fixed Mobile 2	No Policy	-100 (-80)	-100 (-80)	No Policy

Fig. 3. Overview of encoded policies.

For other bands, permissive policies define the strength of signals that can be sensed by the radios and still allow transmission. The thresholds depend on the operational phase. For example, for the broadcast bands, a policy states that if the radio is operating in the "special event" phase and only senses signals that measure -90 dBm or less, then transmission is allowed (we show details of this policy below). If the radio was operating during a natural disaster, it would be all right to transmit even in the presence of a signal up to -85 dBm. For some policies, different thresholds are given for the same frequency band in the two regions to illustrate how different regulatory bodies (different nations, service providers, and so on) might allow the use of spectrum under different circumstances.

Some of the frequency bands we used for the Fixed Mobile policies (all in MHz) are 30-74.8, 75.2-87.2, 225-328.6, 335-400, 420-450, 1240-1390, 1755-1850, and so on. These frequency ranges reflect the current assignments of these bands for non-federal government in the U.S. [4]. However, our goal was not to capture current practices and policies. Our focus was on evaluating CoRaL and its reasoner. To test the expressiveness and utility of our language, we have successfully implemented in CoRaL major parts of the Dynamic Frequency Selection (DFS) algorithms for the unlicensed 5 GHz band [2].

Part of the CoRaL encoding of the restrictive policy for the aeronautical radionavigation band follows.

```
policy aeronautical is
 use request_params,mode;

 disallow if
  (mode(Day-to-Day) or mode(SpecialEvent)
   or mode(TrainingAndTesting) or mode(NaturalDisaster))
  and (centerFrequency(req_transmission)
                       in {74.8 .. 75.2} or ... or
       centerFrequency(req_transmission)
                       in {2700.0 .. 2900.0});
end
```

The policy imports the `mode` ontology for the operational modes. This policy has only one rule, which disallows the use of any of the specified frequency ranges in the specified modes.

The following policy combines phase, sensed evidence about the spectrum state and location. The rule allows access to a set of frequencies during a `SpecialEvent`, but only if the radio is located in region `r1` and if there are no signals stronger than the threshold (-95 dBm).

```
policy fixedMobile is
  use request_params,mode,region;

  allow if
    (centerFrequency(req_transmission)
                     in {30.0 .. 74.8} or ...)
    and (mode(SpecialEvent)
         or
        ((exists ?le : LocationEvi-
dence, ?l : Location)
          req_evidence(?le) and
          location(?le) = ?l and
          locationInEllipse(?l,r1) = true))
    and ((exists ?se:SignalEvidence)
           req_evidence(?se) and
           peakRxPower(?se) =< -95.0);
```

We will demonstrate the PR on the DySPAN policies as well as the LBT policies. The next section gives an overview of the experiments and graphical user interfaces that we propose to show at DySPAN.

C. *Existing Reasoner Capability Demonstration*

XG technology was demonstrated for the first time to key stakeholders at Fort A.P. Hill in Virginia, in August 2006. The demonstration was not open to the public and the policy reasoner was run on recorded data, not with a live sensor. The emphasis of the demonstration was to show that a policy-based approach to opportunistic spectrum sharing allows a fine level of control over spectrum access and a gain in spectrum availability.

For the DySPAN demonstration, we propose to extend the Fort A.P. Hill demonstration with more policies (for the DySPAN test frequencies), with an extended GUI that allows the user to change policies on-the-fly and see the effect of new policies, and also by linking the PR to a live sensor (see second paragraph in Section II-D). We believe that the combination of software and hardware will be perceived as enabling technology by network specialists and radio designers for a new generation of radios that can take advantage of available spectrum.

Policy Reasoner Demonstration on Recorded Data: The test at Fort A.P. Hill was carried out in the geographic region (known as the 'Drop zone') shown in the map on the upper left corner of Figure 4 (Marked as [A]).

Pairs of XG radios formed communication links and traversed a path from the region shown as 'Metropolitan Area' to 'Disaster Area' and back. Throughout the area, legacy radio pairs formed a separate set of communication links. The legacy radios created possible sources of interference if the XG radios did not quickly detect them and abandon the contested frequencies.

The tests conducted at Fort A.P. Hill successfully demonstrated that the XG radios were adept at detecting potential conflicts and changing communication channels rapidly to avoid interference. In fact, the channel switch was so fast that the legacy radios were not affected, showing readiness for real-life scenarios. The XG radios in the field did not use SRI's PR, but instead used a simpler reasoner (developed by Shared Spectrum Company) with a less expressive policy language, but the policies used in the demonstration had the same form/fit/function as those used in SRI's PR demonstration. However, all sensor data from the Fort A.P. Hill demonstration was recorded and the proposed stand-alone demonstration of the PR for DySPAN will use this data.

All types of policies summarized in Figure 2 were active in the PR at Fort AP Hill, showing the wide array of policies that CoRaL can express, and the speed and scalability of the PR, which was fed thousands of transmission requests in a few seconds. We generated requests for transmission for the entire scan range of the Rockwell Collins sensor (described in more detail in the second paragraph in Section II-D) used by the XG radio (from 30 MHz to 2500 MHz) in 1 MHz increments. Each sensor pass yields about 2500 requests, which is many more than any realistic radio would send. Our PR processed about 200 requests per second. This 5 ms average time is more than adequate to support the rapid abandonment time required by XG to avoid interference.

The graphical user interface of the PR demonstration consisted of two windows (Figure 4 for inputs and Figure 5 for outputs). The four parameters that made up a request are location, operational phase, frequency and sensed signal strength, which are depicted by regions

Fig. 4. Request parameters - GUI

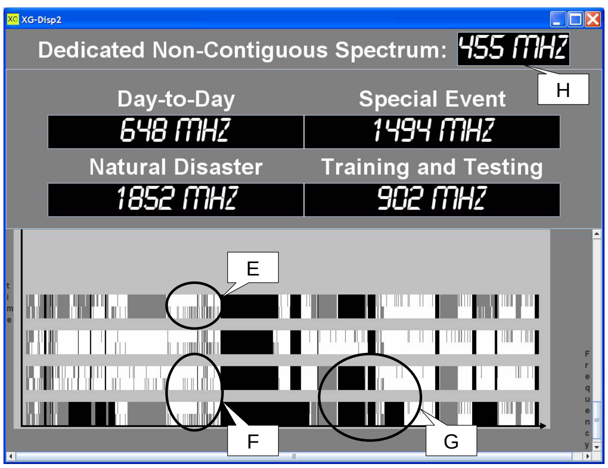

Fig. 5. Reasoner answers - GUI

marked A-D respectively in Figure 4. The drop zone marked [A] consists of two subregions "Metropolitan Area" and "Disaster Area", which were used to depict the PR's ability to do geographic reasoning using latitude/longitude coordinates. The underlying policies change as the radio moves between regions or changes operational phases.

Transmission requests are defined in CoRaL. A typical request in the PR demonstration had the following form:

```
request xgreq is
  centerFrequency(req_transmission) = 1250.00;

  public const se : SignalEvidence;
  req_evidence(se);
  peakRxPower(se) = -79.0;

  mode(SpecialEvent);

  public const le : LocationEvidence;
  req_evidence(le);
  location(le) = (112.0, 215.0);
end
```

Figure 5 depicts the results returned by the PR for the requests submitted to it. The field marked [H] denotes the total spectrum currently available for military use in the 20 MHz to 2500 MHz range [4].

D. Proposed Demonstration

Policy Reasoner with Recorded Data: Using the policies summarized in Section II-B (i.e., the DySPAN policies and the LBT policies), we will demonstrate the use of CoRaL policies to dynamically change how aggressive the radio is in accessing spectrum, based on the location of the XG radio, its operational mode, and the sensed signal strengths.

Sharing some characteristics with the Fort A.P. Hill demonstration, the DySPAN demonstration will be carried out by changing the operational phase in the following sequence: Day-to-Day, Special Event, Natural Disaster, Training and Testing. For each phase, we will run the 2500 requests twice with different sensed data. The results of these requests will look like the bottom of Figure 5 using color coding for the reasoner answers. Each black/gray/white stripe corresponds to the answers for an operational phase, starting with the Day-to-Day phase on the bottom. On the top of Figure 5 are four fields that show the total available spectrum for each of these operational modes using an XG radio. As

Available Spectrum
Currently Unavailable Spectrum
Unavailable Spectrum (Protected Band)

Fig. 6. Color coding of reasoner replies in GUI

expected, this amount increases noticeably from the first operational mode to the third monotonically and is consistent with the behavior specified in the CoRaL policies. The total available spectrum for the operational phase “Special Event” is an intermediate value and depicts the ability of the PR to be fine tuned to fit custom needs.

Three colors (white, black and gray) are used in Figure 5 to denote different responses from the PR for a request. As depicted in Figure 6, black denotes a frequency band that is explicitly protected by one of the active policies. White denotes a band for which transmission is allowed, either because it is assigned or because there is a sharing opportunity given current policies and request parameters. Gray denotes a band for which transmission was disallowed. Given the active policies in the demonstration, this generally indicates an unacceptable probability of causing interference.

The region marked [E] depicts one key advantage of the XG technology. In this case, none of the input parameters has changed except for the location of the XG radio and the strength of the sensed signals. A closer examination shows that in this situation certain requests that were previously denied are now approved, because of the change in location or sensed signals. Such opportunistic spectrum access is the key achievement of the XG technology and shows the policy-based radios adapting to dynamic situations rapidly (the change from gray to white and vice versa).

Regions marked [F] and [G] show that the PR can change its behavior to more aggressive access of spectrum either by removing protections from protected frequency bands [G] (black turns white or gray) or by increasing its thresholds for interference [F] (gray turns white). The latter will, of course, increase the probability of interference, but, at any given time, the PR ensures that the radio behaves according to the currently loaded policies, whatever those might be.

Regions denoted in white in Figure 5 depict requests that were approved. These represent opportunistic spectrum access that conforms with active policies, which implies an acceptably low risk of interference.

We will also demonstrate the reasoner with the nominal DySPAN policies. Currently those policies do not require sensing, but only data about radio location, output power, frequency and bandwidth, and antenna characteristics. We will prepare various scripts for generating transmission requests with different combinations for these parameters and show how the reasoner makes transmission decisions according to the policies. We will also extend the nominal DySPAN policies with sensing requirements, so that we can show the effect of the policies on the radio behavior, depending on what signals are sensed in the environment. We can do so by either using recorded data or by connecting a real-life sensor with the reasoner as described in the next paragraph.

Policy Reasoner with Live Sensor: We will demonstrate a combined hardware/software system by linking a Rockwell Collins sensor to our PR. Under the DARPA XG program, Rockwell Collins has developed a high-speed, low-power, broadband spectrum power sensor (see Figure 7). The novel sensor architecture is based on a combination of super-heterodyne and digital sampling receiver techniques. The sensor is capable of scanning frequencies from 30 MHz to 2500 MHz at a rate up to 18 GHz/sec. The sensor includes signal processing capability in the form of a high speed programmable digital signal processor that provides the ability to download a wide range of spectral processing algorithms. The standard output of the sensor is a Fast Fourier Transform of the RF spectrum with an instantaneous bandwidth of 16 MHz. The sensor can also output time domain samples for further post processing. The sensor utilizes a novel dynamically reconfigurable frequency architecture to eliminate internally generated spurious signals from the output. An innovative power management control algorithm enables DC power consumption of less than 2.5 watts. The sensor utilizes Ethernet 100BaseT for control and data handling. It is packaged in a small form factor (i.e., 3.15 x 5.25 x 0.82 in) with an overall volume of 13.6 in^3. The dynamic range of the sensor is greater than 100 dB, with a noise floor that is less than 105 dBm in a 25 kHz bandwidth. The long term objective is to incorporate spectral sensing into DoD systems enabling warfighters to deploy quickly anywhere in the world and have immediate access to available spectrum without time-consuming manual spectrum management and allocation processes.

For the DySPAN demonstration, the Rockwell Collins sensor will be stationary and record the state of the spectrum at the University of Dublin. We will prepare several scripts that combine this sensor data with different frequency, bandwidth, and power to generate

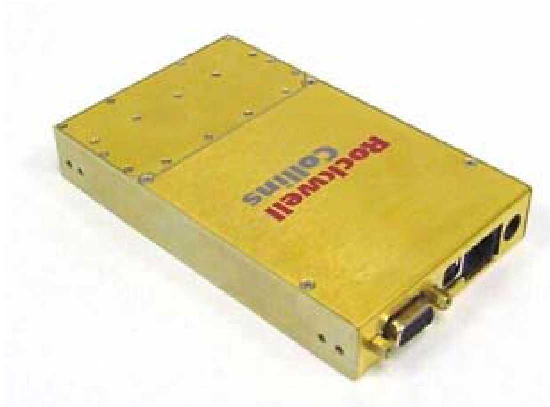

Fig. 7. Rockwell Collins Sensor.

transmission requests for the PR.

On-the-fly Update of Policies: We will extend the GUI to illustrate policy parameters and allow the user to change parameters, and activate or deactivate policies, add new policies, or delete existing policies. We will show that policy updates have an immediate effect and do not require recompiling any software. The effects of policy changes will be seen in changed reasoner output.

In summary, the proposed PR demonstration shows the scalability of the reasoner to many policies over a wide range of frequencies, and to hundreds of requests per second. It will also show the ease of changing policies dynamically, the flexibility of the reasoner to readily adapt to changes in the policy, and the feasibility of linking a live sensor with the reasoner.

III. Significance of a Policy-Based Approach to Spectrum Sharing

The primary goal of this demonstration is to show the feasibility of a policy-based approach for opportunistic spectrum use and for fine-grain control by regulators. The demonstration will also show the magnitude of spectrum made available under those policy conditions. Finally, the demonstrated policy reasoner performs fast enough to support real-life radio operation.

The significance of a policy-based approach to opportunistic spectrum sharing becomes clear when one looks at the many advantages that such an approach has over encoding spectrum-sharing algorithms directly in radios:

- Radio behavior can quickly adapt to a changing situation. While policies can be written to behave differently in different situations, the main advantage is that policies can be dynamically loaded without the need of recompiling any software on the radio.
- Policy changes can be limited to certain regions, frequencies, time of day or any other relevant parameter. Since policies are platform independent, they can be loaded on different types of radios.
- Our approach decouples policy definition, loading, and enforcement from device-specific implementations and optimizations. One advantage is a reduced certification effort [1]. We can certify the PR and each policy once, independent of the radio. Once the radio is certified to correctly interpret PR outputs, it can dynamically load accredited policies without additional certification.
- Another advantage of decoupling policies from radio implementation is that devices and policies can evolve independently over time. New policies do not require changes in radio software or hardware, and existing policies will work on new radio hardware. Today a cyclic dependency exists where regulatory bodies must wait for technology and technology must wait to see what the policies look like.
- A policy-based approach is extensible with respect to the kinds of policies that can be expressed. Our approach provides the means to define new policy parameters. Example parameters include functional allocations of spectrum (e.g., emergency response or aeronautical radio navigation), geographic restrictions, host nations, and authorities.

The proposed demonstration integrates hardware and software, allows the user to change policies, and visually shows the key advantages of spectrum-sharing policies. We believe this will be perceived as significant as it will show to the radio and networking communities that the vision of policy-based opportunistic spectrum access is possible.

IV. Maturity and Operational Capabilities

Current State of the Technology: SRI's policy reasoner was completed and successfully showcased at Fort A.P. Hill in August 2006.

Two tasks are to be completed before the DySPAN demo. First, we must extend the GUI so that policies can be shown and changed by the user. Some of this work has already begun. A simple interface showing the frequency ranges of policies together with their parameters in a spreadsheet-like table has been implemented. The values in any of the columns (corresponding to maximum ERP, bandwidth, and so on) can be changed by the user and the new policies can be uploaded with a click into the reasoner. Moreover, policies can be activated or deactivated selectively. We are currently completing this task to reflect the parameters of the nominal policies we suggest for the DySPAN test frequencies.

Second, we have to link our interface module to the sensor. The current state of the reasoner uses recorded data, but it is still actual sensor data and it does not look different to the computer than the data produced in real time by a sensor. The primary difference is that the interface module must determine what to do with the sensor data and when and how to construct a request from the sets of sensor measurements. Transmission requests are already currently formed from the data read from the file of records. Thus, for the live sensor demo, we need to implement an algorithm that controls which sensor data is used for requests. A simple solution will ignore all sensor data while the PR is processing a request. A somewhat more sophisticated option is to maintain a history of detections (relative to a threshold) for some window of time. Policies of the type "allow transmission if no detections above x dBm for y seconds" could use this data.

Risks and Mitigation Strategies: Few risks exist in the proposed demonstration. As mentioned above, we have not yet completed linking a live sensor to our reasoner. However, the Program Manager of DARPA's XG Program expressed his support of the proposed demonstration for which we plan to use a sensor made by Rockwell Collins. DARPA owns several of these sensors and they loaned us a sensor for experimentation purposes and for setting up the sensor-reasoner link for the DySPAN demonstration.

Even if a sensor fails or becomes unavailable, or if unforeseen difficulties with linking the sensors to the PR occur, we have a mitigation strategy. Our goals of demonstrating the capabilities of the PR – in particular, the fact that policies can be specified and enforced independently of radio code and that policies can be changed without recompiling software – can be achieved without live sensor data. Instead, we can use existing data recorded at the last demonstration.

Known Limitations with Respect to Coexisting Demonstrations: The only dependency of our demonstration on other demonstrations in the environment is the use of a live sensor with the reasoner. Other demonstrations may have an influence on the state of the spectrum, depending on where they are located relative to our sensor, and depending on what signals with what power they emit. This will change the sensed data and therefore could possibly influence the outcome of the reasoner. This will make it difficult to predict the results of an experiment with the live sensor. Experiments will also not easily be repeatable with the same results. However, since the reasoner shows the transmission decisions, one can interpret the changes in outcome when comparing to the policies. For example, if a policy states that "transmission allowed if peak received power is under -80 dBm", and during one run, the reasoner allowed transmission, and at a later point in time, the same request is denied, then we can conclude that now a signal has been sensed that is over the threshold stated by the policy (assuming that none of the other parameters, such as antenna characteristics or request parameters, have changed).

Thus, even though our demonstration results might be influenced by coexisting demonstration, the main purpose of the demonstration is not affected.

V. Logistical Needs

The proposed demonstration will take place at the site of the DySPAN conference at the Unversity of Dublin, Trinity College. For our demonstration, the Rockwell Collins sensor will be set up next to a desktop or laptop with the reasoner software. It is important that the demonstration room or the specific site of our location is not so isolated that no signals can be sensed.

For the demonstration we need an area of about 12 by 12 feet to set up the following equipment: a table with two chairs and two projectors (which we would bring with us) and a white wall across the table, about 8 to 10 feet from the table. Instead of a white wall, we could use screens for the projectors. The reasoner display occupies about a 6-by-6-foot wall or screen area. Furthermore, we need two easles for two posters or equivalent wall space for temporarily mounting the posters.

We need electrical outlets for the two projectors, two desktops, and two laptops. The desktops or laptops use 120 V, as do our projectors.

Assuming that we ship all our equipment, we need secure storage for two desktops and two projectors, plus storage for two easles and two mounted posters, each about 40 by 40 inches.

The minimum required equipment to be provided by DySPAN is a table, about 8 by 4 feet, two chairs, a demonstration area of about 12 by 12 feet, and power outlets as specified above. All other equipment will be shipped to the conference site. We also need to know whether the demonstration area has a flat, white wall.

Acknowledgment

This research was supported by DARPA's neXt Generation (XG) Communications Program under Contract

Numbers FA8750-05-C-0230 and FA8750-05-C-0150. Shared Spectrum Company assisted us in developing radio ontologies.

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