

COGNITIVE RADIO, SPECTRUM POLICY SPECIFICATION, AND THE SEMANTIC WEB

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ABSTRACT

No radio, even a cognitive one, is an island unto itself. Government regulations and policy will always exist to varying degrees regardless of cognitive radio technology capabilities. Therefore, a world of cognitive radios will be a world in which policy makers and radio designers will need to share some common understanding of this evolving technology. The Semantic Web—the ongoing World Wide Web Consortium (W3C) initiative to establish standards for machine-usable formal languages, knowledge representations, and methods—offers an avenue for creating formal specifications of radio behaviors. Of particular relevance, the Rule Interchange Format (RIF) working group within the W3C is developing a standard that can accommodate exchange of rules among systems using different rule languages, possibly with differing formal semantics. As a motivating example this paper considers such an approach for the implementation of the Dynamic Frequency Selection (DFS) behavior which avoids radio bands occupied by active radar systems.

1. INTRODUCTION

Rapid growth in wireless communication has led to demand for more efficient and flexible use of the radio spectrum. Emerging technology, regulatory policy, and standards specification play interlocking roles in determining the directions in which wireless will evolve to satisfy market demands. The pace of change is a function of the speed with which these sectors can negotiate the shared conceptual blueprints required for deploying innovative features and services.

Cognitive radio technology can be viewed in two ways. Narrowly it is a type of technology that exists within wireless devices and makes them behave intelligently. Broadly, it is a way of architecting the systems and conventions surrounding human use of the radio spectrum so as to make it possible for cognitive radio devices (in the narrow sense) to coexist with themselves and other

devices. It is in the latter sense that cognitive radio can be seen as an overall principle for guiding the development of wireless communication. For the sake of brevity we use the term *Cognitive Radio Community Architecture* (CRCA) to capture this concept. Focusing on the CRCA concept, this paper shows how the requirements surrounding such technology naturally associates with the revolution taking place in computer representation and processing of information heralded by the World Wide Web Consortium (W3C) Semantic Web initiative [1]; a general introduction to the field is given in [2]. As MITRE representatives to the Rule Interchange Format (RIF) working group [3], a part of this initiative, we have created a dynamic spectrum access use case [4] that shows how semantic web technologies facilitate the CRCA vision. While this use case considers dynamic access of the 5 GHz band by unlicensed devices, it has general applicability to the problem of coordinating wireless policy, technical standards, and technology implementations.

2. DYNAMIC SPECTRUM ACCESS

Access by unlicensed wireless devices to portions of the 5 GHz band entails some risk of harmful interference due to the activity of radar systems also operating in the band (namely, 5.25-5.35 GHz & 5.47-5.725 GHz). This paper examines a technique defined by the regulatory community, known as dynamic frequency selection (DFS) that can be considered an elementary form of dynamic spectrum access. In general terms, the DFS technique [5] in the 5 GHz band requires a wireless device to monitor the radio channel, and if it does not detect a radar signal the device may use the channel. The device must continuously monitor the channel and stop using the channel if radar signals are detected; the device may then switch to another channel that is not already occupied by radar.

Regulators and affiliated technical committees have codified the description of DFS in more formal, but non-machine-readable, terms [5-8]. Also, several of these

organizations [6-8] have delineated the responsibilities different categories of device have when executing DFS behavior. For example, in the United States the Federal Communications Commission (FCC) regulations on this topic are written in terms of Unlicensed National Information Infrastructure (U-NII) *master* and *client* devices. A master is required to have radar-sensing capability. No client is allowed to use a channel without first associating with a master and receiving a control signal from the master indicating that the desired channel may be used. Before allowing a channel to be used, a master has the responsibility for determining that there is no radar activity on the channel. Also, a master has the responsibility to monitor the channels of the band for the presence of radar signals and commands any affiliated clients to cease activity when radar is detected. There is an additional consideration for in-service monitoring. Unlike the master, client devices are not required to have radar detecting capability, but if they do have the capability they also have the responsibility of sending an alert to the master and ceasing activity on the channel.

Fig. 1 shows a master device in network #1 detecting the presence of radar and broadcasting a control signal letting all clients know that channel 56 must be vacated. In network #2 the client device has in-service radar monitoring capability, just like a master. The figure also shows in network #2 another master that responds somewhat differently. It goes above and beyond what is required; when notifying clients of the presence of radar, it also informs them of an alternate available channel, if one exists. All of these devices are in compliance with the FCC rules.

3. TOWARD COGNITIVE SPECTRUM ACCESS

As illustrated in Fig. 1, there are many ways of being in compliance with a policy; these can be denoted *implementation profiles*. One of the differences between *dynamic* spectrum access and *cognitive* spectrum access, as conceived in the CRCA vision, is that the latter makes it easier to specify and validate useful implementation profiles of a policy. Another advantage of cognitive spectrum access is that it offers the potential of dynamically altering the implementation profile to take advantage of or to be in compliance with regional policy differences.

3.1. Specification of Implementation Profiles

Fig. 2 shows the overall CRCA; the portion within the dashed line rectangle is novel, and the "Industry Consortium" could either be an existing body such as the SDR Forum or a new organization formed solely for the

purpose of supporting the CRCA. This industry consortium uses technical specifications, from either public standards or proprietary sources, as the starting point for creating formal representations of policy implementations.

In the case of the basic 802.11 standard [9] the IEEE P802 working groups extended that technology to operate in the 5 GHz band [10] and made refinements to accommodate variations in regulatory policy from Europe [11] to Japan [12]. From the standpoint of adhering to the policy of the regulatory body, adherence to one or more of these technical standards can be viewed as adhering to a subset of what is permitted by the regulatory body. So, while the FCC sets forth a policy in the United States for unlicensed National Information Infrastructure (U-NII) devices operating in any part of the bands 5.15-5.35 GHz, 5.47-5.725 GHz, and 5.725-5.825 GHz, the IEEE 802.11-series of standards restrict the device to a discrete set of channels within these bands in conjunction with predefined center frequencies, nominal bandwidth, peak powers, spectrum masks, etc.

Even with this reduction in scope there are many possible configurations, and it is common for wireless standards to have many options; hence, evaluating all possible variations of a given standard may be too burdensome. A substantial simplification can be achieved by following the precedent of industrial certification processes. For the purpose of certifying compliance with the specification, industry groups such as the Wi-Fi Alliance test a given device on a per profile basis (i.e., on a specific collection of compatible configuration settings). In a similar manner an industry consortium could identify behavior profiles that would be derived from both the technical specification profile and the role the device plays in adhering to the policy (e.g., the device operates in a master mode versus a client mode [7]).

It is also possible for a policy produced by a regulatory body to be directly interpreted in a form specific to a class of wireless device without the assistance of a technical standards organization. Indeed, it may be preferable in the case of proprietary technologies for the manufacturer implementing such a technology to also create the policy interpretation. One reason is that the original manufacturer may wish to license the technology to a third party that intends to use a general purpose SDR platform. An example relevant to DFS is Motorola's Canopy broadband wireless access network which operates in the 5 GHz band. Canopy differs from the variety of configurations offered by the IEEE 802.11-series in a number of ways; for example, the DFS capability is implemented so that a master (here an access

point) senses the presence of radar, makes the determination to terminate radio transmissions, and informs client devices (here subscriber stations) to stop radio transmissions [13].

As shown in Fig. 2, the consortium produces formal representations of policy interpretations or what we have called implementation profiles. The nature of these representations is discussed in the next section. For now there are two important points that need to be made in order for the logic of the DFS example to be appreciated. First, these representations are formal in the sense that they can be used by processors (machines) to govern their behavior in the intended fashion. Second, we are assuming that the devices in this example are manufactured with processing infrastructure required to use formal representations in the intended manner. That infrastructure can vary from manufacturer to manufacturer and from device to device. So while we would expect every cognitive radio device to have the ability to employ some form of rule-based reasoning, there are myriad ways in which that capability can be realized. The formal representations produced by the consortium are based on standards, the RIF being one of them, but in order to be utilized those representations have to be compiled into forms that are usable by the various platforms used in building device infrastructure.

To see one of the benefits of this process, suppose there is no consortium, no standard for formal representations. Each manufacturer would implement policy profiles for each of their devices independently. If there are two device profiles (for a given policy) and ten manufacturers then twenty separate implementations would need to be written and maintained. However, using the CRCA-based process shown in Fig. 2, each manufacturer only needs to write one “RIF compiler” that will translate formal representations of implementation profiles into a form appropriate for the device platform. Moreover, the same compiler can be used for other policy profiles.

3.2. Dynamic Alteration of Implementation Profile

A wireless device that implements a specific behavior required in one region of the world may, when moved to another region, be operating in an overly restrictive or inappropriate manner. CRCA provides a solution to these kinds of problems by making it possible for devices to dynamically alter their implementation profiles. For example, a device that finds itself in a different regulatory regime than its default region, could reconfigure itself to use an appropriate implementation profile for the new region. Here we assume that a device has the ability to

verify its location through a mechanism external to current wireless protocols.

4. THE ROLE OF THE SEMANTIC WEB

There are a number of areas in which core technologies of the Semantic Web initiative could play a role in the CRCA such as the use of a knowledge representation framework, or *ontology language*, to define the shared concepts used by various groups in the wireless arena. One such language is OWL [14]. These shared concepts are required for the statement of policy as well as the specification of implementation profiles. In this paper the focus is on the role of semantic technology in the formalization of policy and implementation profiles *per se*. It is expected that this formalization will be accomplished, at least in part, using some form of rule-based reasoning. For example the DARPA XG program has created a prototype “policy engine” [15]. To date their work has been based upon CLIPS [15] and SWI-Prolog [16]. Both of these can be considered to be rule-based inference systems, although their underlying logical paradigms differ. Indeed there are many rule-based systems in use or available for use (e.g., a non-exhaustive list is given by http://www.w3.org/2005/rules/wg/wiki/List_of_Rule_Systems). It is not within the scope of this paper to discuss the reasons for the wide variety of rule-based approaches or their relative merits. This diversity is taken as a given, and it is claimed that this underscores the value of the CRCA processes.

4.1. Rules with Declarative Semantics

To elaborate upon the points made in the above discussion the paper considers a concrete example based upon the FCC rules presented in Section 2. Consider the in-service monitoring requirement for a U-NII master device that complies with the policy. According to the FCC’s published compliance test procedures [8], a master is not really expected to continually monitor used channels for radar, nor is it expected to be capable of detecting radar as soon as it exists 100% of the time. Rather, the requirement is that the device should have at least an overall 80% success rate in detecting radar waveforms under well-defined test conditions. Furthermore, the FCC regulations [7] require clients to vacate within 10 seconds of a radar signal being detected. This performance requirement, however, is implicitly dependent upon the reaction time of the master device. In practice, therefore, a master (and its associated clients) can be expected to be in compliance if it senses for radar within an interval that is short enough to allow clients to vacate within 10 seconds of the appearance of radar. For example, if it takes a client less than 1 second to vacate a channel, then

if the master senses every 9 seconds and immediately informs clients when detecting radar, the system should be in compliance. This logic can be encoded as two rules that form part of the implementation profile for in-service monitoring as follows:

```

R1:
  If
    ChanInUse(?ch, tnow) &
    LastRadarCk(?ch, ?t) &
    tnow - ?t ≥ 9
  Then
    RequireAction(rck, ?ch, tnow)

R2:
  If
    RadarSensed(?ch, ?t1) &
    tnow ≥ ?t1 &
    tnow - ?t1 ≤ 9 &
    ChanInUse(?ch, tnow)
  Then
    RequireAction(vsignal, ?ch, tnow)

```

In these rules an item preceded by a ‘?’ is a (universally quantified) variable. One may assume that there is a syntax (not shown here) for specifying the allowed types of such variables, e.g. ‘?ch’ ranges only over *channels* and ‘?t’ ranges only over instances of *time*. The types of entities that qualify as channels and instances of time in the intended senses will be reflected in the presupposed definitions provided by the associated *ontology*. The predicates, such as ‘ChanInUse’ are similarly so defined. Items in italics, such as ‘t_{now}’, ‘vsignal’, ‘rck’ and ‘9’ are individual constants with the following interpretations: ‘t_{now}’ designates the current time, ‘rck’ designates the action of sensing for the presence of radar, and ‘vsignal’ designates the action of broadcasting a vacate signal. **R1**, therefore, says that if a channel is currently in use and had a last radar check at a time that is at least 9 seconds earlier, then the action of performing a radar check on that channel is currently required. **R2** says that if radar has been sensed within the last 9 seconds on a channel currently in use, then the action of sending vacate signal for that channel is currently required.

It seems that these rules might cause repeat vacate signals to be broadcast. There are two points to be made. First, if that were indeed the case, then it would only occur because a client continued to use a channel in the presence of radar. Second, and more importantly, the observation is false, because the semantics of these rules are entirely *declarative* (i.e., based on notions from standard predicate logic). Therefore, these rules can either be true or false (as statements of what the implementation profile requires) but in and of themselves they do not *cause*

anything to happen. To see this as a limitation is to miss the point. The point of this level of formalization in the CRCA process is to precisely state what the policy *is*. This is the type of formulation that is necessary to support machine reasoning about the policy, including issues of consistency and mutual compatibility with other policies. The fewer assumptions that are made about the way in which things are done, the more transparent and accurate the representation will be.

4.2. Rules with Non-Declarative Semantics

Having extolled the virtues of representations with purely declarative semantics, the fact is that formal representations are useful at the CRCA device implementation level only if they allow for more than making true/false statements. For example, the rules above can be used to *guide* or *control* device behavior only if they are coupled with, or compiled into, constructs that have imperative semantics (i.e., *cause* some action to happen). For this reason, many, if not most, rule-based systems have constructs that involve some form of non-declarative semantics. Rules that have imperative import are sometimes called *production rules*. *Event-Condition-Action* rules (ECA rules), are a specialized case of production rules that have a form of the basic following abstract format:

```

ON <event>
  IF <condition>
  DO <action>

```

Relating this to the DFS example, consider the following ECA rule:

```

ECA-1:
  ON
    RadarCheckAlarm.isRinging

  IF ChanInUse(?ch)

  DO
    {
      result = CheckForRadar(?ch);
      if
        (result == FOUND)
      then
        BroadcastVacateSignal(?ch);
    }

```

This rule will be triggered by an event of a **RadarCheckAlarm** object coming to be in the state **isRinging**. Once that happens, the condition will be evaluated. For any channel that satisfies the condition the actions specified in the **DO** block will be executed. Assuming that an event of type

RadarCheckAlarm.isRinging occurs once every 9 seconds, this rule will cause the device to behave in a way that complies with the policy as stated by the declarative rule set given above.

4.3. The Roles of a RIF

Fig. 2 introduced the idea of a “RIF compiler” as a means to translate from a standard representation for an implementation profile into a particular rule-base format. Relating this to CRCA, one can assume that devices will themselves have the ability to couple several types of formal representation paradigms into an application. Therefore, rather than translate declarative representations into ECA rules, the design principle would be to use the latter to augment the former. For example, let us assume that the device can recognize events of a type involving some predicate being concluded from the declarative rules. Then the following ECA rule would provide the bridge that would allow a declarative rule make something happen:

```
ECA-2:
ON
  Concluded(RequireAction,vsignal,?ch)

IF <>

DO
  {
    BroadcastVacateSignal(?ch);
  }
```

Upon it being concluded that a *vsignal* on *?ch* is a required action, this rule will be triggered. The IF part of this rule is empty.

5. DISCUSSION

The RIF is a standard that will initially provide coverage for rule languages with the type of declarative semantics represented by R1 and R2 in our example. It will evolve to handle various types of rule languages, including ECA type rules. Its role as an interchange format that will enable the development of translation programs, what are denoted here as “RIF compilers,” is an important part of the CRCA story.

However, the RIF is only one component of the relationship between CRCA and semantic technologies. As noted earlier, ontologies form the conceptual foundation upon which rules (of all semantic varieties) are built. One of the key questions in current research is the relationship between reasoning based upon the use of ontologies and reasoning based upon the use of rules.

From a high level point of view the two can be seen as being logically equivalent. But from an application level point of view, the availability of ontology-based reasoning systems as independent components raises integration issues vis-à-vis rule-based systems [18, 19]. For example, if an application uses both types of reasoning systems, what determines which system assumes control at any given time, how it passes its conclusions to the other reasoning components, and is that control strategy something that can be specified in a standard representation language itself?

Also, the paper briefly mentioned that CRCA-based processes help make dynamic alteration of implementation profiles possible. That is, in fact, a research direction that the authors have taken and continue to pursue [20]. For example, using its knowledge of regional policy variations, a cognitive radio that knows that it is located on a boundary between two such regions, only one of which is suitable for its current goals, could dynamically reconfigure itself to be in compliance with the suitable regional policy.

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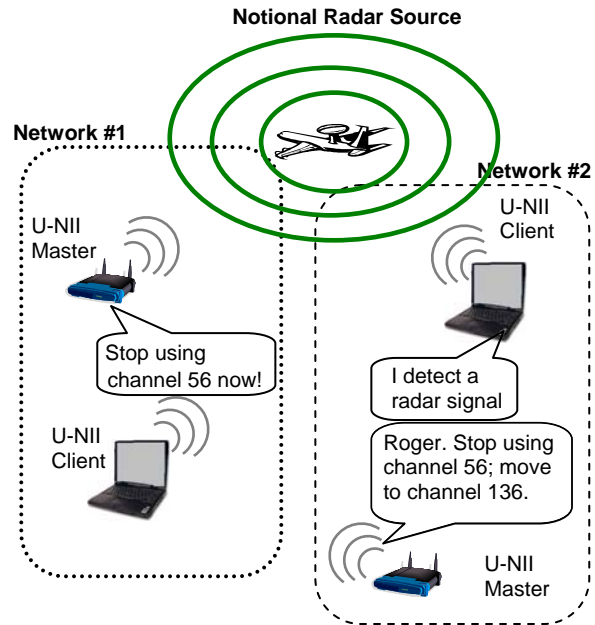


Figure 1. DFS Examples.

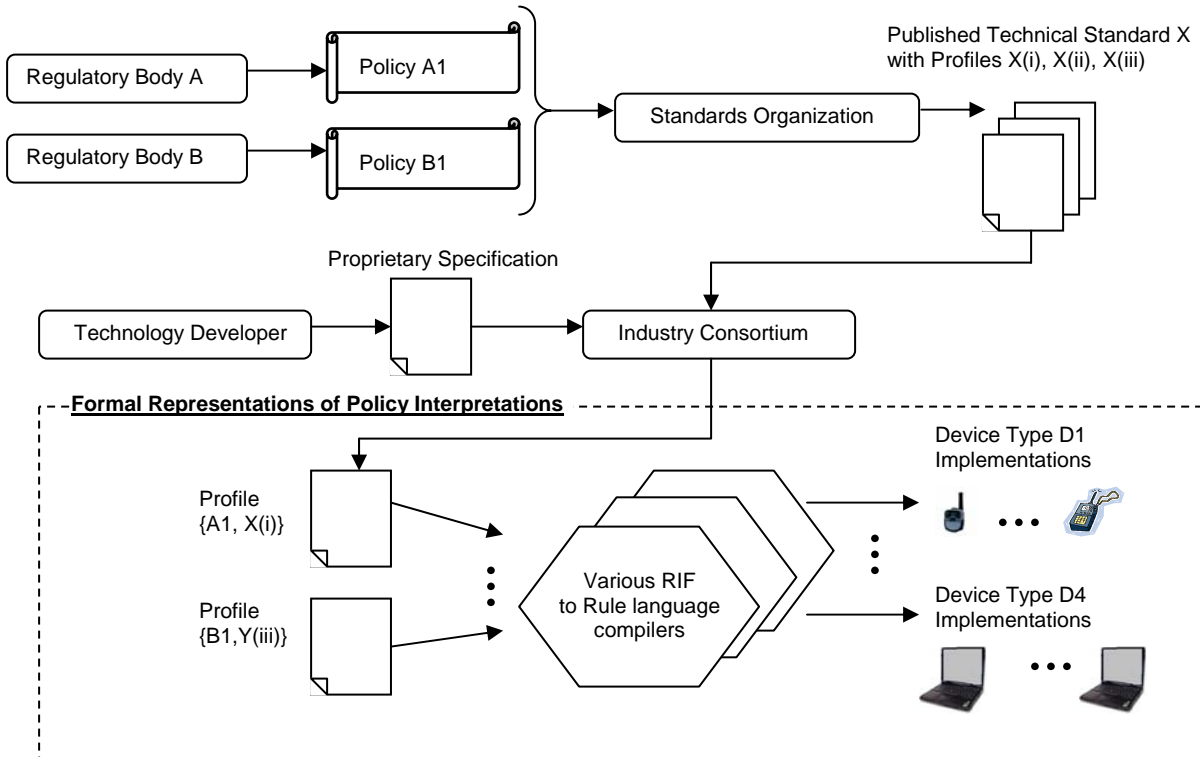


Figure 2. CRCA Overview.