An Overview of Policy-Based Spectrum Management for EM Systems

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ABSTRACT

It has been predicted that many future military radio communication nodes, as well as many other EM spectrum consuming systems, to an increasing degree will make fast, local decisions about their use of the spectrum. This is in contrast to today's situation in military operations, where authorizations to use dedicated spectrum intervals typically come in the form of longer-duration spectrum assignments e.g. from the Theatre Frequency Management Cell. With local, distributed decisions, from a military perspective there is still, however, a need to maintain administrative control of the spectrum resources, and also a need to de-conflict different uses of the spectrum. Policy-based management, where the policies are targets and constraints for a system, provide a way to have such administrative control while still having the benefit of fast, local decisions. The first part of this paper provides an overview of the research status of policy managed spectrum access, both as regards civilian initiatives and standardization efforts and also military projects and efforts. An overview of the remaining challenges in this area is also provided. For the military domain, to a large degree it is developmental and standardization efforts that are needed, e.g. tailored software tools and a standardization of policy language. The computation of opportunities allowed by the policies that apply for particular nodes and regions remains a hard problem where further research is advantageous. A way around this in order to deploy practical solutions is to carefully limit the complexity of the policies. The second part of the paper presents a case study where an ontology (computable conceptual model) for policy-based spectrum management is created and formalized in the Web Ontology Language (OWL) and augmented with policy rules in the SWRL extension. Based on a small population of spectrum availability instances, reasoning is performed and lead times logged in order to evaluate the feasibility of the approach.

1.0 INTRODUCTION

There are several factors that indicate that spectrum use, by radio communication equipment as well as other spectrum consuming devices, will gradually become more dynamic. A facilitator for such dynamic behaviour is the more than two decades long [1] radio platform trend towards reconfigurable and soft implementation platforms. A further enabler is the introduction of machine intelligence in computer-based equipment, that is assumed to also make its way into military radio equipment and enable efficient, local waveform and frequency decisions. The problems with providing sufficient frequency assignments to cover the demand with today's command and control spectrum management processes, e.g. in large coalition exercises, is another driver towards more dynamic use to better exploit the spectrum resources. This situation with the spectrum availability in certain bands sometimes being exhausted from a spectrum assignment point of view, is getting worse due to the increasing spectrum demand over time, e.g. due to requirements such as live video streams. There is also the trend of secondary dynamic use of spectrum that has been primarily allocated to another service type (e.g. secondary communication on radar bands). For EW equipment, the technological development enables more and more frequency agile countermeasures. This again causes a need for the communication equipment to be more frequency agile.

As is described in a recent STO report [2], one way of having faster and shorter duration frequency assignments, and hence more dynamic spectrum use, is to replace manual steps in the spectrum management process with automatic ones, and paper forms with electronic metadata. Still, sending the spectrum request electronically to e.g. a Theatre Spectrum Management Cell, then waiting for the response, is always likely to be slower than making the detailed spectrum decision locally. The key to more dynamic and agile behaviour is hence to have the detailed decisions made locally. This applies both for radio communication equipment as well as for other spectrum consumers and electronic warfare type of equipment.

Even if the detailed spectrum decisions are made in a distributed way, e.g. in the radio communication nodes and electronic countermeasure equipment, there is still a need to manage the spectrum and to manage electronic warfare operations. Ideally, we want to balance the requirements for agile behaviour and the management requirements in a good manner.

Oxford Dictionaries [3] define policy as "A course or principle of action adopted or proposed by an organization or individual". Meriam-Webster [4] provide two alternatives, where the first one leans towards a rather concrete course or plan: "definite course or method of action selected from among alternatives and in light of given conditions to guide and determine present and future decisions". The second alternative is a higher-level plan: "a high-level overall plan embracing the general goals and acceptable procedures especially of a governmental body". Within computer science, a typical definition is [5] 'a set of constraints on the possible behaviour of a system'. Within cognitive radio networks, a typical definition is [6] "set of rules that determine the radio behaviour in the network".

When it comes to the issue of formalizing conceptual models for policies, including constraints, a key concept is that of an ontology, for which there are also many different definitions. A commonly used definition of an ontology within computer science is that of an "explicit representation of a conceptualization" [7], in other words, a *computable conceptual model*. Another informative definition is [8] "a method of representing items of knowledge …. in a way that defines the relationships and classifications of concepts within a specified domain of knowledge".

As will be clearer in Section 2, the use of policies in the management of distributed systems and for behaviour guiding of radio systems, is not new. However, it is still very much an active research area.

The remaining parts of this paper are organized as follows: Section 2 provides the overview of policy-managed spectrum access. Section 3 is a case study of ontology modelling using the Web Ontology Language (OWL) and a related rule extension, the Semantic Web Rule Language (SWRL). A top level ontology model for radio systems as well as general EM systems is presented, and reasoning times for some sample rules are measured. Finally, Section 4 provides the conclusions.

2.0 OVERVIEW OF POLICY-BASED SPECTRUM MANAGEMENT

This part of the paper provides an overview of important literature that directly or indirectly relate to policy-based spectrum management. The literature is considerable, hence this overview does not claim to be exhaustive. After starting with the early references and pioneer projects, the overview is provided thematically focusing on language and ontology standardization, policy and ontology reasoning, influence on military spectrum management processes and tools, and security. Some on-going and past initiatives and projects are also listed, and at the end there is a summary of remaining research challenges within the area, as judged from the openly available publications.

2.1 Early References

Policy as a management approach for general distributed computing systems can [9] be traced back to the works of Robinson [10] (1988) and Moffett [11] (1993). The need arose due to computer system and network management complexity, and examples of early behaviour areas targeted were configuration, security and quality-of-service [9]. The scope of policy management then in the 2000s expanded from traditional distributed computing systems to also multi-agent, mobile and ubiquitous systems.

Radio systems having dynamic spectrum access may be seen as a special case of distributed computing and multi-agent systems, and policy-base spectrum access therefore may be seen as a specialization of earlier policy-managed systems. Mitola's cognitive radio licentiate thesis [12] and dissertation [13] define both a radio domain ontology and a Radio Knowledge Representation Language (RKRL) for reasoning about the radio domain, thereby incorporating conceptual elements needed for external policy guiding of the radio nodes, even if the term policy-based spectrum access is not explicitly mentioned. Cowen-Hirsch et.al. [14] also rather early discusses the use of dynamic band-by-band rules e.g. for the transitioning between legacy radios and smart software radios. By 2006, the cognitive radio book edited by Fette [15] has a thorough treatment of policy based cognitive radios, both from a regulator's perspective and from a policy reasoning module perspective. The same book also has a full chapter on radio ontologies.

2.2 XG and WNAN Programs

A ground-breaking project in terms of policy based spectrum access was the neXt Generation (XG) project, initiated by Defense Advanced Research Agency (DARPA). Public papers concerning the project started appearing in 2002 [16]. The project outlined a radio architecture, of which a simplified version is shown in Figure 2-1. Central in the architecture are the system strategy module and the policy reasoner module, in addition to the sensor module (for determining spectrum opportunities) and the RF module (transmit and receive). The policy reasoner determines if proposed radio configuration and spectrum use solutions are feasible within the policies, "it approves or disapproves any transmission candidate" [17], and ideally also provides hints if they are not. The system strategy reasoner searches for good spectrum and waveform parameter solutions. The architecture also defines a communication protocol between these two modules. This architecture is one that is frequently referred to in later literature.

In XG, an ontology for the radio domain and also a language for reasoning about radio policies, CoRaL, was worked out. A language XGPL, based on OWL, was also used in parts of the project.

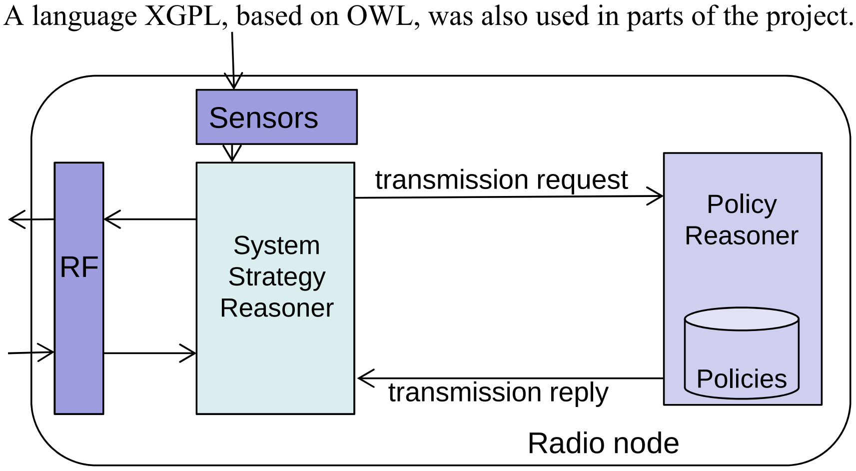

Figure 2-1: The architecture outlined in the XG project (simplified) [18].

A successor DARPA project, the wireless network after next (WNAN), also adapted the policy based spectrum access from XG, but had additional goals of being low-cost, have multi-channel medium access and to form mobile ad-hoc networks with highly scalable routing[19]. It reused the OWL ontology and the reasoner that was developed for the XG project. It is claimed that WNaN has been demonstrated with 100 prototype nodes [20].

2.3 Policy and Ontology Languages

There are a wide number of policy languages, however a large number of them are targeted towards the network configuration and security domains. For dynamic spectrum, the Web Ontology Language (OWL) [21] augmented by the Semantic Web Rule Language (SWRL) [22] is frequently mentioned as a candidate for formalizing policies, and by some regarded as satisfactory for the dynamic spectrum domain [23]. Other related approaches substitute SWRL with other rule languages, such as [24-27], where rules are expressed in a custom BaseVisor format for the BaseVisor inference engine.

The benefit of using OWL as a basis for formalizing policies is that existing tool development efforts made in this area are substantial and can easily be benefitted from, and the related computational complexities are well known, even for simpler sub-fragments of the language. However, OWL lacks some expressive features that are more naturally expressed as rules, and lacks arithmetic operators, hence is often used together with rule extensions. It is worth noting that the interaction with rule languages must be carefully controlled in order to maintain decidability.

Another candidate language for the dynamic spectrum domain is CoRaL [28], which was developed by SRI International for the XG project. CoRaL may express ontologies using types and subtypes [17] as well as allow and disallow policy rules with numerical constraints. This language is well suited in terms of easily being able to express the policies that are needed in the dynamic spectrum domain. However, the high expressiveness means high complexity.

Another language used in the XG project was the XG policy language (XGPL) [29]. This is based on OWL, complemented with spectrum management domain related ontologies.

A major policy language standardization effort was the IEEE 1900.5-2011 “Standard for Policy Language Requirements and System Architectures for Dynamic Spectrum Access Systems” [30;31], brought forward by the IEEE DYSPAN 1900.5 group [31]. This standard provided requirements for a policy language [30-32]. The on-going IEEE 1900.5.1 work aims at creating a policy language as well as a reference ontology based on these requirements [31;32].

Another standardization effort is carried out by the Modeling Language for Mobility (MLM) [33] working group which also works towards a common language for knowledge and information exchange between radios, including ontology standardization. The MLM-WG has a MoU [34] with, coordinates with and contributes to the work in IEEE 1900.5.

Table 2.1 provides a list of ontology and policy languages used in this domain, along with specifics, references and comments.

Table 2-1: Ontology-based approaches in the policy-based spectrum access literature

Language	Ontology or policy rules	Docu-mentation	Dynamic spectrum references	Main originating organization	Comments
CoRaL	Ontology+policy rules	[28]	[17]	SRI	Custom developed language: • Constraints using numerical (in)equalities • Prolog-style rules. • Functions
XGPL (based on OWL)	Ontology + policy rules	[29]		BBN	
OWL (different versions)	Ontology	[21]	[24;35;36]		Constraints using numerical (in) equalities not supported by OWL. Rules not supported.
OWL+SWRL	Ontology + policy rules	[21;22]	[23;37]		
OWL+BaseVisor syntax rules	Ontology + policy rules	[21;38]	[25-27]		
OWL+SPARQL	Ontology + policy rules	[21;39]	[40]		
OWL+MLM (?)	Ontology + policy rules	[21;33]	[41]	Wireless Innovation Forum	Coordinating with IEEE 1900.5.1
1900.5.1	Ontology + policy rules	[30;42]	[31]	IEEE	On-going standardization work. IEEE 1900.5-2011 specifies the requirements for the policy language.

2.5 Reference Ontologies for Cognitive Radio

The *cognitive radio ontology* (CRO) [43] is a comprehensive reference ontology with 230 classes and 188 properties. CRO has been developed by the Modelling Language for Mobility (MLM) [33] work group of the WinnForum, and has also been provided to the 1900.5.1 work group. Fairly extensive radio ontologies were also developed in the XG project [29]. Within the KaOS framework there is also a radio ontology, as well as a network ontology and a core ontology [35]. Cooklev et al. define a fairly comprehensive ontology as well, but presented in plain text [44]. Table 2.2 lists these and some other examples, and provides references to documentation and publications.

Table 2-2: Reference and example ontologies

Ontology	Classes & properties	Originating organization	Docu-mentation	References	Comments
Cognitive Radio Ontology (CRO)	230 classes and 188 properties	Wireless Innovation Forum (Modeling Language for Mobility Work Group)	[33;43]	[25-27;31;41]	
IEEE1900.5.1		IEEE	[42]	[31]	Refers to CRO from WinnF
XG Common Ontology	40 classes, 75 properties	SRI International	[45]	[46]	
XGPL Ontologies		BBN Technologies	[29]		
KaOS ontology				[35]	KaOS Core Ontology, Network ontology and Radio ontology
Various custom ontologies				[47] [36] [44]	
Openly Available Spectrum Sensing ontology				[48]	

2.6 Ontology and Policy Reasoning

The process of reasoning may refer to inferring new implicit facts from a given knowledge base. Referring to the XG architecture previously mentioned, the task of the policy reasoner is typically to find out if a given prospective solution (from the system reasoner) is consistent with the facts, rules and constraints in the knowledge base. If the solution is inconsistent, ideally we also want the policy reasoner to provide hints as to what to change in order to arrive at an acceptable solution.

The time required to determine consistency depends on the expressivity of the language, the complexity of the ontology and policy rules, as well as instance data. For example, for the most expressive part of OWL 2, the DL fragment, it falls within the complexity class N2EXP with the size of the input [49]. However, there are standardized sub-profiles of OWL2 with polynomial time guarantees and feasible in practice. Furthermore, as noted earlier, the combination of OWL with rule languages must be carefully controlled, as OWL 2 DL combined with unconstrained SWRL is undecidable. In any case, reasoning over large ontologies and rule sets is a major challenge in the policy-based spectrum management concept.

A number of different reasoners have been referenced and/or formulated and/or tested in the policy-based spectrum literature. Many papers quote results from using OWL-compatible readily available reasoners such as Pellet [50], Jena [51], and HermiT [52], see table 2-3. Bahrak et al. [37] provide modifications to Pellet such that it computes opportunity constraints. Li et al. [27] describes an approach using BaseVisor [38], with ontologies written in OWL and declarative policy rules written in a form required by the BaseVisor engine.

In the previously mentioned XG program, with the XG policy language framework (XGPL), a Prolog based reasoner as well as a simplified reasoner in c/c++ have been made. Similarly, with the CoRaL language, a Prolog-based reasoner was developed. All of these only provided yes / no answers on tested solutions. There is also an XG Maude-based reasoner, this also may reply with constraints in order to guide towards a valid solution.

There are several papers on the BRESAP/BRESAP+ reasoner, which is based on rewriting the policies into a binary decision tree, then performing the reasoning in this decision tree. While the reasoning when the tree is built is quite effective, a disadvantage is that it takes exponential time (with regard to the number of numerical constraints in a policy) to build the tree.

Arkoudas et al. [53] has proposed to use the theorem proving environment Athena combined with a general satisfiability modulo theories (SMT) solver such as Yices [54] as a spectrum access policy engine. Policy satisfiability performance tests were conducted using up to 100 policies with up to 50 different transmission parameters. The quoted numbers indicate remarkable scalability properties as the number of policies and transmission parameters increase, and thus is a very promising proposal. Still, transmission requests consume many milliseconds even for a small number of policies and transmission parameters.

It is difficult to compare the approaches due to differences in expressiveness, some approaches lacking formal semantics, as well as the general lack of tight time complexities (some are, in the worst-case, undecidable). Furthermore, due to the lack of a standard policy set that can be used for benchmarking dynamic spectrum-related rules, actual run-time values presented in literature are difficult to compare. Nevertheless, in Table 2-3 we quote the performance data that has been provided in the literature.

Table 2-3: Reasoners used in the policy-based dynamic spectrum literature

<table>
<tr><th colspan="2">Reasoner</th><th>Docu-mentation</th><th>DSM refe-rences</th><th>Performance examples</th><th>Comment</th></tr>
<tr><td colspan="2">CoRaL Policy Reasoner (using Prolog)</td><td>[55;56]</td><td>[17]</td><td>“5 msec average response time of policy reasoner”[17] (very limited details of experiment given)</td><td>The reasoner only provided yes/no</td></tr>
<tr><td colspan="2">XGPL + Prolog based reasoner, c/c++ reasoner for resource-constrained devices</td><td></td><td>[57;58]</td><td></td><td>The reasoner only provided yes/no
Few details provided.</td></tr>
<tr><td colspan="2">XG MAUDE-based reasoner</td><td>[59]</td><td>[60]</td><td>“with 11 active spectrum access policies, the reasoner returned 75 opportunity constraints and it took 58 seconds”[60]</td><td>Also returns constraints. (Uses SWRL FOL)</td></tr>
<tr><td colspan="2">BRESAP</td><td></td><td>[37;58;60-64]</td><td>Building tree / adding a policy with n constraints is exponential in n:
n=10 =>50 millisec.
n=20 =>20 sec. @core 2 1.86GHz
Processing tree: 50 policies with 15 constraints per policy => approx. 18 millisec.[64]</td><td>Policies with numeric constraints are converted to binary decision diagram.

Returns transmission opportunity constraint set.</td></tr>
<tr><td colspan="2">BRESAP+</td><td></td><td>[65]</td><td></td><td>Returns multiple transmission opportunity constraint sets</td></tr>
<tr><td rowspan="4">“Standard OWL“ reasoners</td><td>Pellet</td><td>[50;66]</td><td>[37;62]</td><td>(Scalability results provided)</td><td>Algorithm: Tableau+Rete + “modifications to enable the computation of opportunity constraints”[37]</td></tr>
<tr><td>Jena 2.1</td><td>[51]</td><td>[47]</td><td></td><td>Input: OWL-Lite</td></tr>
<tr><td>BaseVisor</td><td>[38]</td><td>[25-27]</td><td></td><td>Input: OWL 2 RL, XML Schema, native rule syntax
Algorithm: Rete</td></tr>
<tr><td>HermiT</td><td>[52]</td><td>[44]</td><td></td><td>Algorithm: Hypertableau</td></tr>
<tr><td colspan="2">(Athena +) SMT solvers</td><td>[54]</td><td>[53]</td><td>100 policies each with 50 parameters in 300 millisec.
5 policies each with 10 parameters in approx. 35 millisec.</td><td>Spectrum access policies are represented in Athena, then adapted to solving in satisfiability-modulo-theories (SMT) solvers, here Yices[54]. Finding optimums (Max-SAT SMT) is also possible.</td></tr>
</table>

2.7 Spectrum Procedures and Processes

A description of the procedures and practical processes for NATO spectrum management in an operational theatre may be found in the report from the STO-IST-104 group [2]. The main baseline procedure that applies is ACP-190. The management of EW operations likewise is guarded by another rigid set of procedures. Communication frequencies then need to be coordinated with the EW operations, for which an instrument is the joint restricted frequency list (JRFL). A challenge when going from conventional (detailed assignments and instructions) to applying policy-based spectrum management and policy-based management of EW operations, is to minimize the procedural changes that are needed to do so. Still, it is desirable to get a more holistic view on operations in the electromagnetic spectrum.

A paper by Normoyle, presenting a team effort by 11 organizations to bring forward the Joint Open Architecture Spectrum Infrastructure (JOASI) [67], conveys such a holistic view on electromagnetic operations, including also EW. It lists several standards, including the IEEE 1900 ones and the 'EW Network Protocol', that form part of the architecture. It does not, however, discuss how today's military spectrum and EW procedures are to be changed in order to get to the new state.

Boksiner et al. [58] refer to the spectrum management lifecycle in US Joint Chiefs of Staff Manual 3320.01, and conclude that the lifecycle in principle does not change significantly from the described 12 step process. The spectrum management tool needs to have electronic interfaces towards databases etc. The assigning of single frequencies is replaced by frequency pools. The JRFL is envisioned to still be created, but in digital spectrum format. The paper describes a policy automation, creation and simulation (PACS) tool that facilitates the 12 step process by automating many of the steps.

Swain et al. [32] refer to the same spectrum management lifecycle in US Joint Chiefs of Staff Manual 3320.01, and present a three-level approach to introducing policy management, where at the first level only one of the 12 process steps are affected (the step for nominating and assigning frequencies) while at the second and third level, more of the lifecycle steps are modified.

2.8 Policy Formulation and Support Tools

In several works, the general tool Protégé [68] has been used for writing and editing ontologies, and with plug-ins to input policy rules and do reasoning. However, for policy-based spectrum management purposes, custom-made tools are beneficial to have, supporting the different spectrum management process steps, and such that policies can be automatically extracted from data material where it is possible.

A limited number of papers describe tools that are planned, are under development or that are prototyped. Sherman et al. [23] outline some of the tools that are needed, including policy generation tools and policy based planning tools. Boksiner et al. [58] provide a description of the DSA policy automation, creation and simulation (PACS) software tool, which contains different modules that support the whole 12-step spectrum management process. This includes e.g. a policy authoring tool (PAT) and a policy visualization tool (PVT). It is, however, difficult on the basis of the paper to judge the implementation status and readiness level of the different modules of PACS. Uszok et al. [35] describe the KAoS policy services framework including screen dumps of the KAoS policy administration tool (KPAT), that allow policy specification in constrained English sentences.

2.8 Security

Dynamic spectrum access radio communication units, and other spectrum consuming equipment using software radio type of platforms, open up for a lot of new security issues [69] that did not exist with legacy more hardwired units. E.g. manipulations of a unit's transmission behaviour may contribute to the launching of jamming attacks. Park et al.[69] point to that policy-based dynamic spectrum radios, through the policy enforcer module, may actually contribute to improved security by disallowing such rogue transmissions. Baldini et al. [70] deals with security issue of policy-based cognitive radio networks and identifies the main security threats related to the policy processes. Policy derivation threats (derivation of wrong/misleading policies), policy distribution threats (inability of distribution or distribution of wrong/misleading policies) and policy reasoning and enforcement threats (threats based on false reasoned information being sent to a policy-based node). Baldini et al. propopose the Trusted Radio Infrastructure [70] to mitigate these security threats, where one of the ingredients is an authentication mechanism. Boksiner et al. also present a threat analysis and risk assessment for policy-based spectrum management, and provides a list of ways to handle these threats. Thakkar et al. [63] also discusses security in policy-based cognitive radio, concluding that security measures for the middleware in such systems is also required.

2.10 Summary of Challenges Related to Policy-Managed Spectrum

Standardization of ontology and policy language: The main ontology and policy language standardization effort for policy-managed spectrum is the IEEE 1900.5.1 work. The released 1900.5-2011 document [30] puts forward the requirements for a policy language, and there is on-going work for a IEEE 1900.5.1 “Standard Policy Language for Dynamic Spectrum Access Systems”. By many, this standard is expected to be the policy language reference also for military systems. Judging from published material, the dominant formalism used so far for expressing policies is OWL along with rule-based additions such as SWRL. Using existing knowledge-representation languages such as OWL for representing policies has the benefit of being able to use general purpose tools and technology that has already been developed, balanced with expressivity such that it is easy to express radio-related knowledge and policies, yet having well-understood reasoning complexity.

Standardized / reference ontology: The evident example of a published reference ontology is the Cognitive Radio Ontology (CRO), made by the Modeling Language for Mobility work group in Wireless Innovation Forum and documented in [43], and which does a detailed breakdown of knowledge classes (230) and properties (188) related to the radio domain. CRO has also been contributed to the work of IEEE 1900.5.1 [31;34]. However, there is no single way to make an ontology, two groups of engineers or scientists working independently on such a task would almost certainly end up with different proposals, and agreeing on a harmonization between the two is difficult. E.g. which level of detail to model, and what to model as classes and properties may depend on personal judgment. Ontology elements for non-communication electromagnetic equipment are also needed. Consensus on a standardized ontology for radio communication, as well as other spectrum consuming equipment and for the military domain, is thus not fully there yet.

Reasoning and reasoning performance: As judged from the literature, the expressivity of the language and the effect on reasoning performance is possibly the most critical issue with policy-based spectrum management. Published results demonstrate that reasoning time can be significant, particularly when compared to the reaction times needed in military spectrum using equipment in challenged environments. As mentioned, the solution complexity depends on the policy language and the set of policies. Limiting the complexity of the knowledge representation language and the set of policies is one way of keeping the reasoning time at practical levels. Another way is using domain-specific reasoners that have good practical performance for typical expected DSM ontologies and policy sets. From the reasoning engines described for dynamic spectrum management in the literature, the most promising approaches appear to either use highly efficient standard SAT Modulo Theories (SMT) solvers, with domain specific functions or use standard OWL/SWRL-based solvers that use tableau and Rete-like approaches.

Influence on spectrum procedures and EW procedures: Policy-based spectrum management appears to be possible to introduce within a framework of keeping the principle spectrum management processes, and only changing the content of some of the steps slightly. E.g. instead of single frequency assignments, policies may specify spectrum pools with access rules. Instead of coordinating single frequencies in the JRFL, policies may be coordinated at the planning level and then the individual frequencies are coordinated at the spectrum consumer level.

Influence on spectrum management tools: The literature on software tools that support the various policy-based spectrum management processes is limited at the moment, however a few papers mention tools that are either planned, underway or being available. Further work on and availability of such tools is considered an important enabler for the introduction of policy-based spectrum management.

Security: While a robust policy enforcer module in a policy-based radio unit may mitigate some security attacks, e.g. rogue transmissions due to infected SDR code, the various processes related to policy-based radios and devices also open up new vulnerabilities, e.g. policy distribution threats (inability of distribution or distribution of wrong/misleading policies). Care must be taken to include measures that mitigate these vulnerabilities, e.g. robust authentication measures.

3 ONTOLOGY AND POLICY MODELLING WITH OWL AND SWRL

From the review of ontology and policy languages in 2.3, it was seen that a presently good compromise between offering expressivity suited for easily expressing spectrum access ontologies and rules, and at the same time have access to tools, including reasoners, is to use OWL augmented with SWRL to provide a rule extension. In this section, a case study of ontology and policies for radios and general EM systems is carried out, using OWL (currently in version 2, OWL 2) and SWRL.

3.1 OWL 2, SWRL, Protégé and SQWRLTab

OWL 2 [21] is a formal knowledge representation language specifically made for expressing ontologies, with well-defined semantics and well understood complexity results. OWL 2 provides concepts such as class and instances of a class, which allows to express knowledge in the form ‘Peter is an instance of the class Person’, or that a particular radio is an instance of the radio class. It also provides the concept of properties, both in the form of description of relations between instances, data properties for instances, as well as many other forms.

The de-facto tool for creating OWL ontologies is the Protégé [68] tool (here version 5.0.0 beta-17), which is used to input and edit the ontology. Although it would have been possible to write the ontology directly, using a text-file editor and write it in one of the OWL-compatible formats, with a tool such as Protégé we know that the produced ontology will be syntactically correct. Furthermore, the tool is easy for a non-expert to use, as well as providing a rich set of extensions and plugins.

SWRL [22] is a rule language for the Semantic Web, and provides a rule extension to OWL. In the case at hand, it is particularly useful that SWRL has built-ins for comparisons (e.g. swrlb:greaterThan) and for doing math (e.g. swrlb:multiply), which allow complex algebraic rules to be defined. While the rules may be saved in RDF/XML format together with the ontology, there is also an abstract syntax which is more human-user-friendly to read, see for example table 3.2.

The SQWRL Tab [71] is an open source program (and plug-in to Protégé) that allows SWRL rules to be run as queries towards an ontology. It uses Drools [72] version 6.2.0, a general-purpose production rule engine, for reasoning.

3.2 A Suggested Radio and EM systems Ontology

For the sake of keeping the example and experiment as simple as possible, a limited ontology was created from scratch rather than reusing one of the previously mentioned published ontologies in our tests.

Figure 3.1 shows the top level classes in the dynamic spectrum management ontology proposed here. The radio network (RNE) class defines the placeholders for information about requirements and restrictions of the waveform standard that the radio networks use, e.g. frequency bands, spectrum access mode etc. Each RNE consists of 1 (if it is a broadcaster) or more radio nodes. A radio network instance uses one or more spectrum element (SE) instances. Each SE instance contains specific information about a part of the radio spectrum that is available at a particular location along with restrictions of its use.

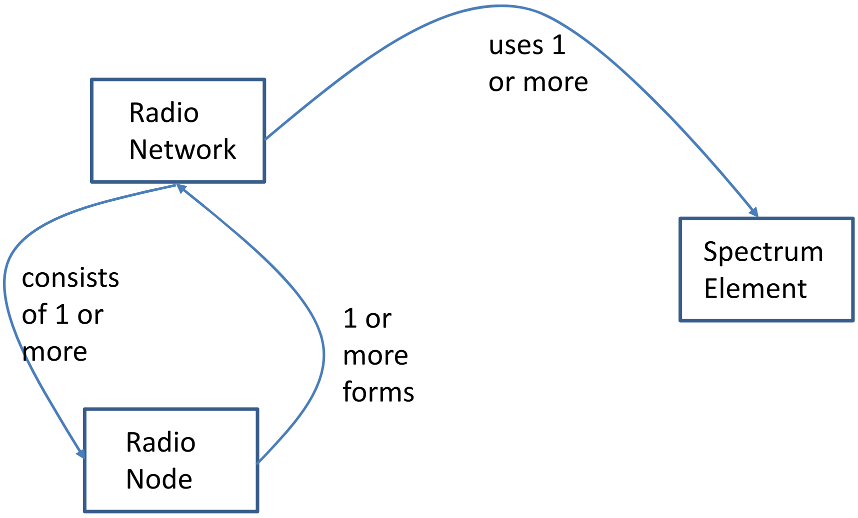

Figure 3-1: The top level structure of the ontology for managed wireless communication.

For general spectrum-consuming electromagnetic systems, the top-level model in Figure 3.1 may be readily extended to distributed groups of other spectrum-consuming nodes, as illustrated in Figure 3.2. Each SE in the same manner contains information about a part of the radio spectrum at a particular location, but with usage restrictions that are meaningful for the particular system.

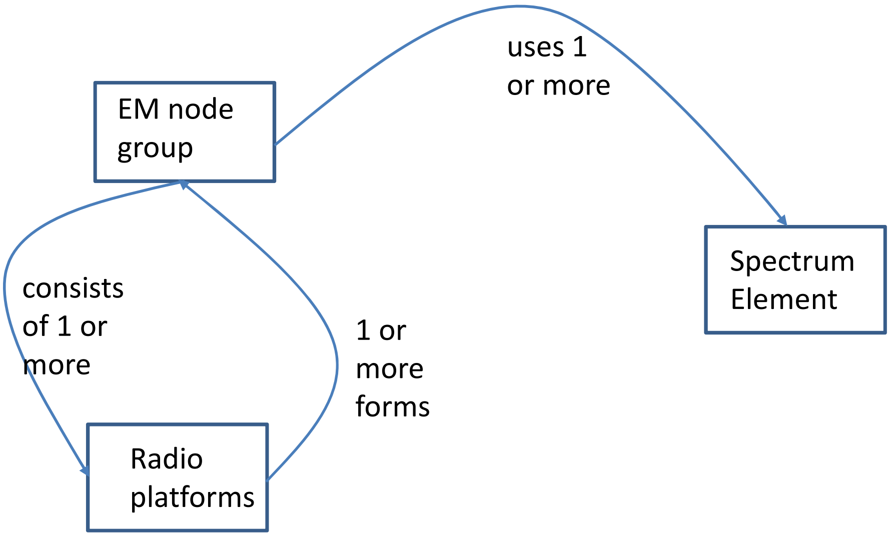

Figure 3-2: The top level structure of the ontology for managed spectrum consumption.

A simple test ontology was created using the radio network and spectrum ontologies, and extended with the following features. A radio network is represented with a geographical position and an identity number, see Figure 3.3. Each spectrum element contains a circular validity area as well as frequency, bandwidth and power specifications. Spectrum access mode is modelled as a hasSpectrumAccessMode property, with alternatives exclusive, primary, secondary, thirdpriority, fourthpriority, fifthpriority and equalpriority. A sample spectrum element instance is shown in Figure 3.4.

For the reasoning tests performed in Section 3.3, the ontology was populated with 1 *radio network* instance and 21 *spectrum element* instances. There are 5 exclusive use instances, 5 primary, 10 secondary and one equalpriority.

Figure 3-3: Radio network instance as input in Protégé.

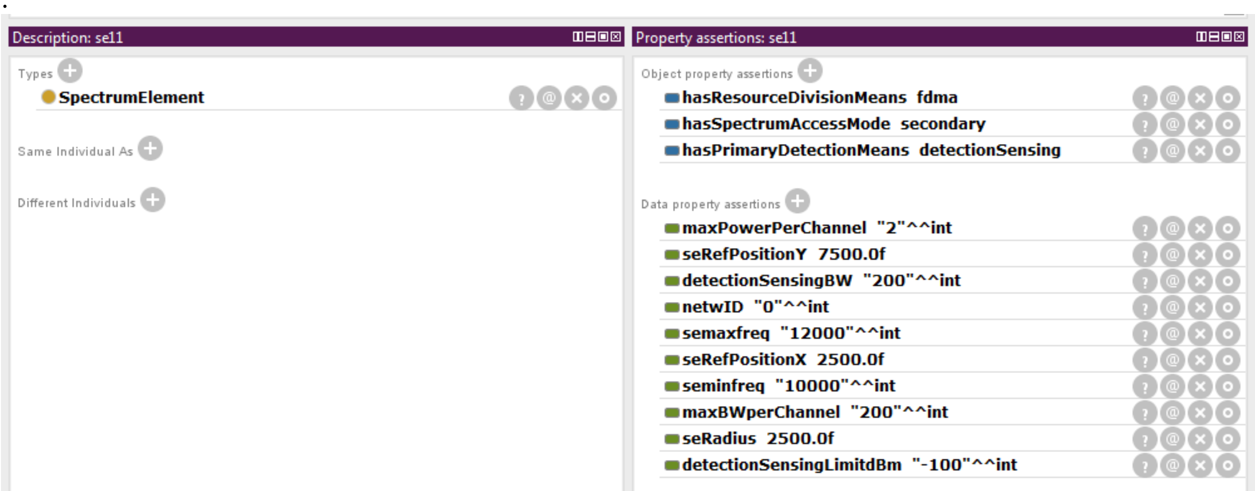

Figure 3-4: Example spectrum element instance as input in Protégé.

3.3 Reasoning, and Reasoning Performance

For the experiment, the SQWRLTab tool is used to run SWRL rules as queries over the combination of the rule and the ontology. SQWRLTab uses the reasoner tool Drools (version 6.2.0.) to perform the underlying reasoning, which furthermore reports the time it takes to complete the reasoning, in milliseconds.

There are three test rules formulated, see table 3.1. The first rule says that the radio network could use spectrum that has been marked as for exclusive use for this particular radio network, if the radio network is inside the region where the exclusive use is permitted. The second rule is a secondary access rule, and responds with secondary access spectrum at the position of the radio network. The third rule is for equal rights spectrum, and again checks spectrum versus the position of the network.

Taking into account that the ontology and rules are quite simple, and is also sparsely populated, the time it takes to complete the SQWRLTab queries is remarkably long. The first rule executed takes close to 3 seconds. Rule two and three take shorter time, but still in the order of 500 milliseconds (561-499 milliseconds). When rule 1 is re-executed, it also runs faster; 531 milliseconds. The reason for this is likely due to the first execution generating internal objects which are reused in intermediate results and that speed up the later executions.

The reasoning times of around 500 milliseonds (and even up to 3 seconds) are somewhat incompatible with the responses required from a dynamic spectrum access radio, or other spectrum-consuming device, where at least in some cases, sub-millisecond reaction times are needed. If each and every proposed spectrum solution is to be checked real-time by the policy reasoner, there is a risk that the response time of the radio / device may be significantly slower than wanted. This confirms that it is important to keep the policy rules simple, and pick knowledge-representation formalisms that are not more expressive than needed, hence keep complexity as low as possible.

The long policy reasoning times also suggest that a loose coupling between the system strategy reasoner ('cognitive engine') and the policy reasoner can be beneficial, i.e. not requiring the SSR/CE to do real-time requests towards the policy reasoner. As an example of a looser model, the policy reasoner can, as a non-time-critical background process, continuously provide spectrum opportunity updates to the system strategy reasoner. The system strategy reasoner may then act quickly to observed environmental changes by using the latest spectrum opportunity update that it has. On the other hand, the tight coupling of strategy and policy reasoning, as per used in SMT and the related Answer Set Programming (ASP) approaches, allows early pruning at the strategy generation stage (informed grounding), hence pruning away obviously flawed proposed configurations at the generation stage before proceeding to the costly policy reasoning (verification) stage.

Table 3-1: The three test rules / SQWRL queries

Rule #	Plain text	SQWRL syntax	Comment
Rule 1	For this network position and network ID, find exclusive use spectrum that applies for this network position and network id number (and show spectrum element number and minimum and maximum frequency).	RadioNetwork(?r) ∧ rnPosX(?r, ?x1) ∧ rnPosY(?r, ?y1) ∧ SpectrumElement(?el) ∧ netwID(?el, ?nID) ∧ rnID(?rn, ?rID) ∧ swrlb:equal(?nID, ?rID) ∧ seRefPositionX(?el, ?x0) ∧ seRefPositionY(?el, ?y0) ∧ swrlb:subtract(?x, ?x1, ?x0) ∧ swrlb:subtract(?y, ?y1, ?y0) ∧ swrlb:pow(?xs, ?x, 2) ∧ swrlb:pow(?ys, ?y, 2) ∧ swrlb:add(?lens, ?xs, ?ys) ∧ swrlb:pow(?len, ?lens, 0.5) ∧ seRadius(?el, ?rad) ∧ swrlb:lessThanOrEqual(?len, ?rad) ∧ hasSpectrumAccessMode(?el, exclusive) ∧ seminfreq(?el, ?minfreq) ∧ semaxfreq(?el, ?maxfreq) → sqwrl:select(?el, ?minfreq, ?maxfreq)	
Rule 2	For this network position, provide secondary access spectrum elements (and show spectrum element number, minimum and maximum frequency, primary detection means and sense limits).	RadioNetwork(?r) ∧ rnPosX(?r, ?x1) ∧ rnPosY(?r, ?y1) ∧ SpectrumElement(?el) ∧ seRefPositionX(?el, ?x0) ∧ seRefPositionY(?el, ?y0) ∧ swrlb:subtract(?x, ?x1, ?x0) ∧ swrlb:subtract(?y, ?y1, ?y0) ∧ swrlb:pow(?xs, ?x, 2) ∧ swrlb:pow(?ys, ?y, 2) ∧ swrlb:add(?lens, ?xs, ?ys) ∧ swrlb:pow(?len, ?lens, 0.5) ∧ seRadius(?el, ?rad) ∧ swrlb:lessThanOrEqual(?len, ?rad) ∧ hasSpectrumAccessMode(?el, secondary) ∧ seminfreq(?el, ?minfreq) ∧ semaxfreq(?el, ?maxfreq) ∧ hasPrimaryDetectionMeans(?el, ?pdetec) ∧ detectionSensingLimitdBm(?el, ?senseLimitdBm) → sqwrl:select(?el, ?minfreq, ?maxfreq, ?pdetec, ?senseLimitdBm)	
Rule 3	For this network position, provide equal rights access spectrum elements (and show spectrum element number and minimum and maximum frequency).	RadioNetwork(?r) ∧ rnPosX(?r, ?x1) ∧ rnPosY(?r, ?y1) ∧ SpectrumElement(?el) ∧ seRefPositionX(?el, ?x0) ∧ seRefPositionY(?el, ?y0) ∧ swrlb:subtract(?x, ?x1, ?x0) ∧ swrlb:subtract(?y, ?y1, ?y0) ∧ swrlb:pow(?xs, ?x, 2) ∧ swrlb:pow(?ys, ?y, 2) ∧ swrlb:add(?lens, ?xs, ?ys) ∧ swrlb:pow(?len, ?lens, 0.5) ∧ seRadius(?el, ?rad) ∧ swrlb:lessThanOrEqual(?len, ?rad) ∧ hasSpectrumAccessMode(?el, equalpriority) ∧ seminfreq(?el, ?minfreq) ∧ semaxfreq(?el, ?maxfreq) → sqwrl:select(?el, ?minfreq, ?maxfreq)	

Table 3-2: Query results and reasoning lead times.

Rule #	SQWRL query result	Time to complete the reasoning, 1st time	Time to complete the reasoning, 2nd time	Comment
Rule 1	el, minfreq, maxfreq :se1, "1000"^^xsd:int, "1100"^^xsd:int	2902 milliseconds	530 milliseconds	The first rule / query executed takes prolonged time
Rule 2	el, minfreq, maxfreq, pdetec, senseLimitdBm :se4, "14000"^^xsd:int, "16000"^^xsd:int, :detectionSensing, "-100"^^xsd:int :se3, "12000"^^xsd:int, "14000"^^xsd:int, :detectionSensing, "-100"^^xsd:int	561 milliseconds	546 milliseconds	
Rule 3	el, minfreq, maxfreq :se21, "20000"^^xsd:int, "30000"^^xsd:int	499 milliseconds	531 milliseconds	

4 CONCLUSIONS

The first part of this paper has provided a summary of important literature, as well as an overview of remaining challenges, in the field of policy-based spectrum management, particularly for military use. In summing up the status and challenges, it is noted that:

- The standardization of an ontology and policy language for such policy-based spectrum management is underway through the IEEE 1900.5.1 work, and this is also expected to be the policy language standard for military spectrum management. Much of the research found in the literature proposes to use OWL with the rule extensions. As exemplified also in the last part of this paper, this provides the benefits of being able to exploit mature standards and general tools.

- A reference ontology named the Cognitive Radio Ontology (CRO) has been published by the Modeling Language for Mobility work group in Wireless Innovation Forum [33] and documented in [43], and there are also other examples in the literature.

- Reasoning performance is possibly the most critical issue with policy-based spectrum management. Published results demonstrate that reasoning time can be significant, particularly when compared to the reaction times needed in military spectrum-using equipment in challenged environments. Limiting the complexity of policies, and picking suitable knowledge representation languages with low complexity is one way of keeping the reasoning time at practical levels. Another way is using reasoners with domain-specific optimizations that have good practical performance for typical expected dynamic spectrum ontologies and policy sets.

- Policy-based spectrum management appears to not need drastic changes to spectrum management processes, only slight changes to the content of some of the steps. E.g. instead of single frequency assignments, policies may specify spectrum pools with access rules.

- The literature on general tools that are suited for the various policy-based spectrum management processes is limited. Further work on and availability of such tools is considered an important enabler for the introduction of policy-based spectrum management.

- The various processes related to policy-based radios and devices also open up new vulnerabilities, e.g. policy distribution threats (inability of distribution or distribution of wrong/misleading policies). Care must be taken to include measures that mitigate these vulnerabilities, e.g. robust authentication measures.

In the second part of the paper, a simple ontology with rules has been sketched out, and a case study has been carried out where this ontology has been defined in OWL using the tool Protégé, then populated with one radio network and 21 spectrum elements. Based on three different SWRL rules (exclusive use, secondary use and equal priority use), reasoning has been performed using the SQWRLTab tool and reasoning times have been logged. Although the ontology and the rules were quite simple, reasoning times in the order of 500 milliseconds, and up to nearly 3 seconds, were observed. The results are in the same range as results reported in the literature. This is far from the (sub-millisecond) response times desired from a dynamic spectrum radio, or from other spectrum users such as a jammer. The results suggest that care must be taken when choosing knowledge representation language wrt. expressivity, regarding how it affects run-time. Furthermore, in terms of reducing run-time, two different approaches warrant further study. One is to loosen the coupling between the dynamic spectrum engine and the policy reasoner, and thus control run time. E.g. the policy reasoner could provide spectrum opportunities as a continuous process, then the dynamic spectrum engine could do quick reactions based on the last set of opportunities. Another approach is tighter coupling, such as that used in SMT, where infeasible configurations are pruned away during the generation stage, before ever reaching the policy checking stage.

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