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Keywords: Cognitive Radio, Open Spectrum, Policy Description Language, Spectrum Navigation

Authors: Lars Berlemann[1], Stefan Mangold[2]

Affiliations: [1] Chair of Communication Networks, RWTH Aachen University
[2] Swisscom Innovations

Addresses: [1] Kopernikusstraße 16, D-52074 Aachen, Germany
[2] Berne, Switzerland

Telephone: [1] +49 241 80 27248

E-Mail: [1] ber@comnets.rwth-aachen.de
[2] stefan.mangold@swisscom.com

Policy-based Spectrum Navigation of Cognitive Radios in Open Spectrum

Lars Berlemann[1], Stefan Mangold[2]
[1]ComNets, RWTH Aachen University, Germany, ber@comnets.rwth-aachen.de
[2]Swisscom Innovations, Berne, Switzerland, stefan.mangold@swisscom.com

***Abstract*— Regulation of spectrum will undergo changes in the future. On the one hand, wireless communication significantly demands additional spectrum. On the other hand, many frequency bands are often under-utilized, because of inefficient spectrum allocations. Intelligent radios, so called cognitive radios, realize the dynamic usage of frequency bands on an opportunistic basis, by identifying and using the under-utilized spectrum. Such spectrum is therefore referred to as spectrum opportunity. Such a flexible spectrum usage requires regulation to realize the vision of an open spectrum. Policies which determine when spectrum is considered as opportunity and which define the possibilities of using these spectrum opportunities are to be specified. This paper introduces two approaches of different complexity that enable distributed QoS support in open spectrum. These algorithms are specified as policies in a machine understandable policy description language. This enables a reasoning, i.e., decision taking, of the cognitive radio about spectrum usage. Thereby not only a multitude of policies has to be combined but also measurements of local spectrum utilization and user/operator preferences are to be taken into account. Thus, the cognitive radio navigates through the dynamic varying opportunities of unused spectrum.**

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I. INTRODUCTION

Wireless Communication is requiring additional spectrum to satisfy the consumers' demand for high data rate applications. At the same time, many of these applications have increasing restrictions to spectrum access. The currently available unlicensed spectrum has reached its limit. A support of *Quality of Service (QoS)* is there impossible due to missing coordination of the multiple different radio systems operating in the same frequency band. The wireless communication market indicates that users and operators are not willing to pay high prices for spectrum access. Today, many frequency bands are often unused as for instance frequencies licensed for TV/radio broadcasts or military usage. The regulation authorities therefore rethink their licensing of spectrum and the regulation of spectrum access fundamentally to the advantage of the public welfare. The *End-To-End-Reconfigurability (E^2R)* [1], funded by the European Commission, and the DARPA *Next Generation Communication (XG)* Program, financed by the US-government, are working on flexible and dynamic spectrum usage and related impacts on spectrum regulation.

Flexible and dynamic spectrum usage requires an intelligent medium access, especially in the face of QoS support. The terms "cognitive" (as used in this paper) and "smart" radios are often used in the context of intelligent spectrum usage [2-4]. Radio systems that autonomously coordinate their usage of spectrum are also referred to as "spectrum agile radios" [5]. Unused spectrum is in the following referred to as spectrum opportunity. In this context, policies are required to restrict the dynamic spectrum usage of cognitive radios. A policy is a selection of facts specifying spectrum usage. These facts are interpreted through a reasoning instance, in this paper referred to as spectrum navigator. This paper targets at the description of spectrum sharing algorithms in a common description language for policies. A policy-adaptive cognitive radio is enabled that operates in considering a flexible amount of different policies. In the case of spectrum sharing, a common description facilitates a comparison and performance evaluation of the different algorithms existing in the research world.

This paper is outlined as follows: Spectrum navigation for opportunistic spectrum usage under consideration of dynamically exchangeable policies is described in Section II. Reasoning for combining multiple policies to a concrete spectrum usage is discussed in Section III. A policy framework including a *Extendable Markup Language* (XML) based policy description language, the DARPA XG policy language [6],[7] is thereafter introduced in Section IV. The regulatory constraints of using one of the U-NII frequency bands illustrate thereby the policy language. Two example algorithms that enable distributed QoS support in spectrum sharing scenarios are introduced and specified in the policy description language in Section V. The paper is concluded with a discussion on the success and difficulties of mapping the introduced spectrum sharing algorithms to a policy description language in Section VI.

II. FLEXIBLE SPECTRUM USAGE OF COGNITIVE RADIOS

Flexible spectrum usage is an essential aspect of the cognitive radio paradigm. It impacts regulation, especially in the context of spectrum sharing. In general, spectrum sharing has two dimensions: The hierarchical spectrum sharing and the spectrum sharing between equals. Hierarchical (or vertical) spectrum sharing refers a scenario where a secondary radio system operates in frequencies licensed to a primary communication system in causing no significant interference to it. The simultaneous operation of WiFi (IEEE 802.11) and WiMAX (IEEE 802.16) in the same frequency band is an example for spectrum sharing between equals (also referred to as horizontal spectrum sharing).

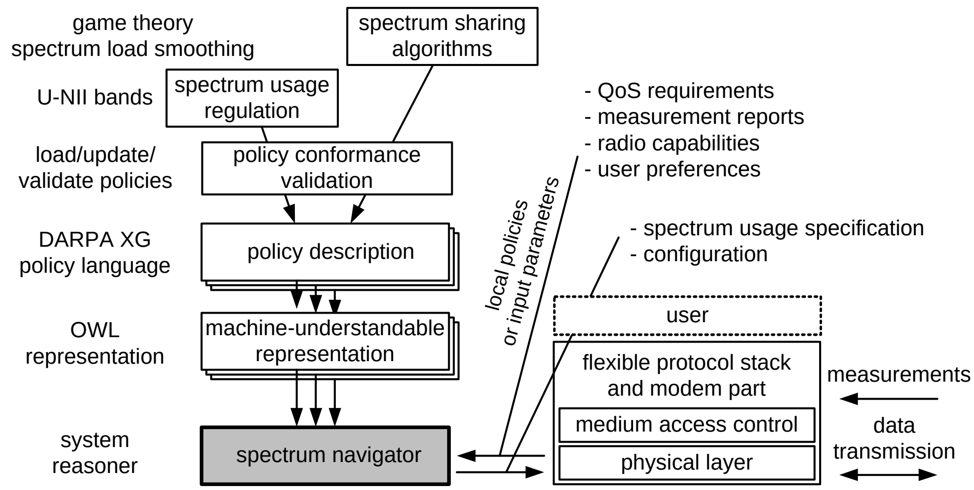


Figure 1. Flexible spectrum usage of a cognitive radio. A spectrum navigator takes multiple policies, spectrum usage measurements and additional restrictions into account, when deciding about spectum allocation.

A. Spectrum Navigatior

Cognitive radios have a flexible protocol stack and modem part which can be both dynamically adapted to the local communication environment. Additionally, a reconfiguration management is required to fulfill all re-configuration related functions. All functions concerning the opportunistic usage of frequency spectrum, i.e., realizing a cognitive medium access, are done by a spectrum navigator as introduced in Figure 1. This spectrum navigator is part of the reconfiguration plane (in case of a completely reconfigurable protocol stack and modem part as considered in the Integrated Project E^{2}R [1]) or located in an “open spectrum mode” (in case of a multi-mode capable radio of configurable modes, as for instance under discussion in the Integrated Project WINNER [1]). The decision about how to allocate which spectrum is taken by the spectrum navigator on the basis of policies.

The spectrum navigator identifies spectrum opportunities with the help of frequent measurements of the spectrum usage provided by the protocol stack. Additionally, the QoS requirements of the supported applications are taken into account together with preferences of the user as for instance transmission costs. The capabilities of a radio, as for example the frequency range that can be used for transmission, the available PHY modes, coding schemes, the number of transmission units etc. determine which spectrum the navigator selects. The reasoning of the spectrum navigator results into specification of the current spectrum usage and a corresponding configuration of the protocol stack as depicted in Figure 1.

B. Policy Based Spectrum Usage

Policy enabled spectrum usage is one of the key features of cognitive radios. The decision taking and learning of a cognitive radio is not limited to policies but has to take many additional factors into account, like radio capabilities and the environment (outside world). This imposes the need for a formal description framework. Initial steps towards a description language for cognitive radios have been introduced in [2] as an ontology of radio knowledge defined in the *Radio Knowledge Representation Language* (RKRL).

Policies have their origin in spectrum usage restrictions imposed by a regulating authority. Further policies may come from other policy makers to reflect for instance preferences of the user or operators. The specification of algorithms for enabling spectrum sharing is another important aspect for using policies. The policies might have a limited validity which depends on multiple factors as for instance the local time, the geographical location of the radio or the country where it is operating. A license holder may also impose policies for using its spectrum by a secondary radio system and the changing a user of a cognitive radio might influence the access privileges to spectrum as well. Thus, cognitive radios have to use policies in an adaptive way.

A well defined policy framework is required to enable such a cognitive radio capable of updating policies. This framework implies language constructs for specifying a policy, a machine-understandable representation of these policies and a reasoning instance, here called spectrum navigator, which decides about spectrum usage as further outlined in Section III. The policy conformance validation is responsible for downloading, updating and validating policies. The syntactical correctness of a policy that has been downloaded to the cognitive radio is verified. After conformance validation, the cognitive radio translates the policies to a machine-understandable language to enable computation through the spectrum navigator.

III. Reasoning for Combining Multiple Policies to Concrete Spectrum Usage [12]

The variety of diverse understandings of what “cognitive radio” refers to, often leads to confusion. The many promises of what can be achieved if cognitive radios are employed moreover lead to high expectations about the cognitive radio approach.

We therefore outline in this section the concept of reasoning as one of the core concepts for cognitive radio. This important aspect of cognitive radio is built on the DARPA XG vision [7]. A cognitive radio is aware of its environment. “Cognition” refers to an act of knowing, being aware, recognizing, judgment, and reasoning. Recent developments in the area of machine-learning, the semantic web, and machine-understandable knowledge representation, allow the efficient implementation of a cognitive radio in the form of a so-called reasoner, which is introduced above as spectrum navigator.

A. *Reasoning*

A reasoner makes the actual decisions on how to share spectrum. A reasoner is a software process that uses a logical system to infer formal conclusions from logical assertions. It is able to formally prove or falsify a hypothesis, and is capable of inferring additional knowledge. The so-called first order predicate logic is the simplest form of a logical system considered to be useful for such a reasoner. As a simple example, a reasoner may be fed with the knowledge (“all cognitive radio devices are capable of operating at frequencies below 3.5 GHz”). A statement (“white space at 2.0 GHz”) would enable this reasoner to infer (“spectrum usage permitted at 2.0 GHz”).

B. *Knowledge Representation*

However, inferring statements from other statements, as illustrated in the example, requires a structured and machine-understandable knowledge base for representing knowledge about radio communication. Such a knowledge base has to be constructed by human domain experts, before the machines will be able to interpret, consume, reuse, and eventually extend the knowledge. For this, semantics are needed to define truth and valuations: so-called radio semantics. To construct radio semantics is one of the key research problems to be solved. Knowledge must be represented in a machine-understandable way, using languages such as the *Web Ontology Language* (OWL). OWL is a rich language based on XML, that allows not only first-order logics, but also higher-order, class-based reasoning.

C. *Traceabiltiy of Decision-Making*

Regulation targets at fair and efficient spectrum usage. Therefore the way a cognitive radio makes decisions must be transparent, contrary to today’s algorithms for spectrum management. Current radio systems have vendor-specific solutions for spectrum management like power control and channel selection and are thus not traceable for the public and the regulation bodies. As a result, today’s standards and regulation have extreme restrictive parameters like power levels and frequency ranges for operation, to achieve a minimum level of coexistence, spectrum efficiency, and fairness in spectrum access. Due to the scarcity of free accessible spectrum on the one hand and frequently unused licensed spectrum on the other hand, spectrum regulation needs a fundamental rethinking towards less restricted spectrum usage. Cognitive radios realize such a weakly constrained radio resource management algorithms imposing the requirement of visibility. The entire algorithms for decision-making have to be visible to the outside world, and control mechanisms for regulators have to be developed.

The concepts discussed in this paper will provide supporting mechanisms for such a control, which relies on the application of a machine-understandable policy language.

IV. Policy Description Language

This section outlines the specification of policies with the help of a XML based description language at the example of the DARPA XG policy language [6].

As illustrated in Figure 2, a policy rule consists of three main elements: First, the selector description which is used to filter policies to a specific environment. This is related for instance to the policy issuing authority or the region where the policy is valid. Second, the opportunity description specifies under which conditions spectrum is considered as unused. A certain received power level of noise is a simple example for this. Third, the usage constraint description which specifies the behavior of the cognitive radio when using a spectrum opportunity. All values that are contained in a policy like frequencies, levels/thresholds or times are described as parameters based on *XML Schema Datatypes* (XSD). Processes enable the execution of functions with input and output parameters. Measurements of the spectrum usage done by the protocol stack of the cognitive radio are an example for such a process.

Policy Description 1 illustrates the usage of the policy language in specifying the regulatory restrictions of using the unlicensed frequency band at 5 GHz in the US, in having the following meanings:

- Line 1 - The selector description for the policy rules. Device and Frequency descriptions are below.
- Line 2 - U-NII Band of three frequency bands
- Line 3 - U-NII Band at 5.15-5.25 GHz
- Line 4 - Maximum transmission power: 40 mW
- Line 5 - Usage description of limiting `MaxTransmitPower` to `TransmitLimit`
- Line 6 - Policy for using the U-NII Band at 5.15-5.25 GHz when it is regarded as opportunity described in `BandUnused`.

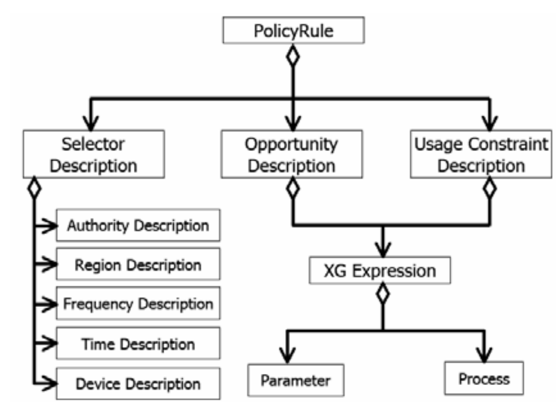


Figure 2. UML Structure of policies in the DARPA XG Policiy Language [6].

Policy Description 1. Policies for using the U-NII Band at 5.15-5.25 GHz expressed in shorthand notation of the DARPA XG policy language [6]

1	`(SelDesc (id S1)`
	`(authDesc US-FCC)`
	`(freqDesc U-NII US)`
	`(regnDesc US)`
	`(timeDesc Forever)`
	`(devcDesc CognitiveRadio_Class1))`

2	`(freqDesc U-NII US` `(frequencyRanges U-NII 1 U-NII 2 UNII 3))`

3	`(freqDesc (id U-NII 1)`
	`(minValue 5.15)`
	`(maxValue 5.25)`
	`(unit GHz))`

4	`(Power (id TransmitLimit)` `(magnitude 40.0) (unit mW))`

5	`(UseDesc (id LimitTransmitPower)`
	`(xgx “(<=`
	`MaxTransmitPower TransmitLimit)”))`

6	`(PolicyRule (id P1) (selDesc S1)`
	`(deny FALSE) (oppDesc BandUnused)`
	`(useDesc LimitTransmitPower))`

Additionally, the capabilities of a device need to be specified as it is shown in Policy Description 2, Line 2.

V. Spectrum Sharing Algorithms as Policies

In the following two decentralized approaches are introduced which allow cognitive radios to support QoS in spectrum sharing scenarios: The idea of Spectrum Load Smoothing (SLS) [8],[9] on the one hand and the application of solution concepts derived from Game Theory [10],[11] on the other hand.

A. *Spectrum Load Smoothing*

The application of waterfilling in time domain enables a decentralized and coordinated, opportunistic usage of the spectrum as depicted in Figure 3. This is referred to as *Spectrum Load Smoothing* (SLS). With SLS, competing radio systems aim simultaneously at an equal utilization of the spectrum. In observing the past usage of the radio resource, the radio systems interact and redistribute their allocations of the spectrum under consideration of their individual QoS requirements. Due to the principle of SLS these allocations are redistributed to less utilized or unallocated spectrum. QoS requirements of the coexisting networks are considered. Further, SLS allows an optimized usage of the available spectrum: An operation in radio spectrum, which was originally licensed for other communication systems, is facilitated, as the SLS implicitly achieves usage of unused spectrum and its release in case it is needed again.

The SLS realizes a distributed coordination of spectrum usage and identifies unused spectrum, i.e., spectrum opportunities.

1) *Aspects Relevant to Description as Policy*

A periodic frame-based MAC protocol is the basis for coordination and interaction. A frame is composed out of time slots, i.e., detected spectrum opportunities, as depicted in Figure 3 for the combined frequencies of 5.26 and 5.28 GHz. In a distributed environment, the slot length can for instance be identified with the help of the autocorrelation function of the observed allocations, in case these are

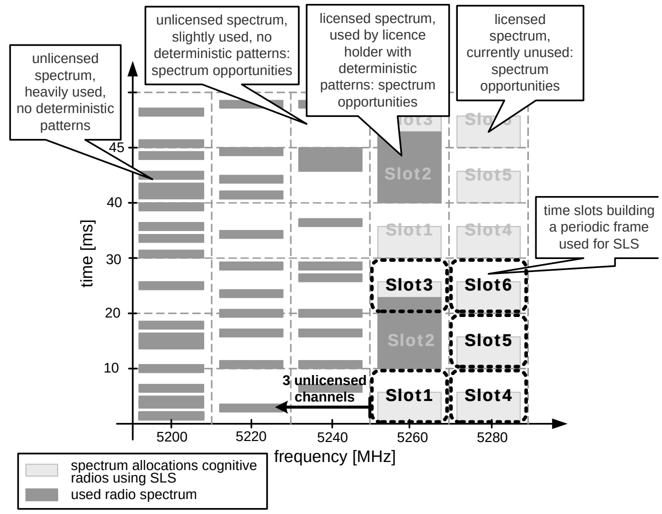


Figure 3. Spectrum usage example at 5 GHz. The dark gray fields indicate used spectrum. Cognitive radios use SLS to identify and allocate spectrum opportunities (light gray indication).

deterministic. The SLS aims at getting an equalized - smoothed - overall utilization of the time slots. In Policy Description 2 of the SLS this smoothed level of utilization is referred to as `SLSLoadLevel` and calculated with the process `SLSCalcLoadLevel`. To enable a convergence in mutual interaction, the SLS is then done step-wise from frame to frame in redistributing a limited amount of allocations from the previous frame. The amount of allocations per frame considered for redistribution through SLS is called `SLSamount`. The access order for the cognitive radios to each slot is given by the order of the devices' initial transmission within the considered coverage area (`DevicesBefore`). Thus a spectrum opportunity corresponding to the SLS is identified in two steps: First the slotted frame structure is defined (`ObserveSlots`) and second the usage, i.e., load, of each slot is observed (`ObserveSlots`) from frame to frame. The decision about allocation of slots within a frame is done simultaneous by all cognitive radios using SLS at the beginning/and of a frame.

2) *SLS asPolicy*

In detail, Policy Description 2 expresses the SLS in the shorthand notation of the DARPA XG policy language.

- Line 1 - The policy `SLS` specifies the usage of spectrum opportunities described in `TimeSlotsForSLS` corresponding to the usage description `SLS2Slots`
- Line 2 - Definition of the parameters (`hasPolicyDefinedParams`) and processes (`hasPolicyDefinedBehaviors`) a cognitive radio has to support in order to use the `SLS` policy. The parameters are differed into (i.) parameters used for observation to detect and specify spectrum opportunities and (ii.) parameters used for specifying the allocation of the time slots as usage description resulting from the `SLS` policy. The processes `ObserveSlots` and `ObserveSlotStructure` are used in the opportunity descriptions. `SLScutAllocations`

and `SLSCalcLoadLevel` are used in the usage description `SLS2Slots`

- Line 3 - These definitions specify the frame structure and the access order for the cognitive radio. These parameters originally result from `ObserveSlotStructure` which is left away here. `Observation.SlotsUsedForSLS` is a multifield variable containing the slots used for SLS
- Line 4 - Opportunity description `TimeSlotsForSLS`: The slots used for SLS are observed within a frame with the `ObserveSlots` process. The list of time slots is input parameter and the observed load for each slot is the output parameter of this process
- Line 5 - Declaration of a set of parameters. The `SlotLoad` variables consist of entries for each slot
- Line 6 - Usage description of the SLS. The allocations to be distributed in this step (the amount is defined by `Allocation.SLSamount` are determined with `SLScutAllocations`. Thereafter, the load level `Allocation.SLSLoadLevel` is calculated and the `AccessDuration` for each slot is determined together with the order for accessing each slot

B. *Application of Game Theory*

The competition between independent radio systems for allocating a common shared radio channel can be modeled as a stage-based game model: Players, each representing radio systems, interact repeatedly in radio resource sharing games, without direct coordination or information exchange. Solution concepts derived from game theory allow the analysis of such models under the microeconomic aspects of welfare. Decisions that the players repeatedly have to make are about when and how often to attempt a medium access. In multi-stage games, players apply strategies in order to maximize their observed utility as summarizing value for successful supported QoS. Strategies determine whether competing radio networks cooperate or ignore the presence of other radio networks. The requirements of the players determine which strategies guarantee QoS.

The application of game theory in spectrum sharing scenarios enables a distributed coordination of multiple cognitive radios sharing the same spectrum opportunity. The identification of a spectrum opportunity is to be done in applying additional policies.

1) *Aspects Relevant to Description as Policy*

This section introduces the aspects of our application of game theory that are to be considered in the context of policies. For a tutorial like description, the reader is referred to [10].

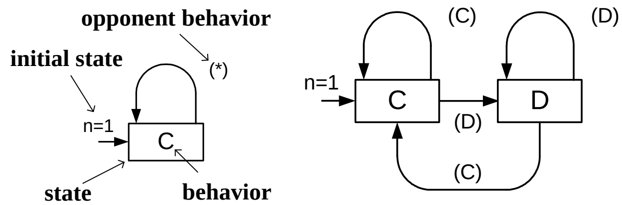
The players, each representing a cognitive radio, interact repeatedly by selecting their own behavior (= a selection of MAC parameters) in so called *Single Stage Games* (SSGs). For the sake of simplicity the behaviors of a player are limited here to cooperation and defection. After each stage of the game the players estimate their opponent's behavior. The estimated behavior of the opponent has to be classified in taking its intention into account. This classification is necessary, as there is no communication between the dissimilar radio systems, i.e., the players, which hinders direct negotiations. Nevertheless, players are aware of their influence on the opponent's utility, which enables interaction on basis of punishment and cooperation. The behavior in a SSG can be regarded as a handpicked allocation of the radio resource aiming at a specific intention. A punishment is realized in choosing the behavior of defection with its utility maximizing best response action. Strategies determine the players' interaction within a *Multi Stage Game* (MSG). Thus, the capability to guarantee QoS depends on the chosen strategy as evaluated in [10]. Strategies can be modeled as state machines as illustrated in Figure 4 at the example of the TitForTat strategy.

Policy Description 2. Spectrum Load Smoothing expressed in shorthand notation of the DARPA XG policy language [6]

```
1  (PolicyRule (id SLS) (selDesc S1)
   (deny FALSE) (oppDesc TimeSlotsForSLS)
   (useDesc SLS2Slots))
2  (DeviceCap (id SLSProfile)
   (hasPolicyDefinedParams
     Observation.SlotLoad
     Observation.SlotsUsedForSLS
     Observation.DevicesBefore
     Allocation.SlotLoad
     Allocation.SLSamount
     Allocation.SLSLoadLevel)
   (hasPolicyDefinedBehaviors
     ObserveSlotStructure ObserveSlots
     SLScutAllocations SLSCalcLoadLevel))
3  (SlotDesc (id Observation.SlotsUsedForSLS)
     (TimeInterval Slot1 Slot3 Slot4 Slot5
   Slot6))
   (TimeDuration (id FrameDuration)
   (magnitude 50) (unit msec))
   (Num (id Observation.DevicesBefore)
     (magnitude 3) (unit NONE))
4  (OppDesc (id TimeSlotsForSLS)
   (xgx "(invoke
     (within FrameDuration) ObserveSlots
     SlotsUsedForSLS
     TimeDuration Observation.SlotLoad)"))
5  (TimeDuration (id Observation.SlotLoad)
                 (unit msec))
   (TimeDuration (id Allocation.SlotLoad)
                 (unit msec))
   (SLSamount (id Allocation.SLSamount)
              (unit Percent)
   (TimeDuration (id Allocation.SLSLoadLevel)
                 (unit usec))
6  (useDesc (id SLS2Slots) (xgx "( and
   (invoke SLScutAllocations
     Allocation.SLSamount
     Observation.SlotLoad
     TimeDuration Allocation.SlotLoad)
   (invoke SLScalcLoadLevel
     Allocation.SLSamount
     Allocation.SlotLoad
     TimeDuration Allocation.SLSLoadLevel)
   (:= AccessDuration
   (- Allocation.SLSLoadLevel
   Allocation.SlotLoad)
   (:= AccessOrder
   (+ Observation.DevicesBefore 1))"))
```

2) *The Mapping from Game Theory Notation to a Policy Language*

Policy Description 3 expresses the TitForTat strategy from our game theory approach as defined in Figure 4 in the



(a) definitions (b) trigger strategy TitForTat

Figure 4. Modeling strategies as state machines.

shorthand notation of the DARPA XG policy language. The strategy of a player is realized as a group `PolicyGrp` of policies `PolicyRule`. The player's behavior is specified as usage description `UsageDesc`. The duration of a single stage game is defined in using the parameter type `TimeDuration`. During the SSG, the players observe their allocations and classify based thereon, whether the opponent is cooperating or not. This characterizes the corresponding spectrum opportunity as cooperative or defective environment. Corresponding to the TitForTat strategy, the cognitive radio cooperates in the case of a cooperating opponent and defects if the opponent is defecting. An action of a player consists of a pair of demanded QoS parameters $(\Theta_{dem},\Delta_{dem})$. In detail the lines of Policy Description 3 have the following meaning:

- Line 1 - The strategy TitForTat consists of two policy rules: `TFTCooperate` (line 1) and `TFTDefect` (line 2)
- Line 2 - For operation matching selector `S1` (defined above), in case of an cooperating opponent, i.e., the opportunity is regarded as `CooperativeEnvironment` (line 6), the player cooperates following the usage description `Cooperate` (line 9)
- Line 3 - For operation matching selector `S1` (defined above), in case of an cooperating opponent, i.e., the opportunity is regarded as `DefectiveEnvironment` (line 7), the player defects following the usage description `Defect` (line 8)
- Line 4 - A stage has the duration of 100 msec
- Line 5 - Parameter to indicate if opponent is cooperating
- Line 6 - This `CooperativeEnvironment` opportunity description has three tests: 1) the process `ObserveStage` observes during a stage all allocations and has the observed QoS of a player and its opponent as output parameter. 2) The process `ClassifyBehavior` invoked at the end of a stage determines based on the observation the players' QoS of the last stage. The process decides about the opponent's behavior contained in the Boolean variable `OpponentCooperating` as output. 3) the opponent cooperates if `OpponentCooperating` = TRUE
- Line 7 - This `DefectiveEnvironment` opportunity description has three tests: 1) the process `ObserveStage` observes during a stage all allocations and has the observed QoS of a player and its opponent as output parameter. 2) The process `ClassifyBehavior` invoked at the end of a stage determines based on the observation the players' QoS of the last stage. The process decides about the opponent's behavior contained in the Boolean variable `OpponentCooperating` as output. 3) the opponent defects if `OpponentCooperating` = FALSE
- Line 8 - Behavior of defection resulting to a concrete action: Best response to the expected opponent's action `oppAction` to optimize own utility
- Line 9 - Behavior of cooperation resulting to a concrete action: Reduce the period length Δ_{dem} to Δ_{min} and demand the required throughput $\Theta_{dem}=\Theta_{req}$

Policy Description 3. TitForTat Strategy expressed in shorthand notation of the DARPA XG policy language [6]

```
1 (PolicyGrp (id StrategyTitForTat)
  (equalPrecedence TRUE)
  (polMembers TFTCooperate TFTDefect))
2 (PolicyRule (id TFTCooperate) (selDesc S1)
  (deny FALSE)
  (oppDesc CooperativeEnvironment)
  (useDesc Cooperate))
3 (PolicyRule (id TFTDefect) (selDesc S1)
  (deny FALSE) (oppDesc DefectiveEnvironment)
  (useDesc Defect))
4 (TimeDuration (id STAGE)
  (magnitude 100) (unit msec))
5 (Boolean (id OpponentCooperating))
6 (OppDesc (id CooperativeEnvironment)
  (xgx "(and
  (invoke (within STAGE) ObserveStage
   ObsParam Observation.ownQoS
   ObsParam Observation.oppQoS)
  (invoke (at-end-of STAGE)
   ClassifyBehavior
   Observation.ownQoS
   Observation.oppQoS
   OppCoop OpponentCooperating)
  (eq OpponentCooperating BoolTrue))"))
7 (OppDesc (id DefectiveEnvironment)
  (xgx "(and
  (invoke (within STAGE) ObserveStage
   ObsParam Observation.ownQoS
  ObsParam Observation.oppQoS)
  (invoke (at-end-of STAGE)
   ClassifyBehavior
   Observation.ownQoS
   Observation.oppQoS
   OppCoop OpponentCooperating)
  (eq OpponentCooperating BoolFalse))"))
8 (useDesc (id Defect) (xgx "(and
  (:= Theta dem BestResponse(oppAction))
  (:= Delta dem BestResponse(oppAction)))))
9 (useDesc (id Cooperate) (xgx "( and
  (:= Theta dem Theta req)
  (:= Delta dem Delta min)))
```

VI. OUTLOOK

The description of spectrum sharing algorithms is one of the most complex tasks to be enabled by a policy language. The mapping of two different spectrum sharing algorithms to a policy description language is successfully done in this paper. The distinction into spectrum opportunity and usage constrain facilitates a hierarchical structuring of the algorithm's policy description. In this paper, the original usage of the XG Policy Language for limiting spectrum usage is extended with the aspect of specifying concrete spectrum access.

This paper indicates limitations of the current, public available, version of the XG Policy Language Framework: Multifield operations (as need for instance here for defining the SLS time slots) are not specified so far and our specification of spectrum sharing algorithms indicated the need for a focus on the measurement/sensing of spectrum for identifying spectrum opportunities. Further, an enhancement of the XG Policy Language is suggested to take user-preferences and device capabilities into account, when deciding about spectrum access.

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