Policy Defined Spectrum Sharing and Medium Access for Cognitive Radios

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***Abstract*— Spectrum regulation will undergo elementary changes in the near future allowing a less restricted and more flexible access to radio spectrum. Intelligent radios, so-called cognitive radios, will realize the dynamic usage of frequency bands on an opportunistic basis, by identifying and using under-utilized spectrum. Such a flexible spectrum usage requires changes in regulation towards a more open spectrum. Policies which determine when spectrum is considered as opportunity and which define the possibilities of using these spectrum opportunities are needed. First, this article discusses an approach that intends to enable distributed QoS support in open spectrum. This algorithm is specified as policy in a machine-understandable policy description language, such that the cognitive radio is capable of reasoning about spectrum usage. Policies that enable a software defined medium access are the second focus of this article. We discuss a step towards the realization of such cognitive radios at the example of the well-known Enhanced Distributed Channel Access of IEEE 802.11e. This channel access protocol is here specified in a machine understandable policy language, instead of lengthy textual description. Such a machine-understandable description of the protocol enables cognitive radios to operate in distributed environments according to the 802.11(e) standard.**

***Index Terms*— Cognitive Radio Networks, EDCA, IEEE 802.11e, Policy Description Language, Spectrum Navigation**

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 is reaching its limit. A support of *Quality-of-Service* (QoS) is difficult because of the missing coordination between the different radio systems operating in the same frequency band. Today, many frequency bands are often unused as for instance frequencies licensed for TV/radio broadcasts or public safety services. The regulation authorities therefore are rethinking their way of spectrum licensing and the regulation of spectrum access. The U.S. DARPA *Next Generation Communication* (XG) Program [1] and the *6th Framework research funding Program* (FP6) [2] of the European Union 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 article) and "smart" radios are often used in the context of intelligent spectrum usage [3]-[6]. Spectrum utilization and the coverage area can be increased, when cognitive radios organize themselves forming a meshed wireless backbone network of infrastructure links. 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 article referred to as spectrum navigator. The spectrum navigator is able to consider a flexible amount of different policies realizing a policy-adaptive cognitive radio. This article has two targets: First, the description of a spectrum sharing algorithm in a common description language for policies. Such a common description of different spectrum sharing algorithms developed in the research world facilitates their comparison and performance evaluation. And second, the description of the underlying MAC protocol, here the *Enhanced Distributed Channel Access* (EDCA) of IEEE 802.11e [8][9] in the same description language for policies.

This article is outlined as follows: Spectrum navigation for flexible spectrum usage of cognitive radios is described in Section II. A policy framework including an *Extendable Markup Language* (XML) based policy description language, the DARPA XG policy language [16][17], is thereafter introduced in Section 0. An example algorithm that enables distributed QoS support in spectrum sharing scenarios is introduced and specified

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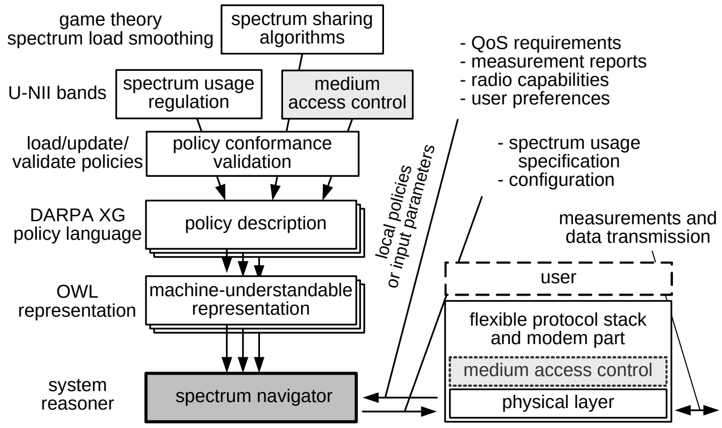

Figure 1. Flexible spectrum usage by a cognitive radio.

in the policy description language in Section IV. The EDCA of IEEE 802.11e is specified in the policy description language in Section V. This article is concluded with a discussion on the success and difficulties of mapping the introduced spectrum sharing algorithm and the EDCA to a policy description language in Section VI.

The introduced example algorithm for spectrum sharing is the application of solution concepts derived from game theory. This game theory based approach is described in [10] and simulation results are given in [11]-[13]. A second approach, namely the Spectrum Load Smoothing, is specified in [15] but is here left away. We continue our work initiated in [14] and [15] in extending the scope of policies from spectrum sharing on the software defined medium access control.

II. Flexible Spectrum Usage by Cognitive Radios

Flexible spectrum usage is an essential aspect of the cognitive radio paradigm. It impacts regulation, especially in the context of spectrum sharing. Spectrum not used by the license holding communication system is individually regarded by all cognitive radios as spectrum opportunity. Its usage by theses cognitive radios requires therefore mutual coordination to enable QoS support in such a distributed environment.

A. Spectrum Navigation

Cognitive radios have a flexible protocol stack and modem part which can be both dynamically adapted to the local communication environment. All functions concerning the opportunistic usage of frequency spectrum, i.e., realizing a cognitive medium access, are done by a spectrum navigator as illustrated in Figure 1. The spectrum navigator is part of the management plane. It decides about how to allocate which spectrum 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 as for instance under standardization in IEEE 802.11k [18]-[20]. There, means are developed for measurement, reporting, estimation and identification of the current spectrum usage in the ISM bands. 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. Policies originally 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. Additionally, less complex medium access procedures can be defined with the help of policies in the same policy language. This realizes a software defined and flexible medium access control for cognitive radios.

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. 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 below. 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.

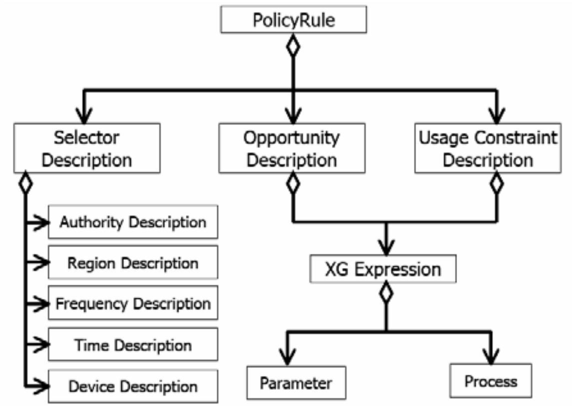

Figure 2. UML Structure of policies in the DARPA XG Policy Language [16].

III. Policy Description Language

We introduce in this section the specification of spectrum policies with the help of a XML based description language, here at the example of the DARPA XG policy language

As illustrated in Figure 2, a policy rule consists of three main elements [16]: First, the *selector description* that is used to filter policies to a specific environment. The policy issuing authority or the region where the policy is valid is considered in this way. Second, the *opportunity description* that specifies the conditions when spectrum is regarded as unused. A certain power level of received noise/interference is a simple example for this. And third, the *usage constraint description* that specifies the behavior of a cognitive radio when using a spectrum opportunity. All values that are contained in a policy are described as *parameters* based on *XML Schema Datatypes* (XSD) [21]. Specific frequencies, power levels, thresholds or times are an example for these values. *Processes* with input and output parameters enable the execution of functions. Measurements of the spectrum usage done by the protocol stack of the cognitive radio are an example for a process used by a policy.

Policy Description 1 illustrates the application of the policy language at the example of the regulatory restrictions for using the *Unlicensed National Information Infrastructure* (U-NII) frequency band at 5 GHz in the US: An IEEE 802.11 WLAN device limits its transmission power to 40 mW when using a frequency channel in the 5 GHz band. Concrete, the lines have the following meaning:

- Line 1 - The selector description `802.11_5GHz_US` for a device named `802.11device`. The issuing authority is the FCC (`authDesc`). The usage of the U-NII frequency band is described (`freqDesc`). The policy's validity is limited to the US (`regnDesc`) and is not restricted to any period of time (`timeDesc`).
- Line 2 - The device `802.11device` is described: It has the type `WLAN_Class1` and has capabilities according to `WLAN_Profile1`

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.

```
1   (SelDesc (id 802.11_5GHz_US)
     (authDesc US-FCC)
     (freqDesc U-NII_US)
     (regnDesc US)
     (timeDesc Forever)
     (devcDesc 802.11device))
2   (DeviceDesc (id 802.11device)
     (deviceTyp WLAN_Class1)
     (deviceCap WLAN_Profile1))
3   (DeviceTyp (id WLAN_Class1))
4   (DeviceCap (id WLAN_Profile1)
     (hasPolicyDefinedParams
       MaxTransmitPower))
5   (FreqDesc U-NII_US
    (frequencyRanges
      U-NII_1 U-NII_2 UNII_3))
6   (FrequencyRange (id U-NII_1)
     (minValue 5.15)
     (maxValue 5.25)
     (unit GHz))
7   (Power (id TransmitLimit)
     (magnitude 40.0) (unit mW))
8   (Power (id MaxTransmitPower)
     (boundBy Device) (unit mW))
9   (UseDesc (id LimitTransmitPower)
     (xgx "(<= MaxTransmitPower
                 TransmitLimit)"))
10  (PolicyRule (id P1)
     (selDesc 802.11_5GHz_US)
     (deny FALSE) (oppDesc BandUnused)
     (useDesc LimitTransmitPower))
```

- Line 3 - The device type `WLAN_Class1`: Its meaning is defined by a regulation authority
- Line 4 - The device's capabilities are defined in `WLAN_Profile1`. The device has to understand and has to provide the parameter `MaxTransmitPower` for computation in policies
- Line 5 - U-NII Band consisting of three frequency bands is described
- Line 6 - The U-NII Band at 5.15-5.25 GHz is specified
- Line 7 - A limit for the transmission power `TransmitLimit` is defined to 40 mW
- Line 8 - `MaxTransmitPower` is declared and bound to a value provided by the protocol stack of the 802.11 device
- Line 9 - Usage description of limiting `MaxTransmitPower` to `TransmitLimit`. `xgx` specifies an XG expression based on parameters that are known to the cognitive radio. It is able to provide values for these parameters
- Line 10 - Policy for using the U-NII band at 5.15-5.25 GHz in case it is regarded as opportunity according to `BandUnused`

The opportunity description `BandUnused` and the frequency band descriptions `U-NII_2` and `U-NII_3` are not defined here.

In the following, an approach to distributed spectrum sharing is introduced and specified in the DARPA XG

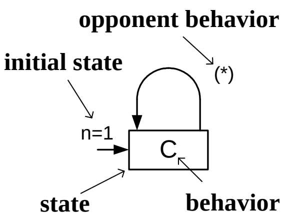

Figure 3. Modeling strategies as state machines [22].

policy language. The approach allows cognitive radios to support QoS when sharing spectrum opportunities.

IV. Application of Game Theory as Policy

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 and is not part of this game theory based approach.

A. Aspects Relevant to Description as Policy

This section discusses 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

Policy Description 2. Game parameters and the behaviors of a players expressed in shorthand notation of the DARPA XG policy language.

```
1  (DeviceCap (id GameTheoryProfile)
   (hasPolicyDefinedParams
    STAGEduration
    Theta dem Delta min Theta req Delta dem)
   (hasPolicyDefinedBehaviors
     ObserveStage ClassifyBehavior
     BestResponse))
2  (TimeDuration (id STAGEduration)
   (boundBy Device) (unit msec))
3  (Boolean (id OpponentCooperating))
   (Boolean (id SelfCooperating))
4  (useDesc (id Defect) (xgx "(and
   (:= Theta dem BestResponse(oppAction))
   (:= Delta dem BestResponse(oppAction))
   (:= SelfCooperating BoolFalse)))
5  (useDesc (id Cooperate) (xgx "( and
   (:= Theta dem Theta req)
   (:= Delta dem Delta min)
   (:= SelfCooperating BoolTrue)))
```

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 [13]. Strategies can be modeled as state machines as illustrated in Figure 3: The state represents the behavior of the player, while the transition between states depends on the opponent's behavior.

B. Mapping from Game Theory Notation to the Policy Language

The transfer of the game theory notation is initiated in defining device capabilities, game parameters and the behavior of a player in Policy Description 2. The behavior, as handpicked allocation of the radio resource, is specified as usage description (`useDesc`). Thereafter the opponent's behavior is classified in order to characterize the spectrum opportunity of the next stage. In taking the own behavior of the present stage into account, every permutation of the players' behavior (here in total four) leads to a dedicated opportunity description (`OppDesc`) as demonstrated in Policy Description 3. Simple static strategies can be defined as `PolicyRule` which is demonstrated in Policy Description 4. Complex strategies, which take the behavior of the opponent into account, are realized as a group `PolicyGrp` of policy rules `PolicyRule`. Thereby each state transition of the strategies' state machine is reflected by a policy rule, defining the reaction of a player on the opponent's behavior in taking the own behavior into account. This is illustrated in comparing two dynamic trigger strategies specified in Policy Description 5 and Policy Description 6 and depicted in Figure 5 and Figure 6.

1) Behaviors as Policies

Policy Description 2 defines device capabilities and describes game parameters and the behavior of a player:

- Line 1 - The capability description of parameters and processes a cognitive radio has to provide in order to apply game theory based policies. They are used in the following policy descriptions
- Line 2 - The duration of a SSG is provided by the cognitive radio, typically it has a duration of 100 msec

Policy Description 3. The classification of the opponent’s behavior expressed in shorthand notation of the DARPA XG policy language.

```
1  (OppDesc (id OwnCoop OpponentCoop)
   (xgx “(and
   (invoke (within STAGE) ObserveStage
    ObsParam Observation.ownQoS
    ObsParam Observation.oppQoS)
   (invoke (at-end-of STAGE)
    ClassifyBehavior
    Observation.ownQoS
    Observation.oppQoS
    OpponentCoop OpponentCooperating)
  (and (eq OpponentCooperating BoolTrue)
     (eq SelfCooperating BoolTrue)”))
2  (OppDesc (id OwnDef OpponentCoop)
   (xgx “(and
   (invoke (within STAGE) ObserveStage
    ObsParam Observation.ownQoS
    ObsParam Observation.oppQoS)
   (invoke (at-end-of STAGE)
    ClassifyBehavior
    Observation.ownQoS
    Observation.oppQoS
    OpponentCoop OpponentCooperating)
  (and (eq OpponentCooperating BoolTrue)
     (eq SelfCooperating BoolFalse))”))
3  (OppDesc (id OwnCoop OpponentDef)
   (xgx “(and
   (invoke (within STAGE) ObserveStage
    ObsParam Observation.ownQoS
   ObsParam Observation.oppQoS)
   (invoke (at-end-of STAGE)
    ClassifyBehavior
    Observation.ownQoS
    Observation.oppQoS
    OppCoop OpponentCooperating)
  (and (eq OpponentCooperating BoolFalse)
     (eq SelfCooperating BoolTrue))”))
4  (OppDesc (id OwnDef OpponentDef)
   (xgx “(and
   (invoke (within STAGE) ObserveStage
    ObsParam Observation.ownQoS
   ObsParam Observation.oppQoS)
   (invoke (at-end-of STAGE)
    ClassifyBehavior
    Observation.ownQoS
    Observation.oppQoS
    OppCoop OpponentCooperating)
  (and (eq OpponentCooperating BoolFalse)
     (eq SelfCooperating BoolFalse))”))
```

- Line 3 - Parameters to indicate if an opponent is cooperating and for storing the player’s own behavior of the present stage
- Line 4 - The behavior of defection as usage description resulting to a concrete action: Best response to the expected opponent’s action `oppAction` to optimize the own utility defined in the process `BestResponse`. This process is not defined here
- Line 5 - The behavior of cooperation as usage description resulting into a concrete action: Reduction of the period length Δ_{dem} to Δ_{min} and demanding the required throughput $\Theta_{dem} = \Theta_{req}$. Note that these parameters specify a dedicated allocation pattern for one stage [11] and are to be provided by the cognitive radio similar to `MaxTransmitPower` in Policy Description 1, line 8

Policy Description 3 introduces the classification of the opponent’s behavior.

- Line 1 - This `OwnCoop_OpponentCoop` opportunity description has three tests: 1) The process `ObserveStage` observes all allocations during a stage and has the observed QoS of a player and of its opponent as output parameter. 2) The process `ClassifyBehavior`, invoked at the end of a stage, determines the players’ QoS of the last stage in observing spectrum usage. The process decides about the opponent’s behavior contained as output in the Boolean variable `OpponentCooperating`. 3) The opponent cooperates (`OpponentCooperating = TRUE`) and player self is coopering in the considered stage (`SelfCooperating = TRUE`). In case all these tests are met the player concludes that both players were cooperating and regards the spectrum opportunity as `OwnCoop_OpponentCoop`
- Line 2 - The `OwnDef_OpponentCoop` opportunity description is similar to the `OwnCoop_OpponentCoop` description, besides the last of the three tests: The player self is defecting in the considered stage `SelfCooperating = FALSE`. In case all tests are met the player concludes that she was defecting while the opponent was cooperating
- Line 3 - This `OwnCoop_OpponentDef` opportunity description has three tests: 1) The process `ObserveStage` observes during a stage all allocations and has the observed QoS of a player and of its opponent as output parameter. 2) The process `ClassifyBehavior`, invoked at the end of a stage, determines the players’ QoS of the last stage in observing spectrum usage. The process decides about the opponent’s behavior contained as output in the Boolean variable `OpponentCooperating`. 3) The opponent defects if `OpponentCooperating = FALSE` and player self is coopering in the considered stage when `SelfCooperating = TRUE`. In case all three tests are met the player concludes that she was cooperating while the opponent was defecting.
- Line 4 - The `OwnDef_OpponentDef` opportunity description is similar to the `OwnCoop_OpponentDef` description, besides the last of the three tests: The player self was defecting in the considered stage `SelfCooperating = FALSE`. In case all tests are met the player concludes that both players were defecting

Policy Description 4. COOP and DEF strategy expressed in shorthand notation of the DARPA XG policy language.

```
1  (PolicyRule (id StrategyCOOP) (selDesc S1)
   (deny FALSE) (oppDesc AnyOpp)
   (useDesc Cooperate))
2  (PolicyRule (id StrategyDEF) (selDesc S1)
   (deny FALSE) (oppDesc AnyOpp)
   (useDesc Defect))
```

(a) COOP (b) DEF

Figure 4. The static strategies of permanent cooperation (a) and defection (b).

2) Static Strategies as Policies

Static strategies are the continuous application of one behavior without regarding the opponent’s strategy. In static strategies the state model contains one single state.

Policy Description 5. GRIM strategy expressed in shorthand notation of the DARPA XG policy language.

1	(PolicyGrp (id StrategyGRIM) (equalPrecedence TRUE) (polMembers GRIMCoop1 GRIMDefect1 GRIMDefect2 GRIMDefect3))
2	(PolicyRule (id GRIMCoop1) (selDesc S1) (deny FALSE) (oppDesc OwnCoop OpponentCoop) (useDesc Cooperate))
3	(PolicyRule (id GRIMDefect1) (selDesc S1) (deny FALSE) (oppDesc OwnCoop OpponentDef) (useDesc Defect))
4	(PolicyRule (id GRIMDefect2) (selDesc S1) (deny FALSE) (oppDesc OwnDef OpponentCoop) (useDesc **Defect**))
5	(PolicyRule (id GRIMDefect3) (selDesc S1) (deny FALSE) (oppDesc OwnDef OpponentDef) (useDesc Defect))

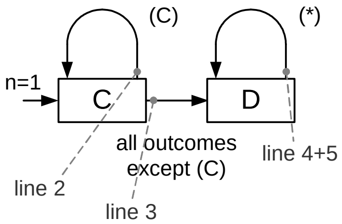

Figure 5. The trigger strategy GRIM, specified in Policy Description 5.

Policy Description 6. TitForTat strategy expressed in shorthand notation of the DARPA XG policy language.

1	(PolicyGrp (id StrategyTitForTat) (equalPrecedence TRUE) (polMembers TFTCoop1 TFTCoop2 TFTDefect1 TFTDefect2))
2	(PolicyRule (id TFTCoop1) (selDesc S1) (deny FALSE) (oppDesc OwnCoop OpponentCoop) (useDesc Cooperate))
3	(PolicyRule (id TFTDefect1) (selDesc S1) (deny FALSE) (oppDesc OwnCoop OpponentDef) (useDesc Defect))
4	(PolicyRule (id TFTCoop2) (selDesc S1) (deny FALSE) (oppDesc OwnDef OpponentCoop) (useDesc **Cooperate**))
5	(PolicyRule (id TFTDefect2) (selDesc S1) (deny FALSE) (oppDesc OwnDef OpponentDef) (useDesc Defect))

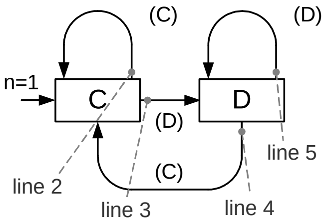

Figure 6. The trigger strategy TitForTat, specified in Policy Description 6.

In our approach, the set of avail-able static strategies is reduced to two: The *cooperation strategy* (COOP) is characterized through cooperating every time, independently from the opponent's influence on the player's utility. The COOP strategy is to the benefit of a player if the opponent cooperates as well. Figure 4(a) illustrates this simple strategy of following a cooperative (C) behavior, as specified in Policy Description 2. Equivalently to the COOP strategy, the *defection strategy* (DEF) consists of a permanently chosen behavior of defection (D). Figure 4(b) illustrates the DEF strategy as a state machine. The static strategies of permanent cooperation and defection are expressed in Policy Description 4 with the following meaning:

- Line 1 - The strategy COOP realized as a `PolicyRule` for the selector description `S1` defined in Policy Description 1. Independent from the opponent behavior, i.e., for any spectrum opportunity `AnyOpp`, the player cooperates. This is specified by the usage description `Cooperate`
- Line 2 - The strategy DEF realized as a `PolicyRule`. Independent from the opponent behavior, i.e., for any spectrum opportunity `AnyOpp`, the player cooperates. This is specified by the usage description `Defect`

3) Dynamic Trigger Strategies as Policies

A trigger strategy is a dynamic strategy where the transition from one state to another state is event-driven [22]: An observed event triggers a behavior change of a player. Depending on the number of states (the number of behaviors a player may select), a large number of trigger strategies is possible. For the sake of simplicity, the familiar *Grim* (GRIM) and *TitForTat* (TFT) trigger strategies are applied in the following. A player with a GRIM strategy punishes the opponent for a single deviation from cooperation with a defection forever. The initial state of the GRIM strategy, selected at the first stage of the MSG, is however the cooperation. The player cooperates as long as the opponent cooperates, and the transition to defection is triggered by the opponent's defection. See Figure 5 for an illustration of the state machine of the GRIM strategy. The TFT strategy selects cooperation as long as the opponent is cooperating, similar to the GRIM strategy, also with cooperation in the initial stage. An opponent's defection in stage N triggers a state transition and is punished by defection in the following stage $N+1$, as illustrated in Figure 6. However, in contrast to the GRIM strategy, TFT changes back to cooperative behavior as soon as the opponent is cooperating again.

Policy Description 5 expresses the GRIM strategy from the game theory based approach. The corresponding state machine is depicted in Figure 5 containing references to the corresponding line of the description in the policy language. In detail the lines of Policy Description 5 have the following meaning:

- Line 1 - The strategy GRIM consists of four policy rules: `GRIMCoop1` (line 2), `GRIMDefect1` (line 3), `GRIMDefect2` (line 4) and `GRIMDefect3` (line 5). All policies in the group have the same priority as indicated by the property `equalPrecedence`
- Line 2 - The policy rule `GRIMCoop1` for operation matching selector `S1` (defined above). In case of a cooperating opponent and own cooperation, i.e., the opportunity is regarded as `OwnCoop_OpponentCoop` (Policy Description 3, line 1), the player chooses the behavior of cooperation in following the usage description `Cooperate` (Policy Description 2, line 4). The term `Deny = FALSE` indicates that the rule represents a valid opportunity

- Line 3 - The policy rule `GRIMDefect1`: In case of own cooperation and a defecting opponent, i.e., the opportunity is regarded as `OwnCoop_OpponentDef` (Policy Description 3, line 2), the player defects following the usage description `Defect` (Policy Description 2, line 3)
- Line 4 - The policy rule `GRIMDefect2`: In case of own defection and a cooperating opponent (Policy Description 3, line 3), the player defects following the usage description `Defect` (Policy Description 2, line 3)
- Line 5 - The policy rule `GRIMDefect3`: In case of own defection and a defecting opponent (Policy Description 3, line 2), the player defects following the usage description `Defect` (Policy Description 2, line 3)

The TFT strategy, as illustrated in Figure 6, is specified in Policy Description 6. The description is analog to the one of the GRIM strategy, reflecting the similarity of the respective state machines:

- Line 1 - The strategy TitForTat consists of four policy rules: `TFTCoop1` (line 2), `TFTDefect1` (line 3), `TFTCoop2` (line 4) and `TFTDefect2` (line 5). The property `equalPrecedence` indicates that all policies in the group have the same priority
- Lines 2,3 and 5 are the same as in Policy Description 5 of the GRIM strategy
- Line 4 - The reaction on a cooperating opponent in case of own defection (Policy Description 3, line 3) is different. This dissimilarity is marked bold in the policy descriptions of GRIM and TFT. Here, the player cooperates following the usage description `Cooperate` (Policy Description 2, line 4), reflecting the different state transitions in Figure 5 and Figure 6

The introduced examples illustrate the general applicability of the approach: It is a common method for translating strategies represented as state machines to the DARPA XG policy language.

V. Enhanced Distributed Channel Access of 802.11e as Policy

A. *Introduction of Enhanced Distributed Channel Access*

The EDCA realizes the contention-based access of the 802.11e under decentralized operation [8]. It is used to provide differentiated services. In order to support QoS, the EDCA introduces four *Access Categories* (ACs). Each AC has a corresponding backoff entity. The four backoff entities of a QSTA operate in parallel and realize the contention-based access corresponding to the respective AC. The four ACs of 802.11e are AC_BK ("background"), AC_BE ("best effort"), AC_VI ("video") and AC_VO ("voice"). They are derived from the user priorities from Annex H.2 of IEEE 802.1D [23]. The prioritization between the four backoff entities is realized through different AC specific parameters in the following denoted as EDCA parameters set. These EDCA parameter sets modify the backoff process with individual interframe spaces and contention window sizes per AC introducing a probability-based prioritization as explained next.

The EDCA parameters of each backoff entity are defined by the HC and may be adapted over time. Default values for the EDCA parameters are given in [8]. Only a QAP may change these parameters according to the traffic within the QBSS. The EDCA parameters are broadcasted therefore via information fields in the beacon frames. Identical EDCA parameters must be used by all backoff entities with the same AC within a QBSS in order to enable this centrally controlled prioritization. In case of an independent QBSS, i.e., in the absence of an access point, the beacon holder is responsible for defining the sets of EDCA parameters.

Within a QSTA, each backoff entity individually contends for obtaining a TXOP. When multiple backoff entities of a QSTA try a parallel access to the same slot an internal virtual collisions resolution is performed: The backoff entity with the highest AC transmits, while the other backoff entities act as if a collision occurred. Nevertheless, the transmission attempt of the highest AC may collide with frames from other stations.

4) *Arbitration Interframe Space*

A backoff entity starts decreasing its backoff counter after detecting that a channel is idle for an *Arbitration Interframe Space* (AIFS). The AIFS has at least a duration of *DCF Interframe Space* (DIFS) and depends on the corresponding AC as illustrated in the timing diagram depicted in Figure 7 of the four ACs of 802.11e. To express this dependency, it is denoted therefore in the following as $AIFS[AC]$. The *Short Interframe Space* (SIFS) is the shortest interframe space of 802.11. It is used between the frames of the RTS/CTS/DATA/ACK sequence. The *PCF Interframe Space* (PIFS) is used by the PCF to gain access to the radio channel. The *Arbitration Interframe Space Number* (AIFSN) is defined per AC according to [8] and enlarges $AIFS[AC]$. A small $AIFSN[AC]$ implies a high access priority. The earliest channel access time after an idle channel, i.e., the shortest value of $AIFS[AC\_VO]$ =DIFS is similar to the legacy DCF of 802.11, which has an AIFSN of 2. Prioritization is reached in this case through different values of the contention window as described below. AIFS is used in the context of obtaining an EDCA TXOP in Section V.C.

5) *Contention Window Size*

The *Contention Window* (CW) of the backoff process is also used in 802.11e to introduce priorities. Its minimum $CWmin[AC]$ and maximum value $CWmax[AC]$ depends on the AC as illustrated in Figure 7 and default values are given in [8]. For the legacy 802.11a PHY, the minimum and maximum value is given by $CWmin = 15$ and $CWmax = 1023$. A small $CWmin[AC]$ leads to a high access priority. Nevertheless increases a small $CWmin[AC]$ the collision probability when multiple backoff entities of the same AC compete for channel access within a QBSS. In case of a failed frame transmission, the contention

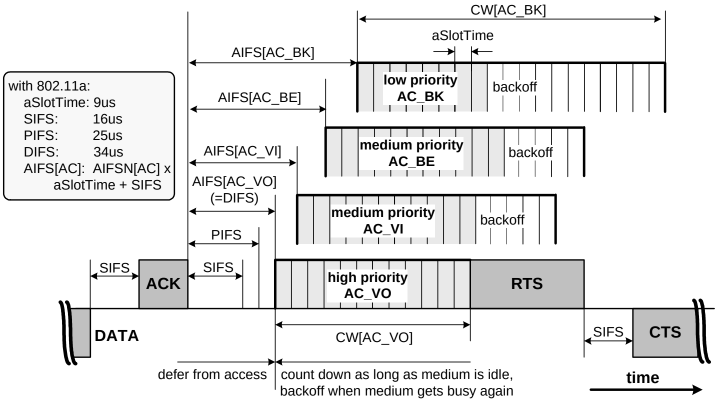

Figure 7. EDCA timing diagram of the four backoff entities defined in 802.11e with different AIFSs and contention window sizes.

window increases up to a value of $CWmax[AC]$. A small $CWmax[AC]$ implies a high priority for accessing the channel.

The strict prioritization is lost when high priority backoff entities increase their contention window after a collision while low priority backoff entities experience no collisions. The relative difference between the contention windows of different ACs, necessary for prioritization, is lost in such a case. Legacy stations have $CWmin = 15$, $CWmax = 1023$ and an earliest channel access time of AIFS = DIFS = 34 µs. An 802.11e QSTA has a higher priority than legacy STAs in setting its $CWmin[AC] < 15$ and $CWmax[AC] << 1023$.

The backoff procedure of the EDCA on the basis of the contention window is described in detail in Section V.D.

B. *Policy Description*

The capabilities, parameters and process that are required to enable a cognitive radio the operation according to the EDCA of 802.11e are specified in Policy Description 7. The way an EDCA TXOP is obtained is described in Policy Description 8. Opportunity (`OppDesc`) and usage descriptions (`UseDesc`) are combined and define policies (`PolicyRule`) for spectrum usage. These policies are aggregated in a group of policies (`PolicyGrp`). This group is specified in Policy Description 9 and represents all rules of the EDCA. The reasons for invoking the backoff procedure are specified as spectrum opportunity descriptions in Policy Description 10. The manipulation of the EDCA parameter set in the backoff procedure according to the standard are described as usage descriptions in Policy Description 11. We assume that the EDCA's policies are repeatedly processed by a cognitive radio for each idle time slot. Additionally, the policies are processed upon the end of a (failed or successful) frame transmission sequence.

The slotting in the time domain is introduced by *aSlotTime*, which depends on PHY mode used by the 802.11e MAC. In case of 802.11a, a time slot has for instance a duration of 9 µs. The PHY mode dependent parameters of 802.11 are provided by the cognitive radio (`boundBy Device`) to enable the processing of the

TABLE I.
DEFAULT VALUES OF EDCA PARAMETERS BASED ON [23]. THE STAR INDICATES DEPENDENCY ON PHYSICAL LAYER, HERE 802.11A.

AC	CWmin	CWmax	AIFSN	AIFS*
legacy	15	1023	2	34 us
AC_BK	15	1023	7	79 us
AC_BE	15	1023	3	43 us
AC_VI	7	15	2	34 us
AC_VO	3	7	2	34 us

EDCA policies. These parameters are specified in Policy Description 7 together with the processes required for executing the EDCA policies. The EDCA parameter set of an AC (here AC_VI) is defined in Policy Description 7, line 4 according to Table 1. A backoff entity with a different AC would here assign other values to the parameters of the backoff procedure.

C. *Obtaining an EDCA TXOP*

Before attempting a transmission, a backoff entity decreases its backoff counter when detecting an idle channel for the duration of $AIFS[AC]$. The following description of the ECDA procedures for obtaining a TXOP is based on [8], pages 78 and 79.

Each backoff entity maintains a backoff counter, which specifies the number of backoff slots an entity waits before initiating a transmission. The duration $AIFS[AC]$ is defined corresponding to

$$AIFS[AC] = SIFS + AIFSN[AC] \cdot aSlotTime .$$

$AIFS[AC]$ is specified in Policy Description 7, line 5. The attempt to obtain an EDCA TXOP is determined according to the following conventions:

The backoff entity of an AC performs on specific slot boundaries, defined by *aSlotTime*, exactly one of the functions below. These functions are mapped in Policy Description 8 to usage descriptions. The conditions for performing one of these functions are reflected in the opportunity descriptions of unused spectrum (here a frequency channel). Usage and opportunity description form together the EDCA policies for

Policy Description 7. Device capabilities, parameters and processes of the EDCA expressed in shorthand notation of the DARPA XG policy language.

```
1 (DeviceCap (id 802.11EDCA_Profile)
  (hasPolicyDefinedParams
   /* constant parameters */
   CWmax CWmin AIFSN AIFS
   /* variable parameters */
   BackoffCounter CW QSRC QLRC
   /* parameters bound by 802.11 device */
   aSlotTime aSIFSTime
   dot11ShortRetryLimit
  dot11LongRetryLimit)
  (hasPolicyDefinedBehaviors
   random /* draws random integer value */
   SenseIdleChannelDuration
   InitiateFrameSequence
   SenseSlot DiscardAttempt))
2 (Process (id random)
   (input lower_border upper_border)
   (output random_value))
3 (TimeDuration (id aSlotTime)
   (boundBy Device) (unit msec))
  (TimeDuration (id aSIFSTime)
   (boundBy Device) (unit msec))
  (RetryCnt (id dot11ShortRetryLimit)
   (boundBy Device) (unit NONE))
  (RetryCnt (id dot11LongRetryLimit)
   (boundBy Device) (unit NONE))
4 (Integer (id AIFSN)
   (magnitude 2) (unit NONE)) /* AC_VI*/
  (CWsize (id CWmin))
   (magnitude 7) (unit NONE)) /* AC_VI*/
  (CWsize (id CWmax))
   (magnitude 15) (unit NONE)) /* AC_VI*/
5 (TimeDuration (id AIFS)
   (magnitude
    (xgx "(+(* AIFSN aSlotTime)
  aSIFSTime)"))
   (unit msec))
```

- **Obtaining an EDCA TXOP** (`TransmitFrameSequence`, Policy Description 8, line 1-3): Initiate a frame exchange sequence (`useDesc InitTrans`) if (i) there is a frame available for transmission, (ii) the backoff counter has reached zero and (iii) no internal backoff entity with higher priority is scheduled for initiating a transmission. These three conditions form together with the channel idle time of AIFS the spectrum opportunity description `Idle1`.
- **Decrementing the backoff counter** (`DecreaseBackoffCounter`, Policy Description 8, line 4-6): The backoff counter is decremented (`useDesc DecBackoff`) if it has a non-zero value. This leads to opportunity description `Idle2`.
- **Invoking the backoff procedure** (`useDesc Backoff2`) because of an internal collision (`InternalCollision`, Policy Description 8, line 7-8) if (i) there is a frame available for transmission, (ii) the backoff counter has reached zero and (iii) an internal backoff entity with higher priority is scheduled for initiating a transmission (`oppDesc Idle3`). This rule can also be found below in the EDCA backoff procedure as (`oppDesc Fail4`).

Policy Description 8. Procedure of obtaining an EDCA TXOP expressed in the shorthand notation of the DARPA XG policy language.

```
1 (PolicyRule (id TransmitFrameSequence)
   (selDesc 802.11_5GHz_US) (deny FALSE)
   (oppDesc Idle1) (useDesc InitTrans))
2 (OppDesc (id Idle1) (xgx "(and
   (invoke SenseIdleChannelDuration
     TimeDuration IdleChannelDuration)
   (>= IdleChannelDuration AIFS)
   (eq FrameAvailable BoolTrue)
   (= BackoffCounter 0)
   (eq HigherPriorTransmit BoolFalse))"))
3 (UseDesc (id InitTrans)
   (xgx "(invoke InitiateFrameSequence)"))
4 (PolicyRule (id DecreaseBackoffCounter)
   (selDesc 802.11_5GHz_US) (deny FALSE)
   (oppDesc Idle2)(useDesc DecBackoff))
5 (OppDesc (id Idle2) (xgx "(and
   (invoke SenseIdleChannelDuration
     TimeDuration IdleChannelDuration)
   (>= IdleChannelDuration AIFS)
   (< BackoffCounter 0)"))
6 (UseDesc (id DecBackoff) (xgx "(:=
    BackoffCounter (- BackoffCounter 1))"))
7 (PolicyRule (id InternalCollision)
   (selDesc 802.11_5GHz_US) (deny FALSE)
   (oppDesc Idle3) (useDesc Backoff2))
8 (OppDesc (id Idle3) (xgx "(and
   (invoke SenseIdleChannelDuration
     TimeDuration IdleChannelDuration)
   (>= IdleChannelDuration AIFS)
   (eq FrameAvailable BoolTrue)
   (= BackoffCounter 0)
   (eq HigherPriorityTransmit BoolTrue))"))
```

- **Doing nothing**. This function requires no specification as policy.

The specific slot boundaries, at which one of these operations is performed, essentially depend on the point of time after which the channel is regarded as being idle. These boundaries are defined for each backoff entity in [8] on pages 78 and 79 in introducing modifications to the $AIFS[AC]$ from above. We neglect these modifications in the following for the sake of simplicity.

D. EDCA Backoff Procedure

The following description of the ECDA backoff procedure is based on (IEEE, 2005), page 81. The backoff procedure of an AC is invoked in case of a transmission failure or in case of a virtual collision due to an internal transmission attempt of multiple ACs. Each backoff entity of the EDCA has a state variable *CW[AC]* that represents the current size of the contention window of the backoff procedure. *CW[AC]* has an initial value of *CWmin[AC]*. The size of the contention window $CW_i[AC]$ in backoff stage *i* is defined thereby as

$$CW_i[AC] = min\left[2^i\left(CWmin[AC]+1\right)-1, CWmax[AC]\right].$$

This definition is specified in `Policy Description 11`, line 5.

In case of a successful frame transmission *CW[AC]* is reset to *CWmin[AC]* (`useDesc_Success`). A successful transmission is indicated by:

Policy Description 9. All policies specifying an operation according to the EDCA are gathered in a policy group.

```
1 (PolicyGrp (id 802.11EDCA)
   (equalPrecedence TRUE)
   (polMembers
     TransmitFrameSequence
     DecreaseBackoffCounter
     InternalCollision
     TransSucc1 ... TransSucc7
     BusyChannel1  BusyChannel2
     TransFail1 ... TransFail5))
2 (PolicyRule (id TransSucc1)
   (selDesc 802.11_5GHz_US)
   (deny FALSE) (oppDesc Success1)
   (useDesc Success))
  ...
  (PolicyRule (id TransSucc7)
   (selDesc 802.11_5GHz_US)
   (deny FALSE) (oppDesc Success7)
   (useDesc Success))
3 (PolicyRule (id BusyChannel1)
   (selDesc 802.11_5GHz_US)
   (deny FALSE) (oppDesc Busy1)
   (useDesc Backoff1))
  (PolicyRule (id BusyChannel2)
   (selDesc 802.11_5GHz_US)
   (deny FALSE) (oppDesc Busy2)
   (useDesc Backoff1))
4 (PolicyRule (id TransFail1)
   (selDesc 802.11_5GHz_US)
   (deny FALSE) (oppDesc Fail1)
   (useDesc Backoff2))
  ...
  (PolicyRule (id TransFail5)
   (selDesc 802.11_5GHz_US)
   (deny FALSE) (oppDesc Fail5)
   (useDesc Backoff2))
```

- A reception of a CTS in response to an RTS (`oppDesc Success1,` Policy Description 10, line 1)
- A reception of a unicast MPDU or BlockAck (`oppDesc Success2,` Policy Description 10, line 2)
- A reception of a BlockAck in response to a BlockAckReq (`oppDesc Success3,` not specified here)
- A reception of an ACK in response to a BlockAckReq (`oppDesc Success4,` not specified here)
- Transmitting a multicast frame with a “no acknowledgement” policy (`oppDesc Success5,` not specified here)
- Transmitting a frame with a “no acknowledgement” policy (`oppDesc Success6,` not specified here)

The backoff procedure of a backoff entity is invoked when

- (i) a frame is intended to be transmitted, (ii) the backoff counter has reached a value of zero and (iii) the medium is busy. This may be indicated by either a physical (`oppDesc Busy1,` Policy Description 10, line 3) or virtual (`oppDesc Busy2,` Policy Description 10, line 4) carrier sense. In this case the backoff procedure is invoked and the value of *CW[AC]* remains unchanged (`useDesc Backoff1,` Policy Description 11, line 2).
- The final transmission of a TXOP holder during its TXOP is successful (`OppDesc Success7, not specified here`). The value of *CW[AC]* is reset to *CWmin[AC]* (`useDesc Success,` Policy Description 11, line 1).
- A frame transmission fails. This is indicated by a failing to receive a CTS in response on an RTS (`oppDesc Fail1,` Policy Description 10, line 5), a failure of receiving an ACK that is expected on a unicast MPDU (`oppDesc Fail2,` Policy Description 10, line 6), a failure of receiving a BlockAck in response to a BlockAckReq (`oppDesc Fail3, not specified here`) or a failure of receiving an ACK in response to a BlockAckReq (`oppDesc Fail4,` not specified here).
- The transmission attempt of an AC collides internally with a higher priority AC (`oppDesc Fail5,` not specified here).

Policy Description 10. Reasons for invoking the EDCA backoff procedure expressed as spectrum opportunities in the shorthand notation of the DARPA XG policy language.

```
1 (OppDesc (id Success1) (xgx “(and
   (invoke SenseSlot
     SlotStateType SlotState)
   (eq SlotState CTSonRTS)”))
2 (OppDesc (id Success2) (xgx “(and
   (invoke SenseSlot
     SlotStateType SlotState)
   (or (eq SlotState MPDU)
       (eq SlotState BlockAck))”))
  ...
3 (OppDesc (id Busy1) (xgx “(and
   (eq FrameAvailable BoolTrue)
   (= BackoffCounter 0)
   (invoke SenseSlot
     SlotStateType SlotState)
   (eq SlotState PhysicalCS)”))
4 (OppDesc (id Busy2) (xgx “(and
   (eq FrameAvailable BoolTrue)
   (= BackoffCounter 0)
   (invoke SenseSlot
     SlotStateType SlotState)
   (eq SlotState VirtualCS)”))
5 (OppDesc (id Fail1) (xgx “(and
   (invoke SenseSlot
     SlotStateType SlotState)
   (eq SlotState failCTSonRTS)”))
6 (OppDesc (id Fail2) (xgx “(and
   (invoke SenseSlot
     SlotStateType SlotState)
   (eq SlotState failACKonMPDU)”))
  ...
```

In case of a frame transmission failure the value of *CW[AC]* is updated as described in the following (`useDesc Backoff2,` Policy Description 11, line 3-6) before invoking the backoff procedure:

- In case *QSRC[AC]* or *QLRC[AC]* has reached dot11ShortRetryLimit or dot11LongRetryLimit respectively, *CW[AC]* is reset to *CWmin[AC]* and the transmission attempt is discarded (Policy Description 11, line 4).

Policy Description 11. Parameter manipulation of the EDCA backoff procedure expressed in shorthand notation of the DARPA XG policy language.

```
1  (UseDesc (id Success) (xgx “(and
    (:= CW CWmin)
    (:= BackoffCounter random(0,CW))
    (:= QSRC 0) (:= QLRC 0))”))
2  (UseDesc (id Backoff1) (xgx “(and
    (:= CW CW) /* CW remains fixed */
    (:= QSRC (+ QSRC 1)) /*QSRC=QSRC+1*/
    (:= QLRC (+ QLRC 1)) /*QLRC=QLRC+1*/
    (:= BackoffCounter
        random(0,CW)))”))
3  (UseDesc (id Backoff2) (xgx “(and
4   (if (or (= QSRC dot11ShortRetryLimit)
            (= QLRC dot11LongRetryLimit))
        (and (:= CW CWmin)
             (:= QSRC 0) (:= QLRC 0)
             (invoke DiscardAttempt)))
5   (if (or (< QSRC dot11ShortRetryLimit)
            (< QLRC dot11LongRetryLimit))
        (and
          (if (< CW CWmax)
            (:= CW (- 1 (* 2 (+ CW 1)))))
            /* CW=(CW+1)·2-1) */
          (if (= CW CWmax) (:= CW CW))
        (:= QSRC (+ QSRC 1))
        (:= QLRC (+ QLRC 1))))
6   (:= BackoffCounter random(0,CW)))”))
```

- Otherwise, *CW[AC]* is set to (*CW[AC]*+1)·2-1 when *CW[AC]* < *CWmax[AC]* or *CW[AC]* remains unchanged if *CW[AC]* = *CWmax[AC]*. For the rest of the retransmission attempts the size of the contention window is not changed (Policy Description 11, line 5).

After setting the contention window size *CW[AC]* the backoff procedure sets the backoff counter to a randomly chosen integer value with a uniform distribution over the interval *[*0,*CW[AC]]* (Policy Description 11, line 6).

VI. Conclusion

The description of spectrum sharing algorithms in a machine-understandable way is one of the most challenging tasks that has to be supported with a policy language. To illustrate how such algorithms could be specified, the mapping of a spectrum sharing algorithm to a policy description language is illustrated in this article. The distinction into spectrum opportunity and usage constraint facilitates a hierarchical structuring of the algorithm’s policy description. In this article, the usage of the XG Policy Language for regulating spectrum access through usage restrictions is extended with the aspect of specifying parameters of spectrum access.

Additionally, policies that assist the dynamic adaptation of medium access control protocols have been discussed in this article. The 802.11e channel access protocol has been specified in a machine understandable policy language, which can be used by cognitive radios. This specification is also applicable to the distributed medium access of 802.11.

The interface between device (radio platform) and spectrum navigator (policy reasoner) is important. We identified the need for specifying the frequency of policy processing: A policy language for describing spectrum access requires more intensive policy processing compared to the specification with a policy language of basic parameters used for limiting this spectrum access such as a maximum transmission power.

Our attempt to describe protocols as policies is a step towards software defined medium access control of cognitive radios. In future work, it is intended to describe algorithms for spectrum management such as dynamic frequency selection and power control as machine-understandable policy.

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