Policy Description of Distributed Medium Access in IEEE 802.11(e)
- invited paper -

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***Abstract*— The current framework for radio spectrum regulation and spectrum usage is undergoing fundamental changes. In the face of scarce radio resources on the one hand and under-utilized licensed spectrum on the other hand, regulators, industry and the research community are launching initiatives towards a flexible usage of spectrum. Cognitive radios realize the dynamic usage of frequency bands on an opportunistic basis. They identify and use under-utilized spectrum in a coordinated way. Policies that enable a software defined medium access are in the focus of this paper. 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.**

***Keywords*— Cognitive Radio, Enhanced Distributed Channel Access, IEEE 802.11e, Policy Description Language**

I. INTRODUCTION

Many frequency bands are today under-utilized like for instance the frequencies licensed for TV/radio broadcasts or military usage. The regulation authorities therefore fundamentally rethink their licensing of spectrum and the regulation of spectrum access. In the face of scarce radio resources, regulators, industry and the research community are launching initiatives towards a flexible usage of spectrum. The *End-To-End-Reconfigurability* (E^2R) [1], funded by the European Commission, and the DARPA *Next Generation Communication* (XG) Program [2], financed by the US-government, are examples for this. Both projects 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 *Quality-of-Service* (QoS) support. Radios designed for efficiently using shared spectrum and not causing at the same time significant harmful interference to incumbent (primary, license holding) radio systems are referred to as "cognitive radios" [3, 4]. Cognitive radios are radio systems that autonomously coordinate the usage of shared spectrum. They identify radio spectrum when it is unused by the incumbent radio system and use this spectrum in an intelligent way based on spectrum observation. Under-utilized 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 here referred to as spectrum navigator. We describe in [5, 6] algorithms for distributed coordination of cognitive radios' medium access in spectrum sharing scenarios as policies. The spectrum navigator processes these policies through reasoning. The reasoning results into guideline values for *Medium Access Control* (MAC) and cognitive radios adapt their transmission parameters in taking them into account [7].

This paper targets at the description of the underlying MAC protocol, here the *Enhanced Distributed Channel Access* (EDCA) of IEEE 802.11e [8, 9], in a common description language for policies. Distributed spectrum sharing is performed with the help of the contention-based protocol of 802.11e. A software defined medium access control of cognitive radios is enabled that allows operation according to the EDCA of 802.11e. The paper is outlined as follows: The medium access control of 802.11e is described in Section II. A policy framework including a *Extendable Markup Language* (XML) based policy description language, the DARPA XG policy language [10-12], is thereafter introduced in Section III[1]. The application of this policy language is illustrated at the example of the regulatory constraints of using the U-NII frequency bands at 5 GHz. The EDCA of 802.11e is specified in the policy description language in Section IV. The paper is concluded with a discussion on the success and difficulties of mapping the EDCA to a policy language in Section V.

II. MEDIUM ACCESS CONTROL IN 802.11E

The main element of the enhancements of 802.11e is the introduction of a new central entity: The *Hybrid Coordination Function* (HCF). The HCF realizes a contention free, centrally controlled medium access denoted as *HCF Controlled Channel Access* (HCCA) and a contention-based, distributed medium access, in 802.11e referred to as EDCA. The HCF is able to schedule a *Contention Free Period* (CFP) and a *Contention Period* (CP) in an 802.11e beacon interval. This beacon interval is in the following referred to as superframe. An *802.11e Access Point* (QAP) forms with its associated stations a QoS supporting Basic Service Set.

A time interval during that stations have the exclusive right to initiate transmissions is in 802.11e referred to as *Transmission Opportunity* (TXOP). TXOPs can either be allocated in the contention-based

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[1] By the time of writing this paper, DARPA delegated the responsibility for developing the XG Policy Language from BBN to SRI.

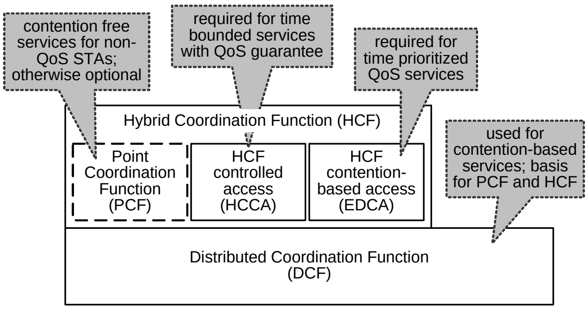

Figure 1: Medium access control architecture of IEEE 802.11e.

EDCA in the CP or are assigned by the HC in the CFP or CP. In the first case, the TXOP is also denoted as EDCA TXOP and in the latter case the TXOP is called a *Controlled Access Phase* (CAP) or HCCA TXOP. The CAP is protected by a timer referred to as *Network Allocation Vector* (NAV). It is used for virtual carrier sensing and reservation of the channel for the indicated time duration. TXOPs obtained by the EDCA have a limited duration referred to as *TXOPlimit*. It is a QBSS-wide parameter that is broadcast by the HC as part of the information field of a beacon. The beacon is regularly transmitted by the HC at the beginning of each superframe. Legacy STAs ignore this new information field and consequently may have longer transmission durations.

A. Architecture

Figure 1 illustrates the main elements of the 802.11e MAC architecture. The legacy 802.11 *Distributed Coordination Function* (DCF) is the basis for the contention-based access of the HCF and the legacy 802.11 *Point Coordination Function* (PCF). The PCF offers contention free services to legacy STAs and is used by the HCF for polling stations as discussed below. The HCCA introduces the possibility to guarantee QoS, while the EDCA is used for prioritized contention-based QoS support. HCCA and EDCA use the known 802.11 MAC frames of the DCF to transmit user data on the radio channel, namely the DATA/*Acknowledge* (ACK) frame exchange sequence with an optional preceding *Request to Send* (RTS) / *Clear to Send* (CTS).

B. Enhanced Distributed Channel Access

The EDCA realizes the contention-based access of the HCF as illustrated in Figure 1. 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 [13]. 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 Table 1. 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.

1) 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 2 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 Table 1 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 IV.A.

2) 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 2 and default values are given in Table 1. 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

Table 1: Default values of EDCA parameters based on [8]. 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

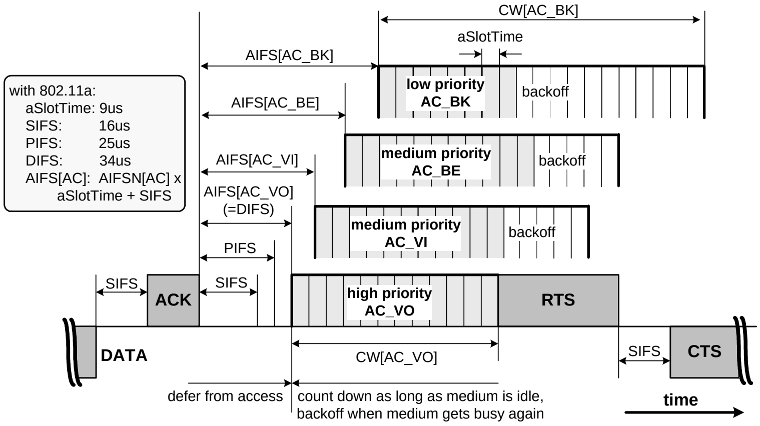

Figure 2: EDCA timing diagram of the four backoff entities defined in 802.11e with different AIFSs and contention window sizes.

the same AC compete for channel access within a QBSS. In case of a failed frame transmission, the contention 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 IV.B.

C. Additional EDCA Parameters

Every QSTA has a short retry counter and a long retry counter for each AC with initial values of zero, denoted as *QSRC[AC]* and *QLRC[AC]*. These two retry counters are used to differentiate between MAC frames of different lengths and default values for these counters are not given in the standard [8]. The retry counters determine how often a frame is retransmitted after a collision until it is discarded. In the case of AC_VO and AC_VI small retry counters are required while AC_BE and AC_BK are less sensitive to many retransmissions. The retries of failed transmissions may lead to problematic situations, especially in the context of TCP retransmissions.

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 [10].

As illustrated in Figure 3, a policy rule consists of three main elements [10]: 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) [14]. 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

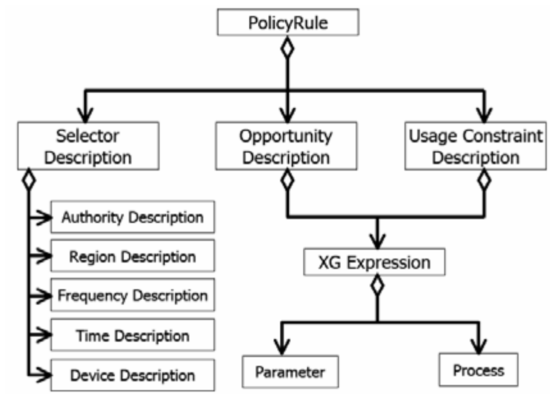

Figure 3. UML Structure of policies in the DARPA XG Policy Language [10].

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))
```

according to `WLAN_Profile1`

- 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.

IV. Enhanced Distributed Channel Access of 802.11e as Policy

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 2. The way an EDCA TXOP is obtained is described in Policy Description 3. 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 4 and represents all rules of the EDCA. The reasons for invoking the backoff procedure are specified as spectrum opportunity descriptions in Policy Description 5. The manipulation of the EDCA parameter set in the backoff procedure according to the standard are described as usage descriptions in Policy Description 6. 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 EDCA policies. These parameters are specified in Policy Description 2 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 2, 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.

A. 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 2, 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 3 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

- **Obtaining an EDCA TXOP** (`TransmitFrameSequence`, Policy Description 3, line 1-3): Initiate a frame

Policy Description 2. 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))`

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 3, 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 3, 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`).
- **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

Policy Description 3. 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))”))`

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.

B. EDCA Backoff Procedure

The following description of the ECDA backoff procedure is based on [8], 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 6, line 5.

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

- A reception of a CTS in response to an RTS (`oppDesc Success1`, Policy Description 5, line 1)
- A reception of a unicast MPDU or BlockAck (`oppDesc Success2`, Policy Description 5, line 2)

Policy Description 4. 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 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 5, line 3) or virtual (`oppDesc Busy2`, Policy Description 5, line 4) carrier sense. In this case the backoff procedure is invoked and the value of *CW[AC]* remains unchanged (`useDesc Backoff1`, Policy Description 6, 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 6, line 1).

Policy Description 5. 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)"))
   ...
```

- A frame transmission fails. This is indicated by a failing to receive a CTS in response on an RTS (`oppDesc Fail1`, Policy Description 5, line 5), a failure of receiving an ACK that is expected on a unicast MPDU (`oppDesc Fail2`, Policy Description 5, 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).

In case of a frame transmission failure the value of *CW[AC]* is updated as described in the following (`useDesc Backoff2`, Policy Description 6, 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 6, line 4).
- Otherwise, *CW[AC]* is set to $(CW[AC]+1)\cdot 2-1$ 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 6, 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 6, line 6).

Policy Description 6. 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)))"))
```

V. CONCLUSION AND OUTLOOK

The way spectrum is regulated is currently under review. Many frequency bands are often under-utilized, because of mismatched regulatory decisions. Adaptive radios, also referred to as cognitive radios, will help to improve spectrum utilization. Policies that assist the dynamic adaptation of medium access control protocols have been discussed in this paper. 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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