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Title: **Enhanced Distributed Channel Access of IEEE 802.11e as Policy for Cognitive Radios**

Abstract: Fundamental changes in the way spectrum is regulated are currently discussed in literature. On the one hand, the employment of more wireless communication systems in the future will continue to request significant amount of additional spectrum. On the other hand, many frequency bands are often under-utilized, because of inefficient spectrum allocations. Adaptive radios, also referred to as 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. To make use of such spectrum opportunities, policies are needed to determine when spectrum is an opportunity, and in addition to determine the constraints of using these opportunities. Policies that assist the dynamic adaptation of medium access control protocols are in the focus of this paper. We discuss a step towards the realization of cognitive radios at the example of the well-known Enhanced Distributed Channel Access of IEEE 802.11e Wireless Local Area Networks. 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 according to the 802.11e standard. Distributed spectrum sharing is performed with the help of the contention-based protocol 802.11e. Spectrum may be shared among different cognitive radios, either in unlicensed spectrum or in opportunistically used licensed spectrum. Our attempt to describe protocols as policies may be a step to software defined medium access control of cognitive radios.

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Enhanced Distributed Channel Access of IEEE 802.11e as Policy for Cognitive Radios

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***Abstract*— Fundamental changes in the way spectrum is regulated are currently discussed in literature. On the one hand, the employment of more wireless communication systems in the future will continue to request significant amount of additional spectrum. On the other hand, many frequency bands are often under-utilized, because of inefficient spectrum allocations. Adaptive radios, also referred to as 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. To make use of such spectrum opportunities, policies are needed to determine when spectrum is an opportunity, and in addition to determine the constraints of using these opportunities. Policies that assist the dynamic adaptation of medium access control protocols are in the focus of this paper. We discuss a step towards the realization of cognitive radios at the example of the well-known Enhanced Distributed Channel Access of IEEE 802.11e Wireless Local Area Networks. 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 according to the 802.11e standard. Distributed spectrum sharing is performed with the help of the contention-based protocol 802.11e. Spectrum may be shared among different cognitive radios, either in unlicensed spectrum or in opportunistically used licensed spectrum. Our attempt to describe protocols as policies may be a step to software defined medium access control of cognitive radios.**

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I. INTRODUCTION

Many frequency bands are today often unused like the 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 [2], 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. 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 referred to as spectrum navigator [3, 4]. This paper targets at the description of the *Enhanced Distributed Channel Access* (EDCA) of IEEE 802.11e [5, 6] in a common description language for policies. A policy-adaptive cognitive radio is enabled that operates according to the EDCA of 802.11e.

This 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 [7, 8] is thereafter introduced in Section III. The regulatory constraints of using one of the U-NII frequency bands illustrate thereby the policy language. 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 introduced EDCA to a policy description language in Section V.

II. MEDIUM ACCESS CONTROL IN IEEE 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. Therefore, the HCF is able to schedule in an 802.11e beacon interval that in the following is referred to as superframe a *Contention Free Period* (CFP) and a *Contention Period* (CP) as outlined below. An 802.11e access point forms with its associated stations a *QoS supporting Basic Service Set* (QBSS).

A time interval during which 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 EDCA of 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). 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

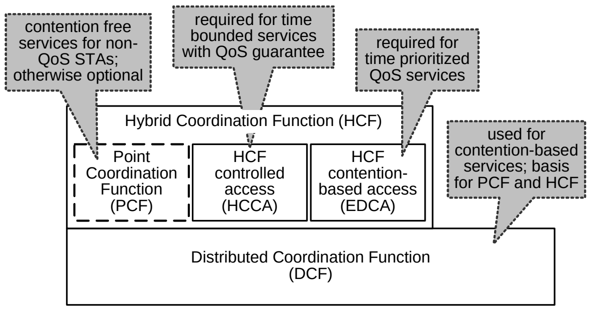

Figure 1: Medium access control architecture of IEEE 802.11e.

duration. TXOPs obtained by the EDCA have a limited duration named *TXOPlimit*. It is a QBSS-wide parameter which is broadcasted 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 do not take this limitation into account. Thus, legacy STAs 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. Both HCCA as well as 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).

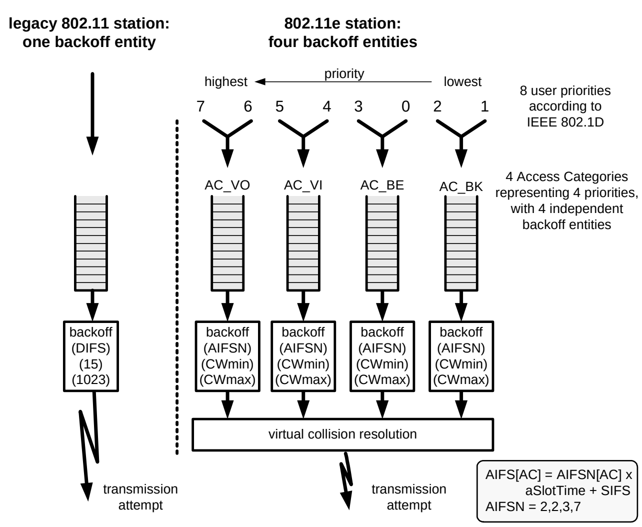

Figure 2: The backoff entity of a legacy 802.11 STA compared to the four parallel backoff entities of an 802.11e QSTA.

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 as illustrated in Figure 2. The four backoff entities of an 802.11e station operate in parallel and realize the contention-based access corresponding to the respective AC. The four ACs of 802.11e, namely AC_BK ("background"), AC_BE ("best effort"), AC_VI ("video") and AC_VO ("voice"), result from a mapping of the user priorities from Annex H.2 of IEEE 802.1D [9], as also illustrated in Figure 2. The prioritization between the four backoff entities is realized through different AC-specific parameters in the following denoted as set of EDCA parameters. 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.

Each backoff entity within a QSTA 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 the 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 3 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

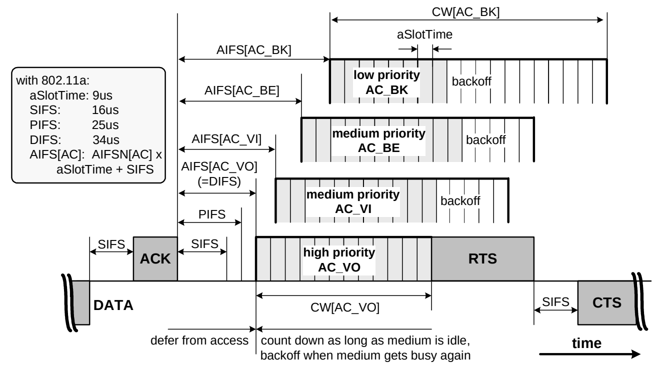

Figure 3: EDCA timing diagram of the four backoff entities defined in 802.11e with different AIFSs and contention window sizes.

channel, i.e., the shortest value of $AIFS[AC\_VO]$=DIFS is similar to the legacy DCF of 802.11 which would have 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 3 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 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 $CWmax[AC]$ results into 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.

Table 1: Default values of EDCA parameters based on [5]. The star indicates dependency on the PHY, here 802.11b/802.11a are selected.

AC	CWmin	CWmax	AIFSN
AC_BK	*CWmin**	*CWmax**	7
AC_BE	*CWmin**	*CWmax**	3
AC_VI	(*CWmin**+1)/2-1	*CWmin**	2
AC_VO	(*CWmin**+1)/4-1	(*CWmin**+1)/2-1	2

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 [5]. 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. As neither default values nor a capability for centralized management are defined in the standard, the prioritization through retry counters is not possible.

III. 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 [7].

As illustrated in Figure 4, 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 at the example of the regulatory restrictions of

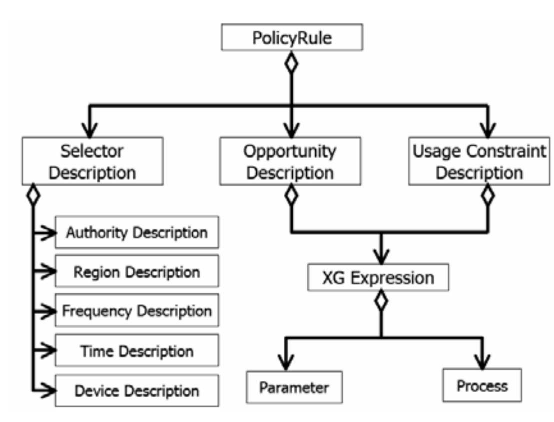

Figure 4. UML Structure of policies in the DARPA XG Policy Language [5].

using the *Unlicensed National Information Infrastructure* (U-NII) frequency band at 5 GHz in the US: An IEEE 802.11 *Wireless Local Area Network* (WLAN) device limits its transmission power to 40 mW when using 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 policies 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 is of the type `WLAN_Class1` and has the capabilities defined in `WLAN_Profile1`
- Line 3 - A device type named `WLAN_Class1`. The meaning of the name is defined by a regulation authority
- Line 4 - The capabilities of the device are defined as `WLAN_Profile1`. The device must understand and be able to provide the parameter `MaxTransmitPower` for computation in policies
- Line 5 - U-NII Band consisting of three frequency bands
- Line 6 - The U-NII Band at 5.15-5.25 GHz is described
- 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 to which the radio is able to provide values
- Line 10 - Policy for using the U-NII Band at 5.15-5.25 GHz when it is regarded as opportunity described in `BandUnused`

The opportunity description `BandUnused` and the frequency 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 are specified in Policy Description 2. The obtaining of an EDCA TXOP is described in Policy Description 3 in grouping opportunity (`OppDesc`) and usage descriptions (`UseDesc`) to policies (`PolicyRule`). These policies are aggregated in a group of policies (`PolicyGrp`) that represents all rules of the EDCA in Policy Description 4. The reasons for invoking the backoff procedure are specified as

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))
```

spectrum opportunity descriptions in Policy Description 5. The manipulation of the EDCA parameters according to the backoff procedure defined in the standard are introduced as usage descriptions in Policy Description 6. We assume that the given EDCA policies are processed by a cognitive decision-making entity repeatedly every idle time slot, and in addition upon the end of a (failed or successful) frame transmission sequence.

The slotting in the time domain is introduced by *aSlotTime* which is introduced by the used PHY mode of 802.11e. The PHY mode dependent parameters of 802.11 are to be 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 of a different AC would assign in this line other values to the EDCA parameters.

A. *Obtaining an EDCA TXOP*

Before initiating a transmission attempt, 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 [5], pages 78 and 79.

The backoff entity of an AC of the EDCA maintains a backoff counter which specifies the number of backoff slots

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)) /*here: AC_VI*/
   (CWsize (id CWmin))
    (magnitude 7) (unit NONE)) /*here: AC_VI*/
   (CWsize (id CWmax))
    (magnitude 15) (unit NONE)) /*here: AC_VI*/
5  (TimeDuration (id AIFS)
    (magnitude
     (xgx "(+(* AIFSN aSlotTime) aSIFSTime)"))
    (unit msec))
```

an entity waits before initiating a transmission. The duration $AIFS[AC]$ is defined corresponding to

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

as specified in Policy Description 2, line 5. The initiation of an attempt to obtain an EDCA TXOP for a frame exchange sequence is determined according to the following conventions:

On specific slot boundaries, defined by aSlotTime, the backoff entity of an AC performs exactly one of the functions below. These functions are mapped in Policy Description 3 to usage descriptions. The conditions for performing a function are reflected in the descriptions of spectrum opportunities. Usage and opportunity description form together the EDCA policies for

- **Obtaining an EDCA TXOP** (`TransmitFrameSequence`, Policy Description 3, 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`.

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))"))
```

- **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 of time after which the channel is regarded as being idle. These boundaries are defined for each backoff entity in [5] 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 clarity.

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))
```

B. *EDCA Backoff Procedure*

The backoff procedure of an AC is invoked in case of a transmission failure or 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

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

The following description of the ECDA backoff procedure is based on [5], page 81.

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

- Reception of a CTS in response to an RTS (`oppDesc Success1`, Policy Description 5, line 1)
- Reception of a unicast MPDU or BlockAck (`oppDesc Success2`, Policy Description 5, line 2)
- Reception of a BlockAck in response to a BlockAckReq (`oppDesc Success3`, not specified here)

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)”))
   ...
```

- 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 in not changing the value of *CW[AC]* (`useDesc Backoff1`, Policy Description 6, line 2).
- The final transmission of a TXOP holder during this 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).
- A frame transmission fails. This is indicated by a failure of receiving 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

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=(CW+1)·2-1)*/
           (:= CW (- 1 (* 2 (+ CW 1)))))
       (if (= CW CWmax) (:= CW CW))
       (:= QSRC (+ QSRC 1))
       (:= QLRC (+ QLRC 1))))
6   (:= BackoffCounter random(0,CW)))”))
```

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 a ACK in response to a BlockAckReq (`oppDesc Fail4`, not specified here).

- The transmission attempt of an AC collides internally with an AC that has a higher priority (`oppDesc Fail5`, not specified here).

In case of a frame transmission failure, as indicated by the last two items, the value of *CW[AC]* is updated as follows (`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)·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).

V. 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.

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 may be a step to software defined medium access control of cognitive radios. In future work, it may be desirable to describe spectrum management such as dynamic frequency selection and power control as machine-understandable policy.

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