Paper published at

PIMRC'05
16th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications

September 11 - 14, Berlin, Germany

Title: **Spectrum Load Smoothing for Cognitive Medium Access in Open Spectrum**

Abstract: Today's framework for radio spectrum regulation and the way the usage of radio spectrum is coordinated, is undergoing vital changes. In the face of scarce radio resources, regulators, industry, and the research community are initiating promising approaches towards a more flexible spectrum usage, referred to as open spectrum. In this paper we discuss medium access control protocols for spectrum agile radios that opportunistically use spectrum, also referred to as "cognitive radio". Spectrum agile radios operate in parts of the spectrum originally licensed to other radio services. They identify free spectrum, coordinate its usage and release it when this is required by licensed radio systems. The application of "waterfilling" from the information theory, referred to as Spectrum Load Smoothing (SLS), and its realization in IEEE 802.11e-based spectrum agile wireless networks is examined in this paper. The SLS, as intelligent principle of spectrum usage, targets at the distributed quality-of-service support in scenarios of coexisting spectrum agile radios. With SLS, spectrum agile radios observe the past usage of the spectrum, while at the same time a harmful interference to license holding radio systems is avoided. The SLS can therefore be referred to as cognitive medium access. In this paper, the capability to support quality-of-service in the presence of other, competing spectrum agile networks and the protection of licensed radio networks are evaluated with the help of simulation. The efficiency of SLS for open spectrum access is demonstrated.

Keywords: Open Spectrum, Cognitive Radio, Spectrum Load Smoothing, IEEE 802.11e

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Spectrum Load Smoothing for Cognitive Medium Access in Open Spectrum

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Abstract- **Today's framework for radio spectrum regulation and the way the usage of radio spectrum is coordinated, is undergoing vital changes. In the face of scarce radio resources, regulators, industry, and the research community are initiating promising approaches towards a more flexible spectrum usage, referred to as open spectrum. In this paper we discuss medium access control protocols for spectrum agile radios that opportunistically use spectrum, also referred to as "cognitive radio". Spectrum agile radios operate in parts of the spectrum originally licensed to other radio services. They identify free spectrum, coordinate its usage and release it when this is required by licensed radio systems. The application of "waterfilling" from the information theory, referred to as Spectrum Load Smoothing (SLS), and its realization in IEEE 802.11e-based spectrum agile wireless networks is examined in this paper. The SLS, as intelligent principle of spectrum usage, targets at the distributed quality-of-service support in scenarios of coexisting spectrum agile radios. With SLS, spectrum agile radios observe the past usage of the spectrum, while at the same time a harmful interference to license holding radio systems is avoided. The SLS can therefore be referred to as cognitive medium access. In this paper, the capability to support quality-of-service in the presence of other, competing spectrum agile networks and the protection of licensed radio networks are evaluated with the help of simulation. The efficiency of SLS for open spectrum access is demonstrated.**

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I. Introduction

In wireless communication, the rising demand for free available spectrum goes along with increasing restrictions to spectrum utilization, i.e., *Quality of Service (QoS)* requirements, as for instance in consumer electronics or other multimedia applications. The unlicensed spectrum is limited and new spectrum will not be available soon, as regulatory changes of the regulatory status from licensed to unlicensed bands are complicated, and usually take a long time. Further, future radio systems are required to support QoS in a shared spectrum, i.e., in the presence of other radio systems. Flexible, dynamic spectrum usage provides a way out of the regulatory dilemma of on the one hand the need to combine the demand for free spectrum with on the other hand the need to support the current license holders. IEEE 802.22™, which is being standardized at the time this paper is written, is one example for a secondary radio system operating in licensed spectrum that is originally used for TV broadcast. The DARPA *Next Generation Communication (XG)* Program, financed by the US-government, and the Integrated Project *End-To-End-Reconfigurability (E^2R)*, funded by the European Commission, are working on flexible and dynamic spectrum usage and related impacts on spectrum regulation. Radios designed for efficiently using a shared spectrum and not causing at the same time significant interference to incumbent (primary, license holding) radio systems are referred to as "spectrum agile radios" [1]. Spectrum agile 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. The terms "cognitive" and "smart" radios are often used in the context of intelligent spectrum usage [2], [3].

This paper evaluates in Section II the *Spectrum Load Smoothing (SLS)* as *Medium Access Control (MAC)* layer-based approach to cognitive radios, as introduced in [4]. The self-aware, intelligent spectrum usage of spectrum agile radios aiming at the distributed support of QoS can be characterized as "Cognitive Medium Access". The rationale and algorithm of SLS in the time domain at a single frequency is introduced in Section III. A frame-based model for the evaluation of spectrum sharing scenarios is introduced in Section IV. The realization of spectrum agile radios in IEEE 802.11e™ is described and evaluated in terms of QoS in Section V: The SLS is applied in modifying the *Enhanced Distributed Controlled Access (EDCA)* of IEEE 802.11e™. The paper ends with an outlook and conclusion in Section VI.

A. Related Work

The rationale and algorithm of SLS is introduced in [4] and *SLS with reservation* is examined in [5] at the example of modified IEEE 802.11e™ *Hybrid Coordination Functions (HCFs).* Here, the focus is on the *SLS without reservations* and its application in 802.11e™. The idea of SLS is derived from the idea of waterfilling known from the field of multi-user information theory and communications engineering: In a multiple transmitter and receiver environment, waterfilling is used to solve a mutual information maximization problem based on the singular-value decomposition of a channel matrix [6]. Through the application of a multi-carrier modulation, the transmission power can be adapted to the transfer function of the radio channel [7]. This view is extended by iterative waterfilling in the context of multiple access channels as analyzed in detail in

[8],[9]. This paper refers to the transfer of the waterfilling from its application in information theory to the SLS as part of a cognitive medium access of frequency agile spectrum sharing devices.

II. Spectrum Load Smoothing for Spectrum Agile Radios

The SLS targets at the (i) identification of spectrum opportunities, (ii) using them in a coordinated way and (iii) releasing the spectrum again if it is required by the license holding radio network. Thereby *hierarchical spectrum* sharing is enabled in avoiding harmful interference to the primary radio system. The mutual coordination takes individual QoS requirements of the SLS using devices into account. SLS aims at spectrum usage efficiency, and decentralized (distributed) coordination of QoS support. This is achieved in allocating spectrum with deterministic and predictable spectrum allocation patterns, i.e., in time uniformly distributed medium accesses, which occur periodically during the interval which was identified as usable for the shared radio spectrum. The predictability of devices' allocations facilitates the mutual coordination of spectrum usage among different spectrum agile radios, even in scenarios where dissimilar devices cannot communicate with each other, but mutually detect interference from each other.

Spectrum usage by opportunistic operation in licensed and unlicensed frequencies is illustrated in Fig. 1. The spectrum usage at 5 GHz at the example of three IEEE 802.11a™ channels located in the unlicensed frequency band and two adjacent channels in the licensed frequencies above is depicted. The spectrum agile radios differ between three kinds of spectrum opportunities: (i) spectrum that is most of the time unused as it is reserved for radio systems that do not operate frequently as for instance emergency services or military services, (ii) deterministically used licensed spectrum, and (iii) rarely and predictably used unlicensed spectrum. The detection of such spectrum opportunities can be facilitated with the medium sensing time histogram measurement, which is part of IEEE 802.11k™, as discussed in [1]. The example of Fig. 1 illustrates the allocations (light gray) of spectrum sharing agile radios which apply the principle of SLS when allocating spectrum opportunities. IEEE 802.11a™ radios demand the access to the channels at 5220 MHz and 5240 MHz with the same random pattern: At the latter frequency the agile radios distribute their allocations between the 802.11a™ allocations and delay them in correspondence to the *Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA)* of 802.11a™. At 5260 MHz a license holding primary radio system uses spectrum with deterministic patterns, respected and not interfered by the spectrum agile radio. At 5280 MHz, a sporadically used licensed spectrum with a few spectrum accesses, the spectrum agile radios

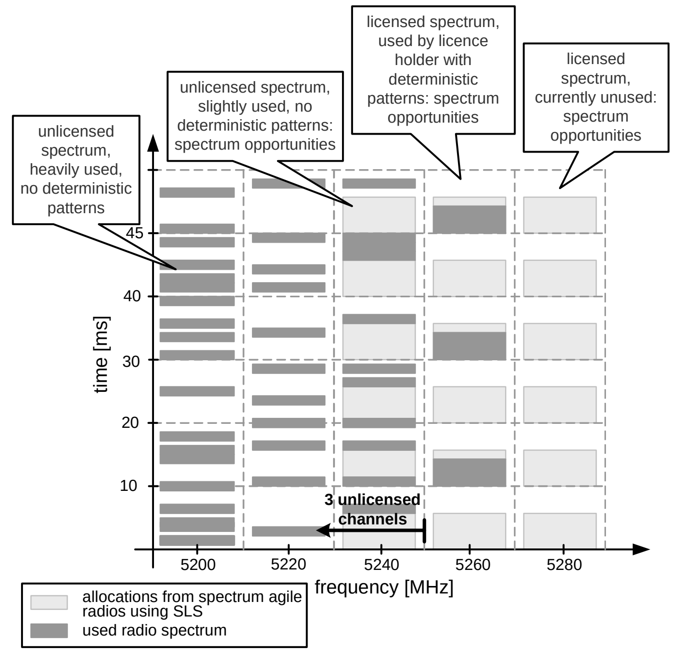

Figure 1. Spectrum usage example at 5 GHz. Three 802.11a™ channels and frequencies above are depicted. The dark gray fields indicate used spectrum. Frequency agile radios use Spectrum Load Smoothing (SLS) to identify and allocate spectrum opportunities (light gray indication).

coordinate each other with the SLS, therefore they coexist in this spectrum. Spectrum is released for usage of the licensed radio system if required.

III. Spectrum Load Smoothing in the Time Domain

The SLS is described in the following. For further details on the algorithm of SLS, its convergence and duration after which a steady state is reached, and a discussion of the advantages of the SLS, see [4].

A. The Algorithm

Fig. 2 describes the principle of SLS at the example of the time domain and a fixed, single frequency. Here, a periodic frame-based MAC protocol is the basis for coordination and interaction. It is in Section IV regarded as IEEE 802.11e™ superframe and the SLS is done by a device once per frame. The frame consists of four slots of equal lengths whereby a slot is a time interval during which the multiple access occurs. The slot length is respected by all devices. In a distributed environment, the slot length can be identified with the help of the autocorrelation function of the observed allocations [1]. The slotted structure is regarded as mandatory and respected by all devices. Coexisting legacy communication systems or protocol specific limitations may lead nevertheless to offences against the slotted structure. The SLS is able to deal with such offences in regarding an ongoing allocation from the last slot as first allocation of the current slot and

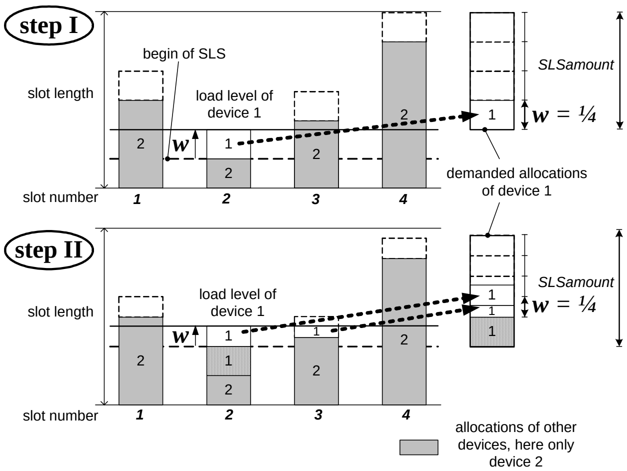

Figure 2. The principle of SLS in the time domain over a frame divided into four slots of the same length. The initial two iterative steps are depicted [4].

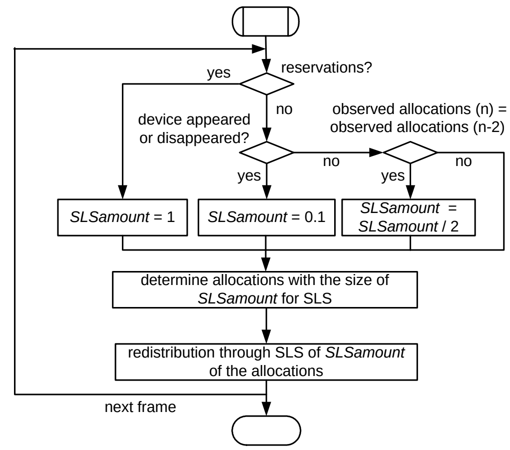

Figure 3. Iterative SLS with adaptive amount of redistributed allocations targeting on smoothed allocations [4].

following thereafter the intended access order of smoothed allocations.

The SLS is an iterative algorithm: It redistributes the allocations of a device with the aim of getting an equalized - smoothed - overall utilization of the four slots which is referred to as load level. The initial two steps of the iterative determination of the smoothed load level are shown in Fig 2. The iterative distribution of the devices' allocations on the available slots considers the added allocations of all other devices as common basis. In Fig. 2 only one device, namely device 2 is present as interferer. The initial load level of device 1 is increased stepwise beginning with the lowest allocation of device 2, here located in slot *2*. The step size *w* of increasing the load level is given by the quotient of "amount of allocations to be distributed" through the "number of slots". The difference between the load level and the allocations of device 2 is filled with allocations of device 1 (see Fig. 2, step I, slot *2* and in step II, slot *2* and *3*). These (spectrum load) smoothed allocations are subtracted from the amount, which is still to be distributed, depicted in the upper right corner of each step in Fig. 2. Thus from iteration to iteration the step size *w* decreases as well as the remaining amount of allocations. The accuracy of the algorithm defines a criterion for ending this iterative algorithm.

B. Spectrum Load Smoothing with and without Reservations

It has to be distinguished between (i) SLS improved through reservations as evaluated in [5] and (ii) SLS based on the observation of past frames as it is analyzed in this paper. The *SLS without reservations* is done simultaneously at the beginning/end of a frame. To enable a mutual interaction, the SLS is then done step-wise from frame to frame in redistributing a limited amount of allocations from the previous frame. The amount of allocations per frame considered for redistribution through SLS is called *SLSamount*. For SLS with reservations all allocations can be shifted at once (*SLSamount=1*). To enable a fast coordinated and stable smoothed allocation scheme without reservations, the *SLSamount* is decreased, on the way to the smoothed allocation solution. Based on control theory, the *SLSamount* can be regarded therefore as attenuation factor. The flow chart of Fig. 3 depicts the SLS with and without reservations with a flexible amount of redistributed allocations. Our simulations, as introduced in [4], have indicated that an initial value of *SLSamount=0.1* is a suitable to enable stability in an adequate duration of time. Before redistributing a specific amount of allocations through the SLS, the most destructive allocations on the way to a smoothed overall allocation scheme have to be identified. Destructive means in this context parts of allocations which are above the ideal smoothed load level of the slots. The *SLSamount* is halved, as outlined in Fig. 3, if the overall allocations of the last but one frame equal the allocations of the present frame: Devices shift allocations at the same time to less utilized slots, overload these together and shift in the consecutive frame these allocations back to the original slots [4]. In case of a device initiating or ending transmissions the smoothed mutually agreed allocations are obsolete and have do be coordinated again and the *SLSamount* is reset therefore to *0.1*.

The emerging steady point of interaction can be regarded as *Nash Equilibrium* from the perspective of game theory. In focusing on the throughput no device can gain a higher throughput in deviating from this solution [11].

C. Redistribution of Allocations through SLS

Fig. 4 depicts the SLS in the time domain based on a slotted, periodic frame; the definitions are used below. Here, three decentralized devices coordinate each other. Each device performs SLS, i.e., distributes its allocations over a *distance of smoothing* introduced by the maximum tolerable delay of the device's applications. The timing diagram of the resulting channel is additionally depicted. The decision about the distribution of the devices' allocations is done at the beginning of the frame and cannot be modified within the frame. The *distance of smoothing* is a multiple of the slot length, corresponding to the slotted structure of the frame which is introduced by device 1 as first device initiating a transmission. The order of SLS is given through the temporal appearance of the devices. The coordination period for broadcasting reservations is not considered here but is used for beacon broadcasts in a HCCA coexistence scenario [5].

IV. Evaluation of Spectrum Load Smoothing in IEEE 802.11e™ Coexistence Scenarios

We define a frame-based coordination model to analyze and evaluate the SLS together with the resulting interaction in the context of IEEE 802.11e™. The following definitions correspond to the ones of the game model introduced in [10] and refined in [11]. The coordination model enables a frame-based interaction consisting of three phases: (i) the decision about the intended allocations of the current frame corresponding to the SLS, (ii) the allocations of the shared medium and (iii) thereby the observation of the medium utilization as basis for the decision in the following frame. In an initial step, we assume a simplistic radio channel and ignore the hidden station problem.

A. Definitions

We define four abstract and (to the frame duration) normalized representations of QoS targets in the context of the coordination model with the help of Fig. 4: (i) the throughput $\Theta \in [0,1]$, (ii) the period length $\Delta \in [0,0.1]$ and (iii) the delay $\Xi \in [0,0.1]$. The supported applications of the devices define the requirements for these QoS targets.

The normalized throughput $\Theta^i(n)$ represents the share of capacity a device *i* demands in frame *n*, and is defined as

$$\Theta^i(n) = \frac{1}{FrameLength} \sum_{l=1}^{L^i(n)} d_l^i(n) \quad \in [0,1]. \qquad (1)$$

$L^i(n)$ is the number of allocations per frame *n* and $FrameLength$ the duration of the frame. The parameter $d_l^i(n)$ describes the duration of an allocation *l*, *l=1..L*, of device *i* in frame *n*. The normalized period length $\Delta^i(n)$ specifies distance between two allocations

$$\Delta^i(n) = \frac{1}{FrameLength} max\left[D_l^i(n)\right]_{l=1..L^i(n)-1} \quad \in [0,0.1]. \qquad (2)$$

The period length is observable by all devices and plays an important role for the distributed QoS support. The period length can be estimated by other devices and is regarded as contribution to cooperation [4],[10]. In this way, the period length is a measure for predictability and thus the success of mutual coordination

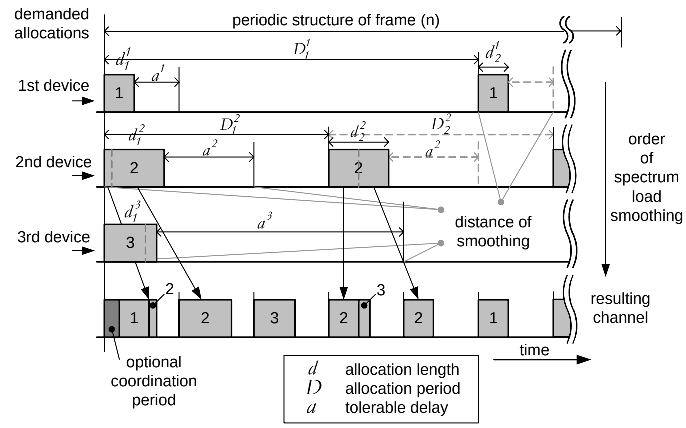

Figure 4. SLS in the time domain. Each device has an individual distance of smoothing. The periodic allocations are smoothed.

(without reservations). The normalized observed delay $\Xi^i(n)$ is defined as difference between demanded and observed allocation point of time and is part of our QoS evaluation below. The jitter can be directly derived from this observed delay. The tolerable delay $a^i(n)$ is the maximum delay that the device *i* tolerates in frame *n* and is above introduced as to as distance of smoothing. Allocation attempts which would lead to higher delays than the tolerable delay are discarded.

V. SLS without Reservations – Coexisting IEEE 802.11e™ EDCA Stations

The main element of the enhancements to IEEE 802.11™ for the support of QoS is a central instance called *Hybrid Coordinator (HC)*. The distributed, contention-based access, as considered in this section, of the HC to the channel is called EDCA. For a detailed description and evaluation of IEEE 802.11e™ see [10]: There it is shown that for the support QoS on the basis of the EDCA mutual coordination for collision avoidance is desirable. The necessary harmonization of the competitive access to each slot of the periodic frame is done by the SLS under consideration of observed past frames. Collision avoidance is intended to be reached by defining access order mechanism to the transmission medium.

The application of SLS in an EDCA coexistence scenario is illustrated in Fig. 5. The point of time where the (spectrum load) smoothed allocations begin is referred to as *ground*. The ground is identical with the beginning of the time slot if the slot is used completely for SLS. In Fig. 5, the first slot has an increased ground, by means of that the primary radio system (here: EDCA0) is protected and its designated allocation time is not considered for SLS. The ground is adequately chosen so that lower priority allocations and legacy devices have no time to initiate their transmissions corresponding to their waiting times

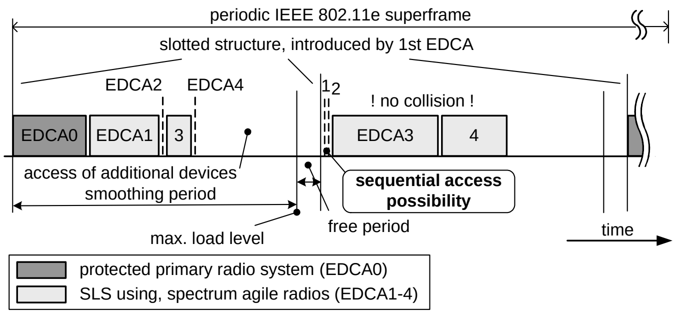

Figure 5. IEEE 802.11e™ EDCA coexistence scenario. SLS without reservations: The stations have an individual access period within a slot in the order of their initial transmission in the considered area.

before accessing the medium.

Within the (spectrum load) *smoothing period*, bordered at the one side by the ground and at the other side by the maximum load level, the SLS using spectrum agile devices (here: EDCA1-4) follow a coordinated order of access to prevent collisions: The sequential order of access possibilities for each EDCA through intended left free periods, common to all slots of the frame, is given by the order of the devices' initial transmission within the considered coverage area. The *maximum load level* is the upper border of the smoothing period within a slot. In the case of a completely used slot for SLS the maximum load level is identical with the end of the slot. The ground and the maximum load level imply means for realizing priorities and admission control of the medium access of the SLS as they limit the time of a slot which is used for allocation. Protected periods can be placed in each frame in increasing the ground of one or several slots enabling the operation of an incumbent radio system without interference.

In our scenario of coexisting IEEE 802.11e™ stations using EDCA, the SLS is done simultaneously at the beginning/end of each frame. As illustrated in Fig. 5, the SLS can be done without an announcement of reservation information with the help of an individual access period for each device in each slot. The period for the opportunity to access the medium is left free in each slot for each device independently from the real demanded allocation of a certain slot.

A. Coexistence of Legacy 802.11e™ EDCA Stations

Fig. 6 illustrates the QoS results, corresponding to the definitions above, of three coexisting legacy EDCAs (EDCA0, EDCA1 and EDCA2) sharing the same single frequency. The normalized observed throughput $\Theta^i(n), i \in 0..2$ (above), the observed period length $\Delta^i(n), i \in 0..2$ (in between) and the observed maximum delay $\Xi^i(n), i \in 0..2$ (below) of frame *n* are depicted in Fig. 6 and 7 for different coexistence scenarios. We evaluate the mutual interference of the EDCA s' allocation attempts over *15* IEEE 802.11e™ superframes. Each frame has a typical duration of *FrameLength=SFDUR=100ms*. The QoS requirements for the throughput and period length are marked gray. In the scenarios of this evaluation, the three 802.11e™ EDCA devices have the fixed requirement of allocating *20%* of the medium: $\Theta^i_{req} = 0.2, i \in 0..2$. The requirements for the period lengths are assumed as follows: $\Delta^0_{req} = 0.1$, $\Delta^1_{req} = 0.1$ and $\Delta^2_{req} = 0.05$. In the scenario considered in this section, the allocations attempts of the EDCAs collide frequently, mutually delay each other and have to be discarded. Thus the observed throughput is reduced and fulfills not the requirement. The observed distance between allocations attempts indicates that a lot of allocations have been randomly delayed and discarded corresponding to the random backoff after collision of the legacy EDCAs. This leads to unpredictable allocations of the shared medium and thus illustrates the inability of the legacy EDCAs to guarantee QoS.

B. EDCA Scenario – SLS without Reservations

A spectrum sharing scenario of one incumbent primary radio system, here EDCA0, and two EDCAs (1 and 2) using SLS without reservations for mutual coordination is depicted in Fig. 7. The primary radio system is the license holder and its allocations are to be protected: The SLS using EDCA1 and EDCA2 identify free time intervals and distribute their allocations around the transmissions from the incumbent EDCA0. The slotting for SLS is introduced by the periodic allocations of EDCA0. The transmission interval is observable and can be identified by EDCA1 and EDCA2 with the procedures of IEEE 802.11k™ [1],[10]. Here, the frame is divided for SLS into *40* slots and we assume that EDCA1 has a fixed distance of SLS (tolerable delay) of *3* slots while EDCS2 has a distance of SLS of *2* slots; thus $a^1 = 7.5\,ms$ and $a^2 = 5\,ms$.

In the HCCA scenario from [5] all allocations can be redistributed per frame (*SLSamount=1*) due to the utilization of reservations. Contrary, our coexistence scenario of EDCA stations implies a more complicated coordination problem as introduced above: As no reservations are used, the SLS is based here on the less accurate observation of past frames. An adaptive amount of allocations considered for SLS is required to enable convergence of the simultaneous redistribution of the allocations, see Fig. 3. Due to the missing information about current frame allocations, *11* frames are required in this scenario to reach a coordinated solution. Nevertheless, EDCA0 is not interfered and all EDCAs observe their required throughput. Their allocations - fixed (EDCA0) or distributed by the SLS (EDCA1 and EDCA2) - do not collide or delay each other. The advantages of these smoothed allocation distribution in the context of fairness and cooperation with the aim of QoS support are introduced in [4]. The presence of the incumbent radio system increases the distance between two consecutive allocations and EDCA2 fails to meet its requirement $\Delta^2_{req} = 0.05$.

In comparing the results from SLS without reservation as introduced above to the results from [5] of SLS with reservations the advantage of reservations is clear observable. In two comparable scenarios the usage of reservations leads in [5] after *4* frames to a coordinated solution. The introduction of reservations used by all devices implies a restrictive regulatory intervention to all radio systems which contradicts the paradigm of spectrum agile radios. The reservation-based SLS is therefore suggested for the distributed coordination of reservations of same devices in WPANs like IEEE 802.15.3a™.[5]

VI. CONCLUSIONS

Spectrum licensing may change radically over the next years towards open spectrum. Many new exciting research challenges in wireless communications will emerge. Spectrum agile radios are promising candidates for dynamic as well as flexible spectrum regulation and usage, ultimately increasing the efficiency of spectrum utilization. The coexistence problem of supporting QoS in distributed environments of unlicensed spectrum equals the coordination problem of spectrum agile radio networks that opportunistically share the same spectrum. Additionally, primary license holding radio systems have to be protected.

We have shown that the principle of SLS realizes a cognitive medium access in spectrum agile radio networks. The QoS evaluation of the EDCA coexistence scenario indictates that the SLS is a promising new approach to mitigate the problem of distributed QoS support in spectrum agile radio networks. As shown, the SLS can be integrated into existing protocol standards. The applicability of SLS is independent form the number of radio networks and accounts for both completely and partially overlapping wireless networks. Future work will concentrate on the refinement of the SLS in concreting the grade of detail considered for evaluation of QoS in spectrum agile radio networks. An integration into a policy framework as for instance suggested by DARPA XG [12] is envisaged.

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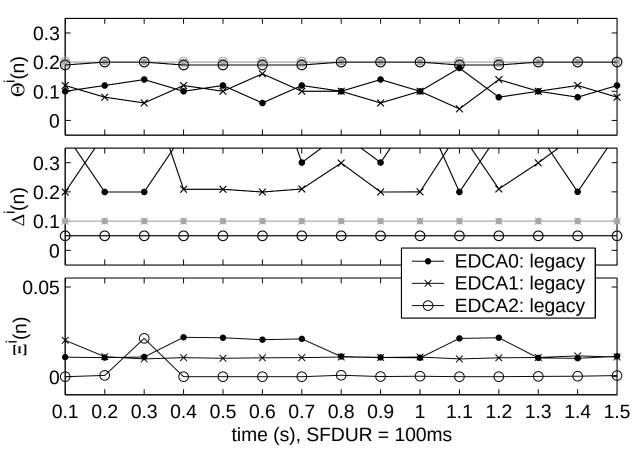

Figure 6. Legacy IEEE 802.11e™ EDCA coexistence scenario. The allocation attemps are uncoordinated and fail in colliding. A QoS support is impossible.

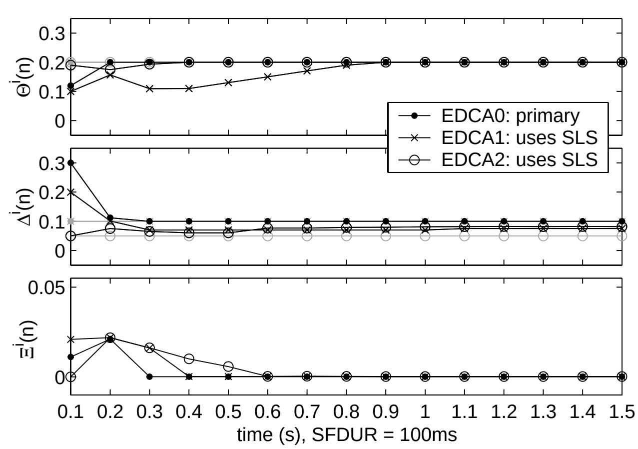

Figure 7. IEEE 802.11e™ EDCA coexistence scenario. One protected primary radio system uses EDCA and two secondary EDCAs use SLS without reservations. A coordinated distribution of allocations is reached after *11* frames.