EUROPEAN TRANSACTIONS ON TELECOMMUNICATIONS
Euro. Trans. Telecomms. 2006; **17**:395–406
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/ett.1121

Special Issue

Spectrum load smoothing: distributed quality-of-service support for cognitive radios in open spectrum

Lars Berlemann[1]*, Stefan Mangold[2], Guido R. Hiertz[1] and Bernhard H. Walke[1]

[1]*RWTH Aachen University, Faculty 6, Chair of Communication Networks, Germany*
[2]*Swisscom Innovations, Berne, Switzerland*

SUMMARY

Today's framework for radio spectrum regulation and spectrum usage is undergoing fundamental changes. In the face of scarce radio resources, regulators, industry and the research community are launching initiatives towards a flexible usage of spectrum. Intelligent radio systems so-called cognitive radios that autonomously coordinate their spectrum usage are a promising approach towards an opening of spectrum. In this article, we therefore discuss medium access control protocols for cognitive radios operating in parts of the spectrum originally licensed to other radio services. They identify underutilised spectrum, coordinate its usage and release it again when required by licensed radio systems. We apply therefore 'waterfilling', a known principle in information theory, in the time-domain for the distributed coordination of cognitive radios in spectrum sharing scenarios. This application is here referred to as spectrum load smoothing (SLS). Cognitive radios are realised in this article in modifying the medium access of IEEE 802.11e with the SLS. The ability of SLS to support quality-of-service in the presence of other, competing cognitive radios, and the prevention of harmful interference to licensed radio systems are evaluated. Copyright © 2006 AEIT.

1. INTRODUCTION

In wireless communication, the demand for free accessible spectrum is tremendously increasing. It comes along with stringent restrictions to spectrum utilisation resulting from quality-of-service (QoS) requirements. These requirements are imposed, for instance, by consumer electronics or multimedia applications. Unlicensed spectrum is limited and additional unlicensed spectrum will not be available in the foreseeable future. Regulatory changes from licensed to unlicensed bands are complicated and usually take a long time. It is therefore helpful if future radio systems could autonomously coordinate themselves to support QoS in scenarios where spectrum is shared that is in the presence of other, competing radio systems.

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' [1, 2]. 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. The terms 'smart' and 'spectrum agile' radios are also used in this context [3]. Cognitive radios enable flexible and dynamic spectrum assignment and thus offer a way out of today's regulatory dilemma. On the one hand, the acute demand for open, unlicensed spectrum, and on the other hand the legal rights of license holders.

This article discusses in Section 2 the principle of *spectrum load smoothing (SLS)* as *medium access control (MAC)*-based approach to cognitive radios at two examples: The SLS is applied for coordinating (i) the reservations in a scenario of secondary spectrum usage (here:

* Correspondence to: Lars Berlemann, RWTH Aachen University, Faculty 6, Chair of Communication Networks, Germany.
E-mail: ber@comnets.rwth-aachen.de

Received 30 October 2005
Revised 31 January 2006
Accepted 1 March 2006

reuse of TV-bands) and (ii) for directly coordinating opportunistic spectrum access of multiple cognitive radios. The rationale and the basic algorithm of SLS in time domain are discussed in Section 3, at the example of a single frequency channel. Note that SLS can be generalised towards multiple frequency channels, and towards frequency instead of time domain. A time frame-based interaction model for the evaluation of spectrum sharing scenarios is introduced in Section 4. QoS support in IEEE 802.11e and its limitations in coexistence scenarios are outlined in Section 5. The application of SLS for the re-use of TV-bands in modifying the IEEE 802.11e *hybrid coordinator controlled access (HCCA)* is described in Section 6. Section 7 describes the extension of the *enhanced distributed controlled access (EDCA)* of IEEE 802.11e with the SLS for enabling opportunistic spectrum access. The interaction of radios using SLS, their interference to a primary radio system and the time to reach a mutually agreed distribution of allocations is evaluated. We end with the evaluation of the SLS's ability to support QoS in Section 8, followed by an outlook and conclusion in Section 9.

1.1. Related work

This article continues a row of publications: The rationale and algorithm of SLS is introduced in Reference [4]. *SLS with reservation* is examined in Reference [5] at the example of IEEE 802.15.3a WPANs autonomously coordinating their resource reservations. The *SLS without reservations* and its application in EDCA spectrum sharing scenarios is introduced in Reference [6]. In addition to that, this article introduces another application scenario of SLS with reservations for re-using unused licensed spectrum (here: TV bands). Further on, we summarise our previous work in evaluating the SLS with and without reservations in terms of capabilities to support QoS. A specification of the SLS as policy in the DARPA XG Policy Language [7] in the context of policy adaptive cognitive radios is given in Reference [8].

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 maximisation problem based on the singular-value decomposition of a channel matrix [9]. Through the application of a multi-carrier modulation, the transmission power can be adapted to the transfer function of the radio channel [10]. This view is extended by iterative waterfilling in the context of multiple access channels as analysed in detail in References [11, 12]. In the context of cognitive radios, the iterative waterfilling is also identified in [2] as an alternative to game theoretic interaction in a distributed transmit power control problem. We focus in our article on the transfer of the waterfilling from its application in information theory to the SLS as part of the medium access of spectrum sharing cognitive radios.

2. SPECTRUM LOAD SMOOTHING FOR COGNITIVE RADIOS

SLS realises the secondary usage of spectrum: *Vertical spectrum sharing* is enabled in avoiding harmful interference to primary radio systems. Additionally, the usage of shared spectrum is coordinated in a decentralised way, by taking individual QoS requirements into account. The SLS aims at an improved efficiency of spectrum usage and at the support of QoS in distributed environments. The key objective of SLS is to allocate spectrum with deterministic and predictable patterns. Medium access intervals that are periodically distributed in time are an example for this. The predictability of devices' allocations facilitates the mutual coordination of spectrum usage among different cognitive radios. This is especially the case in scenarios where dissimilar radios cannot communicate with each other directly, but are able to mutually detect interference from each other.

2.1. Distributed coordination of reservations for secondary spectrum usage

The terrestrial TV broadcasts are currently digitalised. This digitalisation improves the utilisation of spectrum, resulting in a reduction of the required spectrum when the number and quality of the TV channels remains unchanged. It is therefore envisioned to allow such unlicensed re-use of the

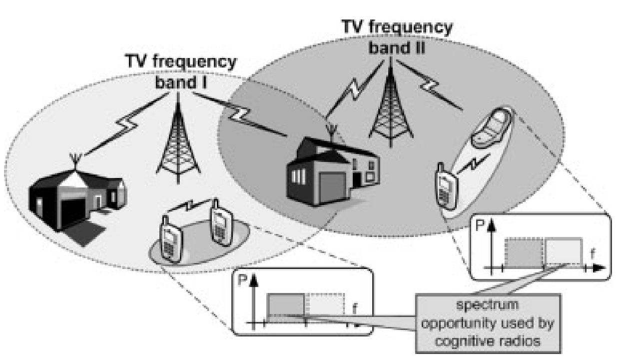

Figure 1. Cognitive radios operating in frequency bands of TV and radio broadcasts. At different locations, the cognitive radios identify different frequencies as unused and regard them as spectrum opportunities.

entire TV broadcast band for cognitive radios that scan all TV channels throughout the band and operate only upon identification of spectrum opportunities [13]. The working group 802.22 of the IEEE takes up this idea and is targeting at the standardisation of the secondary access to TV-bands as illustrated in Figure 1. Two adjacent TV broadcast sites and two independent pairs of communication cognitive radio devices are shown. The cognitive radios identify locally under-utilised spectrum, here unused TV channels, as spectrum opportunities.

One widely used approach of spectrum sharing is the usage of a *common spectrum coordination channel (CSCC)*. The basic idea of CSCC is to standardise a simple common protocol for periodically signalling radio and service parameters [14]. The DARPA XG Program [15] suggests a dedicated control channel located in licensed spectrum for coordination of sharing the spectrum. We take up these ideas and apply the SLS for distributed coordination of reservations transmitted on this dedicated control channel for re-using TV-bands as outlined in Section 6.

2.2. Opportunistic spectrum usage

Additionally, we concentrated on the direct coordination of medium access in opportunistically used spectrum without using reservations. The SLS enables opportunistic spectrum usage through (i) identification of spectrum opportunities, (ii) using them in a coordinated way and (iii) releasing the spectrum again if it is required by primary radio systems. Spectrum usage by opportunistic operation in licensed and unlicensed frequencies is illustrated in Figure 2. Characteristic spectrum usage patterns in the frequency bands at 5 GHz are depicted: Three IEEE 802.11a frequency channels of 20 kHz located in unlicensed spectrum are shown, together with two adjacent channels in licensed spectrum. Cognitive 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 frequently operate 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 spectrum usage measurements of IEEE 802.11k [16, 17], which are not considered here. The example of Figure 2 illustrates the allocations (light grey) of spectrum sharing cognitive radios, which apply the principle of SLS when allocating spectrum opportunities. IEEE 802.11a radios demand the access to the channels at 5200 MHz, 5220 MHz and 5240 MHz with the same random pattern: At 5240 MHz, cognitive 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 is not interfered by the cognitive radios. At 5280 MHz, no radio systems of the license holder are operating. Thus the cognitive radios access this spectrum in coordinating each other with the help of SLS.

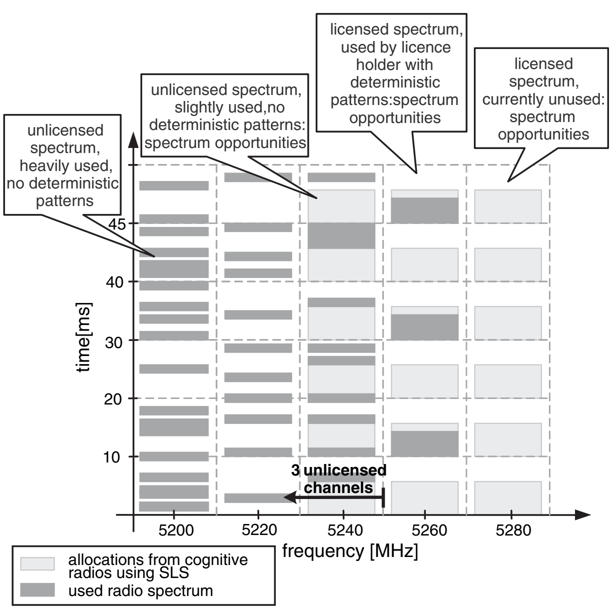

Figure 2. Spectrum usage example at 5 GHz. Three 802.11a channels and frequencies above are depicted. The dark grey fields indicate used spectrum. Cognitive radios use SLS to identify and allocate spectrum opportunities (light grey indication).

3. SPECTRUM LOAD SMOOTHING IN TIME DOMAIN

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

3.1. Algorithm

Figure 3 describes the principle of SLS at the example of the time domain and a fixed, single frequency channel. A periodic, frame-based MAC protocol provides the basis for coordination and interaction. It is later in this article introduced by the IEEE 802.11e beacon period

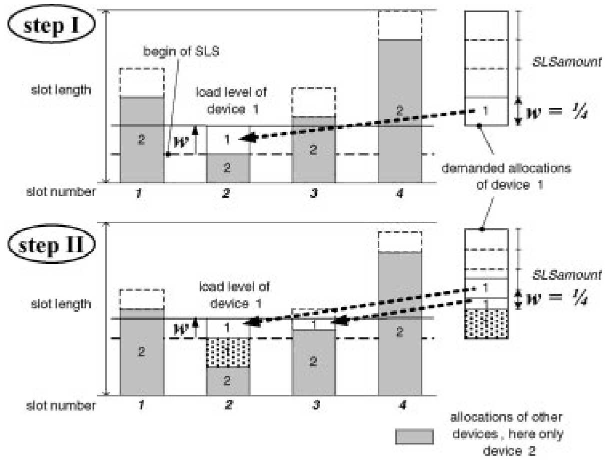

Figure 3. The principle of SLS in the time domain over a frame divided into four time slots with same lengths. The initial two steps of the iterative algorithm are depicted.

(superframe). Once per MAC frame, a device decides about its spectrum access in applying the SLS. The frame consists here of four slots with equal durations. A slot is a time interval during which the multiple access occurs. The slotted structure is regarded as mandatory and respected by all devices. All devices need to know the slot structure *a priori* or have to learn it from spectrum observation. In a distributed environment, the slot length can be identified with the help of the autocorrelation function of the observed allocations [18]. Coexisting legacy communication systems or protocol specific limitations may however lead to violations of the slotted structure. The SLS deals with such violations in regarding an ongoing allocation from the last slot as first allocation of the current slot. Thereafter, the devices follow the intended access order of smoothed allocations of the ongoing slot.

The SLS is an iterative algorithm: It redistributes the allocations of a device with the aim of getting an equalised—smoothed—overall utilisation of the four slots. This smoothed utilisation is referred to as *load level*. The initial two steps of the iterative determination of the smoothed load level are depicted in Figure 3. The iterative distribution of the devices' allocations on the available slots considers the added allocations of all other devices. In Figure 3 only one device, namely device 2 is present as interferer. The initial load level of device 1 is increased stepwise beginning with the less utilised slot, here 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 Figure 3, step I, slot 2 and in step II, slots 2 and 3). These (spectrum load) smoothed allocations are subtracted from the amount, which is still to be distributed, depicted in Figure 3 in the upper right corner of each step. Thus from iteration to iteration, the step size w decreases as well as the remaining amount of allocations while the load level increases. The accuracy of the algorithm defines a criterion for ending this iterative algorithm.

3.2. Spectrum load smoothing with and without reservations

SLS may be based on observing past frames, as introduced in Section 7. The SLS can be improved through the usage of reservations as outlined in Section 6. The *SLS without reservations* is performed 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 ($SLSamount = 100\%$). To enable without reservations, a fast coordinated and stable smoothed allocation scheme, the *SLSamount* is decreased, on the way to the smoothed allocation solution. In control theory, the *SLSamount* would therefore be regarded as an attenuation factor. The flow chart of Figure 4 depicts the SLS with and without reservations under consideration of a flexible amount of redistributed allocations. Our simulations, as introduced in [4], have indicated that an initial value of $SLSamount = 10\%$ is suitable to enable stability and reaching a smoothed overall allocation distribution in a short

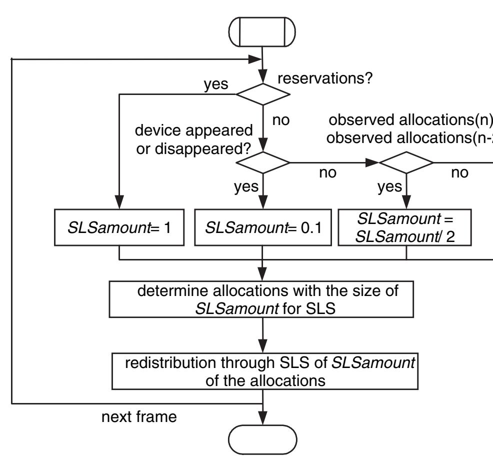

Figure 4. Flow chart of iterative SLS with an adaptive amount of redistributed allocations.

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 all slots. The *SLSamount* is halved, as outlined in Figure 4, if the overall allocations of the last but one frame equal the allocations of the present frame. This is done to prevent a yo-yo effect: Devices simultaneously identify a less utilised slot, redistribute their allocations to this slot, overload it and shift in the consecutive frame these allocations back to the original now underutilised slots. In case of a device initiating or ending transmissions the smoothed, mutually agreed allocations are obsolete and have do be coordinated again. The *SLSamount* is, therefore, reset to 10%.

3.3. Redistribution of allocations through SLS

Figure 5 depicts the SLS in the time domain based on a slotted, periodic frame (the definitions are used below). Here, three decentralised operating devices coordinate their spectrum allocations. Each device performs SLS, that is distributes its allocations over a *distance of smoothing* introduced by the maximum tolerable service time of the device's applications. The services time refers to the total duration required for completely transmitting a higher layer data packet from one MAC layer entity to another including segmentation and reassembly. The timing diagram of the resulting channel is additionally depicted. The devices decide about their demanded allocations during a frame at the beginning of the corresponding frame. This decision cannot be modified during the frame. The *distance of smoothing* is measured in a multiple of the slot lengths. The slotted structure of the frame is introduced by device 1 as first

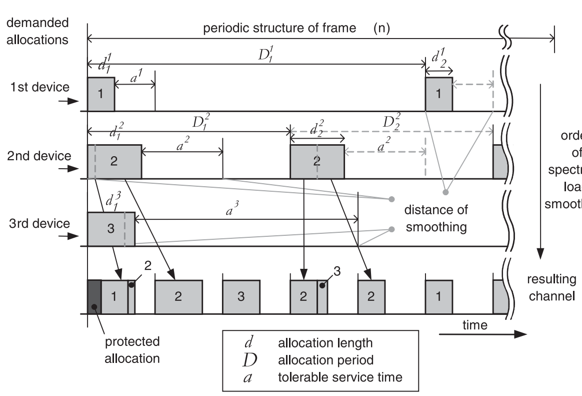

Figure 5. Timing diagram of SLS in the time domain. Each device has an individual distance of smoothing.

device initiating a transmission at the surveyed location. The order of SLS is given through the temporal appearance of the devices. The protected allocation, marked dark grey in Figure 5, may belong to a primary radio system or represents a dedicated coordination period. Such a coordination period can be used for broadcasting reservations. It is not considered here but is used for broadcasting beacons holding reservations in the IEEE 802.15.3a WPAN scenario of [5].

4. EVALUATION OF SPECTRUM LOAD SMOOTHING IN SPECTRUM SHARING SCENARIOS

We define a frame-based coordination model to analyse and evaluate the SLS together with the resulting interaction in spectrum sharing scenarios. We will modify the medium access of IEEE 802.11e in applying the SLS. The following definitions correspond to the ones of the game model [19] introduced in Reference [18] and refined in Reference [20]. The coordination model enables a frame-based interaction consisting of three phases: (i) the decision taking about the intended allocations during a frame corresponding to the SLS, (ii) the allocations of the shared medium within the frame and (iii) the observation of the medium utilisation as basis for a decision in the next frame.

4.1. Definitions

The coordination model considers three (to the frame duration normalised) abstract QoS targets with the help of the definitions from Figure 5: (i) the throughput $\Theta \in [0, 1]$, (ii) the period length $\Delta \in [0, 1]$ and (iii) the delay $\Xi \in [0, 1]$. The supported applications and services impose the devices' requirements for these QoS targets.

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

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

$L^i(n)$ 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 $l, l = 1 \ldots L$, of device i in frame n. The normalised period length $\Delta^i(n)$ specifies the time between two consecutive allocations

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

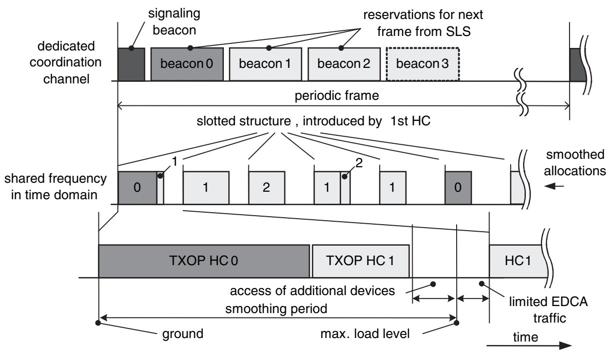

Figure 6. Re-use of TV-bands: IEEE 802.11e HC spectrum sharing scenario. HCs use a dedicated coordination channel for a broadcasting their beacons containing reservations. SLS is applied for the decentralised coordination of these reservations.

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 can thus be regarded as cooperation [4, 18]. The period length is a measure for predictability and the success of mutual coordination (without reservations). The normalised 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 application of SLS as MAC layer-based approach for distributed coordination leads to an additional segmentation of allocations. Therefore, the service time is evaluated as fourth QoS parameter in Section 8 in order to enable a fair comparison to legacy scenarios without SLS. The duration of an allocation, in 802.11e referred to as *Transmission Opportunity (TXOP)* duration, is part of the service time. The tolerable service time $a^i(n)$ is the maximum service time that the device i tolerates in frame n and is above introduced as *distance of smoothing*. Allocation attempts, which lead to longer service times than tolerated, are discarded.

5. QoS SUPPORT IN IEEE 802.11E

In order to support QoS, IEEE 802.11e introduces a central instance referred to as *hybrid coordinator (HC)*. Its medium access is called HCCA. The distributed, contention-based channel access of the HC is called EDCA. For a detailed description and evaluation of IEEE 802.11e see for instance References [21, 22]. It is shown there that for the support of QoS on the basis of the EDCA mutual coordination for collision avoidance is desirable. The IEEE 802.11 spectrum access corresponds to the CSMA/CA principle. The competitive access to each slot of the periodic frame is here harmonised by the SLS under consideration of observed past frames or reservations. Collision avoidance is established in defining access order mechanisms to the wireless medium.

The following sections evaluate the level of QoS support in different spectrum sharing scenarios. Our frame-based coordination model and the basic IEEE 802.11e access mechanisms to a shared resource are evaluated with the help of our Matlab-based simulator YouShi2 [18]. We consider spectrum sharing scenarios of completely overlapping networks that operate at the same frequency channel, time and location. Further, we neglect side effects resulting from the hidden-station problem, link adaptation and power control and we assume a simplistic radio channel. A decision taking instance, as part of the *station management entity (SME)*, realises the SLS in the protocol stack of IEEE 802.11e [18].

5.1. Coexistence of legacy IEEE 802.11e

The behaviour of a HC in case of a collision is not clearly standardised. Therefore, the HC falls back to the EDCA in order to resolute the congestion. Figure 7 illustrates the QoS results, corresponding to the definitions above, of three coexisting HCs (HC0, HC1 and HC2) sharing the same frequency channel. The normalised observed throughput $\Theta^i(n), i \in 0 \ldots 2$ (above), the observed period length $\Delta^i(n), i \in 0 \ldots 2$ (in between) and the observed maximum delay $\Xi^i(n), i \in 0 \ldots 2$ (below) in frame n are depicted. Figure 8 and Figure 9 are structured in the same

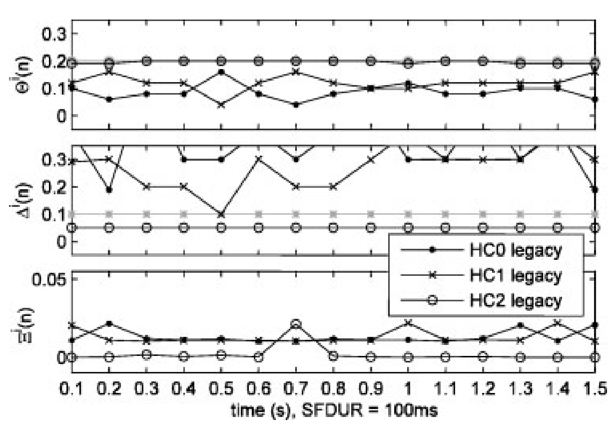

Figure 7. Legacy IEEE 802.11e HC coexistence scenario. The allocation attempts are uncoordinated and fail in colliding. A QoS support is impossible.

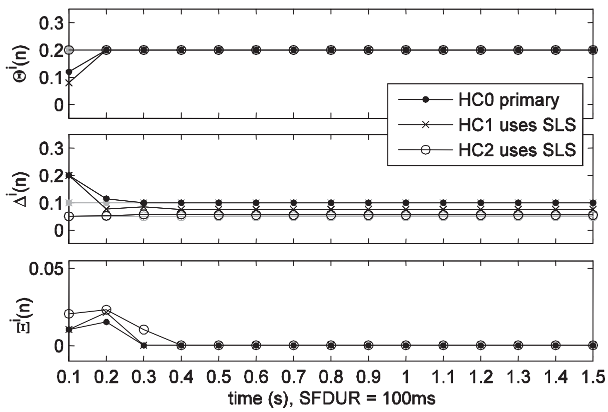

Figure 8. IEEE 802.11e HC spectrum sharing scenario. One protected primary HC and two HCs using SLS with reservations. A stable, coordinated allocation distribution is reached after four frames.

way and illustrate similar coexistence scenarios that are introduced later. We evaluate the mutual interference of the HCs' allocation attempts over 15 IEEE 802.11e superframes. Each frame has a typical duration of $FrameLength = SFDUR = 100$ ms. The QoS requirements for the throughput and period length are marked grey. In the scenarios of this evaluation, the three 802.11e HCs have a fixed requirement of allocating 20% of the medium: $\Theta^i_{\text{req}} = 0.2, i \in 0 \ldots 2$. The requirements for the period lengths are assumed as follows: $\Delta^0_{\text{req}} = 0.1, \Delta^1_{\text{req}} = 0.1$ and $\Delta^2_{\text{req}} = 0.05$. In the legacy, HC coexistence scenario of Figure 7, the allocations attempts of the HCs collide frequently, mutually delay each other and/or have to be discarded. Thus the observed throughput is reduced and the requirement is missed. 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 back-fallen used EDCA. This leads to unpredictable allocations of the shared medium and thus illustrates the inability of legacy HCs to guarantee QoS without exclusive access to a shared medium.

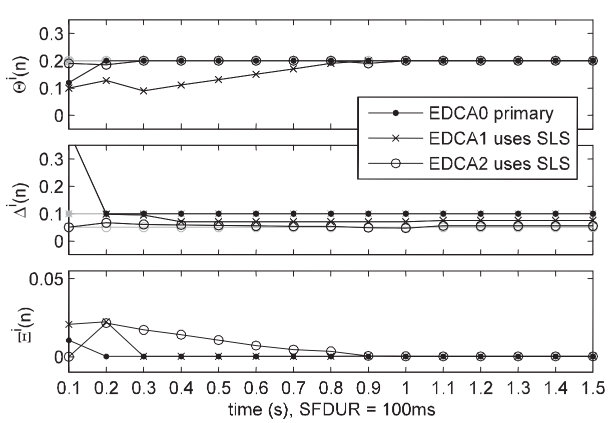

Figure 9. IEEE 802.11e EDCA spectrum sharing scenario. A primary radio system, here EDCA0, is to be protected and two secondary EDCAs use SLS without reservations. A coordinated distribution of allocations is reached after 11 frames.

6. SLS WITH RESERVATIONS—APPROACH TO RE-USE OF TV-BANDS

As outlined in Section 2.1, a dedicated coordination channel is one option for enabling secondary spectrum usage through signalling. The successful reception of a periodic signalling beacon indicates spectrum opportunities to the cognitive radios. In case the periodic signalling, beacon is missed or the beacon itself prohibits spectrum access, the cognitive radios defer immediately from spectrum access. In this way, an instantaneous release of spectrum is guaranteed when the primary system requires spectrum usage. Installing the equipment for broadcasting the signalling beacon is part of the rules imposed by spectrum regulation for allowing secondary spectrum access. The coordination channel is protected against interference in using a fraction of the unused licensed spectrum designated for secondary usage. This approach requires two independent radio parts for simultaneous reception and transmission on two frequencies.

As illustrated in Figure 6, modified IEEE 802.11e HCs can realise secondary spectrum usage: The HCs sequentially transmit their beacons on the coordination channel in the order of their local appearance. Frequencies that are available for secondary usage are broadcasted in the signalling beacon. The HCs' beacons contain piggy-backed reservations for spectrum access to these frequencies. The HCs apply the SLS for decentralised coordination of their reservations. Figure 6 exemplarily depicts a single frequency channel shared by multiple HCs. The timing diagram and composition of a MAC frame are depicted. The periodic signalling beacon transmitted on the coordination channel introduces a periodic frame structure for mutual coordination of the HCs on the shared frequency. The reservations transmitted on the coordination channel refer to the subsequent frame (and not to the ongoing one). The HCs observe each frame and re-distribute thereafter their demanded allocations for the next frame and adapt their broadcasted reservations accordingly.

Besides television broadcasts, TV broadcasting companies often operate additional communication systems in underutilised TV-bands assigned to them: Proprietary wireless communication systems are used to connect television cameras and microphones with outside broadcast vans. The nature of the SLS enables the prioritisation and protection of such communication systems in case of spectrum sharing. The primary communication system, in Figure 6 represented by HC0, may introduce the slotted structure of the periodic frame corresponding to its QoS requirements and allocate spectrum accordingly. The SLS using HCs, here HC1 and HC2 coordinate their reservations in taking HC0 into account and distribute their allocations around HC0's allocations. The presence of the prioritised HC0 is not required for the SLS of the other HCs: They are also able to coordinate reservations without any help of HC0.

The point of time where the (spectrum load) smoothed allocations begin is referred to as *ground*. The ground is identical with the beginning of a time slot if the slot is used completely for SLS. 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 HCs initiate transmission corresponding to their reservations on the basis of CSMA/CA. The *maximum load level* is the upper border of the smoothing period within a slot. In the case of a slot completely used for SLS, the maximum load level is identical with the end of a slot. The ground and the maximum load level imply means for realising priorities and admission control of the medium access of the SLS: Less-prior EDCA traffic may access in the limited phase between maximum load level and end of the frame.

A spectrum sharing scenario of one primary radio system, here HC0, and two HCs (HC1 and HC2) using SLS with reservations for mutual coordination is depicted in Figure 8. The QoS requirements are the same as in the legacy HC coexistence scenario. The allocations of the primary radio system are to be prioritised: The SLS using HC1 and HC2 identify free time intervals and distribute their allocations around the transmissions from the license holding HC0. The slotting for SLS is introduced by the periodic allocations of HC0. The transmission interval, that is the slotted frame structure, is broadcasted in the signalling beacon. Alternatively, the interval can be observed and identified by HC1 and HC2 with the help of an autocorrelation function of the observed allocations [18].

Here, the frame is divided for SLS into 40 slots and we assume that HC1 has a fixed distance of smoothing (tolerable service time) of 3 slots while HC2 has a distance of smoothing of 2 slots; thus $a^1 = 7.5$ ms and $a^2 = 5$ ms. Corresponding to the application example introduced above, the reservations are successfully transmitted on a dedicated coordination channel. A coordinated allocation distribution is reached after four frames. This is indicated by the observed period length ($\Delta^i(n)$) of the HCs that is constant thereafter and the demanded allocations do not delay ($\Xi^i(n)$) each other—thus the allocations are fixed and a mutually coordinated solution is reached. The allocations of the incumbent HC0 are unaffected: The requirements regarding the throughput ($\Theta^i(n)$) and period length are fulfilled and no allocations are delayed, besides in the first frame. The first frame is necessary to enable an initial observation of reservations. In applying the SLS, HC1 and HC2 are able to allocate their required allocations to the demanded point of times resulting from the SLS. Additionally, collisions are avoided and a 'smoothed' overall utilisation of the available slots is reached.

7. SLS WITHOUT RESERVATIONS—OPPORTUNISTIC SPECTRUM USAGE SCENARIO

The opportunistic spectrum usage in applying the SLS without reservations is outlined in this section. The timing diagram of a periodic IEEE 802.11e superframe in Figure 10 illustrates the necessary modification at the medium access corresponding to the 802.11e EDCA in order to avoid mutual delays and collisions. The 802.11e superframe has a slotted structure, here introduced by EDCA1, which is used for applying the SLS as discussed in Section 3. The primary radio system is represented by EDCA0: Its allocation attempts have to be successful and may not be interfered by the cognitive radios (realised as modified EDCA1-4). As illustrated in Figure 10, the SLS can be performed without an announcement of reservation information with the help of individual access periods for each device in each slot. These SLS using

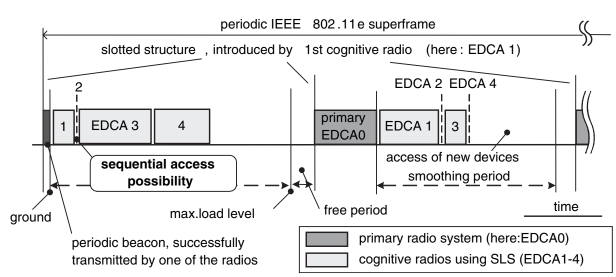

Figure 10. IEEE 802.11e EDCA coexistence scenario. SLS without reservations: The stations have an individual access period within a slot in the order of their initial transmission in the considered area.

EDCAs follow a coordinated order of access to prevent collisions: The EDCAs get access possibilities common to all slots of the frame (through intended left free periods), in the order of their initial transmission within the considered area. Corresponding to the SLS principle, no communication for coordination is required between the primary radio system and the SLS using EDCAs: Each cognitive radio observes the allocations of the past frames and identifies time periods in which the frequency channel is unused. It is assumed that the allocation patters of all spectrum sharing radios do not fluctuate much from one frame to another. If required, an additional buffering is done in order to enable deterministic allocation patterns.

In our scenario of coexisting IEEE 802.11e stations using EDCA, the SLS is done simultaneously at the beginning/end of each frame. A spectrum sharing scenario of one incumbent primary radio system, here EDCA0, and two EDCAs that apply SLS without reservations for mutual coordination is depicted in Figure 9. The QoS requirements are the same as in the legacy HC coexistence scenario from above. The allocations of the primary radio system 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. The frame is again divided for SLS into 40 slots and we assume again that EDCA1 has a fixed distance of smoothing (tolerable service time) of $a^1 = 7.5$ ms while EDCS2 has a distance of smoothing of $a^2 = 5$ ms. The first frame is again required for EDCA1 and EDCA2 to observe the allocation pattern from EDCA0. With the second frame interference to EDCA0 is avoided. An observation of EDCA0 before initially accessing spectrum would prevent this interference but it can not be assumed in general, that the primary radio system is already transmitting, when cognitive radios would like to access spectrum opportunistically.

In the HC spectrum sharing scenario from Section 6 all allocations can be redistributed per frame ($SLSamount = 100\%$) due to the usage of reservations. Contrary, our spectrum sharing scenario of EDCA stations: It implies a more complicated coordination problem as outlined in Section 3.2. 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 Figure 4. In order to focus on the main effects, we assume in the following a constant $SLSamount = 10\%$ [4]. 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 redistributed by the SLS (EDCA1 and EDCA2)—do not collide or delay each other. Nevertheless, the presence of the incumbent radio system increases the distance between two consecutive allocations and EDCA2 fails to meet its requirement of $\Delta^2_{req} = 0.05$.

In comparing the results from SLS without reservation (Figure 9) with the results from SLS with reservations (Figure 8) the advantage of reservations is clearly observable. In two comparable scenarios, the usage of reservations leads in after 4 frames to a coordinated solution in comparison to 11 frames required without reservations. In both scenarios, the primary radio system is successfully protected from interference in applying the SLS principle.

8. EVALUATION OF QoS CAPABILITIES

The three spectrum sharing scenarios from above are analysed in this section related to the support of QoS. Figures 11, 12 and 13 depict, therefore, the normalised observed throughputs and the *complementary Cumulative Distribution Functions (CDF)* of the observed service times from the three radios (either HCs or EDCAs) in the corresponding spectrum sharing scenario. As above, the radios require to access 20% of the medium ($\Theta^i_{req} = 0.2, i \in 0 \ldots 2$) and the required period lengths are assumed again as $\Delta^0_{req} = 0.1, \Delta^1_{req} = 0.1$ and $\Delta^2_{req} = 0.05$. The QoS evaluation is done over 200 frames (with $SFDUR = 100$ ms), while the initial frame required for mutual observation, as illustrated in Figures 7–9, is not considered here. The horizontal dashed grey line marks the 98 percentile of the service times' CDF.

Figure 11 illustrates demonstratively the coexistence problem of legacy HCs sharing the same frequency. Both, HC0 and HC1 fail considerably to meet their required throughput due to frequent collisions, mutual delays and/or discarding of intolerably delayed allocations, as also indicated in Figure 7. The fixed TXOP durations of the HCs of 1 ms and 2 ms respectively are observable, as they are contained in the service times. The steps in the CDF reflect the mutual delays and the trailing edges are reasoned in collisions and resulting backoff of the EDCA for contention resolution. The coexistence problem leads to unpredictable service times, which are out of the control of the HCs.

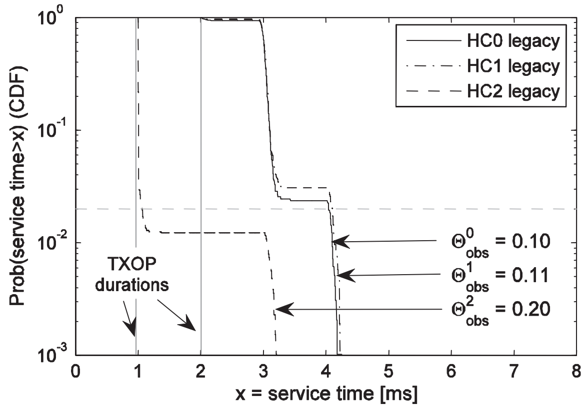

Figure 11. Service times in coexistence scenario of three IEEE 802.11e HCs. Due to missing coordination, the observed throughput is essentially reduced and the HCs' allocations considerably delay each other.

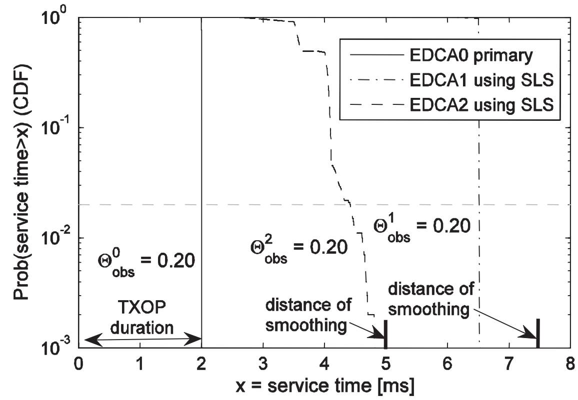

Figure 13. Service times in the IEEE 802.11e EDCA spectrum sharing scenario. EDCA0 represents the primary radio system. EDCA1 and EDCA2 use SLS without reservations to coordinate opportunistic spectrum access. No legacy EDCA traffic is present.

The observed QoS in the HC spectrum sharing scenario with distributed coordination of reservations is shown in Figure 12. In this scenario, a less prior EDCA traffic is present which accesses the medium in case it is idle. The offered EDCA traffic load is 2 Mbit/s and the TXOP duration of the EDCA's allocations is limited to *TXOPlimit* = 0.3 ms. All HCs fulfil their required throughputs. HC0 has a fixed allocation pattern, while HC1 and HC2 separate their allocations and use SLS for redistributing them. The service time distribution of HC0 indicates (i) that HC1 and HC2 are not delaying HC0 and (ii) the legacy EDCA traffic delays HC0's allocations up to its *TXOPlimit*. The fixed TXOP duration of the prioritised HC0 of 2 ms is also well observable. The distance of smoothing (for HC1 7.5 ms and for HC2 5 ms respectively) is an upper limit for the maximum observed service time (transmission duration). Thus the tolerable service time, that is distance of smoothing, is decisive for the observed total service time. A completely interference free operation of HC0 can be guaranteed if EDCA operation is prohibited.

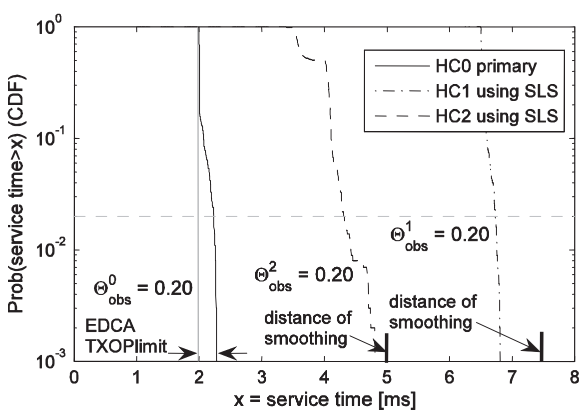

Figure 12. Service times in the IEEE 802.11e HCs spectrum sharing scenario. The HCs use SLS reservations in transmitting them on a dedicated coordination channel. Less-prior EDCA traffic is present.

The opportunistic access to spectrum under protection of a primary radio system is evaluated in Figure 13. EDCA0, representing the primary radio system has a fixed allocation pattern, while EDCA1 and EDCA2 use the SLS without reservations with *SLSamount* = 10% for mutual coordination as outlined in Section 7. Here, no legacy EDCA is allowed, in order to prevent any interference to the primary radio system. All EDCAs fulfil their required throughputs and the primary radio system is not interfered: EDCA0's observed service time is reduced to the transmission duration. The distances of smoothing (the same as above) are again an upper limit for the maximum observed service time. A distributed coordination and deterministic spectrum access, as required for the support of QoS, is successfully reached in applying SLS.

9. CONCLUSION

Spectrum licensing may change radically over the next years towards open spectrum. Many new exciting research challenges in wireless communications will emerge. Cognitive radios are promising candidates for dynamic as well as flexible spectrum regulation and usage, ultimately increasing the efficiency of spectrum utilisation.

The SLS is a candidate approach to realise QoS support in different licensing approaches to secondary spectrum usage: The restricted re-use of licensed spectrum on the basis of reservations can be coordinated by the SLS. Further, the opportunistic access to under-utilised spectrum under protection of a primary radio system is enabled in applying the SLS. The applicability of SLS is independent of the number of radio networks for completely and partially overlapping wireless networks. Future work will concentrate on the consideration of nondeterministic allocation patterns resulting from varying traffic. A more realistic modelling of the radio channel is envisaged.

The MAC protocols of many TDMA-based wireless systems like IEEE 802.16 or H/2 use periodic spectrum allocation patterns and facilitate the usage of SLS. The success of the SLS depends essentially on the cooperation by all radios as no means to enforce cooperation like punishment are considered. Thus the SLS is an option for a spectrum etiquette imposed by the license holder or regulation authority.

REFERENCES

1. Mitola J, III, Maguire GQ, Jr. Cognitive radio: making software radios more personal. *IEEE Personal Communications Magazine* 1999; **6**(4):13–18.
2. Haykin S. Cognitive radio: brain-empowered wireless communications. *IEEE Journal on Selected Areas in Communications* 2005; **23**(2):201–220.
3. Mangold S, Zhong Z, Challapali K, Chou CT. Spectrum agile radio: radio resource measurements for opportunistic spectrum usage. *Proc. of 47th annual IEEE Global Telecommunications Conference, Globecom 2004*, Dallas TX, USA.
4. Berlemann L, Walke B. Spectrum load smoothing for optimized spectrum utilization—rationale and algorithm. *Proc. of IEEE Wireless Communication and Networking Conference, WCNC 2005*, New Orleans LA, USA.
5. Berlemann L, Hiertz GR, Walke B. Reservation-based spectrum load smoothing as cognitive medium access for spectrum sharing wireless networks. *Proc. of European Wireless 2005*, Nicosia, Cyprus; 547–553.
6. Berlemann L, Mangold S, Hiertz GR, Walke BH. Spectrum load smoothing for cognitive medium access in open spectrum. *Proc. of 16th IEEE Conference on Personal, Indoor and Mobile Radio Communications, PIMRC 2005*, Berlin, Germany.
7. DARPA XG Working Group. 'XG Policy Language Framework. Request for Comments,' Version 1.0, Prepared by BBN Technologies, Cambridge MA, USA, April 2004.
8. Berlemann L, Mangold S, Walke BH. Policy-based reasoning for spectrum sharing in cognitive radio networks. *Proc. of 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2005*, Baltimore MD, USA; 1–10.
9. Kasturia S, Aslanis J, Cioffi JM. 1990. Vector coding for partial-response channels. *IEEE Transactions on Information Theory* 1990; **36**(4):741–762.
10. Gallager RG. *Information Theory and Reliable Communication*. Wiley: New York, NY, USA, 1968.
11. Yu W, Rhee W, Boyd S, Cioffi JM. 2004. Iterative water-filling for Gaussian vector multiple-access channels. *IEEE Transactions on Information Theory* 2004; **50**(1):145–152.
12. Popescu DC, Rose C. *Interference Avoidance Methods for Wireless Systems*. Kluwer Academic Publishers: New York, NY, USA, 2004.
13. Federal Communications Commission. 'Notice of Proposed Rulemaking (FCC 04–113): unlicensed operation in the TV broadcast bands,' ET Docket No. 04–186, 25 May 2004.
14. Raychaudhuri D, Jing X. 2003. A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands. *Proc. of 14th IEEE Conference on Personal, Indoor and Mobile Radio Communications, PIMRC 2003*, Beijing, China.
15. DARPA XG Working Group. 'The XG Vision. Request for Comments,' Version 2.0, Prepared by BBN Technologies, Cambridge MA, USA, January 2004.
16. Mangold S, Zhong Z, Hiertz GR, Walke B. 2004. IEEE 802.11e/802.11k Wireless LAN: spectrum awareness for distributed resource sharing. *Wireless Communications and Mobile Computing* 2004; **4**(8):881–902.
17. Mangold S, Berlemann L. 2005. IEEE 802.11k: improving confidence in radio resource measurements. *Proc. of 16th IEEE Conference on Personal, Indoor and Mobile Radio Communications, PIMRC 2005*, Berlin, Germany.
18. Mangold S. 2003. Analysis of IEEE 802.11e and Application of Game Models for Support of Quality-of-Service in Coexisting Wireless Networks; Thesis (PhD): Chair of Communication Networks, RWTH Aachen University, Aachen Germany: Wissenschaftsverlag Mainz.
19. Berlemann L, Mangold S, Hiertz GR, Walke B. Radio resource sharing games: enabling QoS support in unlicensed bands. IEEE Network, Special Issue on 'Wireless Local Area Networking: QoS Provision and Resource Management' 2005; **19**(4):59–65.
20. Berlemann L, Hiertz GR, Walke B, Mangold S. Cooperation in radio resource sharing games of adaptive strategies. *Proc. of IEEE 60th Vehicular Technology Conference, VTC-Fall 2004*, Los Angeles CA, USA; 3004–3009.
21. Choi S, del Prado J, Shankar S, Mangold S. IEEE 802.11 e contention-based channel access (EDCF) performance evaluation. *Proc. of IEEE International Conference on Communications,. ICC 2003*, Anchorage, Alaska; 1151 – 1156.
22. Mangold S, *et al.* 2003. Analysis of IEEE 802.11e for QoS support in wireless LANs. *IEEE Wireless Communications* 2003; **10**(6):40–50.

AUTHORS' BIOGRAPHIES

Lars Berlemann received his Dr and Diploma degree in Electrical Engineering from RWTH Aachen University, Germany, in 2006 and 2002 respectively. He additionally holds a Diploma degree in Business and Economics from the same university. Since 2002, he serves as a research assistant at the Chair of Communication Networks of RWTH Aachen University, where he is now working as a senior research scientist at various national and European Union funded research projects. Dr Berlemann has published more than 40 reviewed publications including 5 journal articles and was scientific organiser of European Wireless Conference 2005 and PIMRC 2005. His current research interests include the IEEE 802 standard family, coexistence, spectrum sharing, cognitive radio and flexible protocol stacks.

Stefan Mangold is project leader at Swisscom Innovations Ltd., Bern Switzerland, where he is working on cognitive radio, spectrum management, and IEEE 802 standards. Before joining Swisscom in April 2005, Dr Mangold worked at a research lab in the U.S. (2003–2005), and before that at the Chair of Communication Networks (ComNets) of RWTH Aachen University, Germany (1998–2003). He received his Diploma degree and Dr-Ing. degree (summa cum laude) in electrical engineering in 1997 and 2003, respectively, both from RWTH Aachen University. Dr Mangold's current areas of research are operator assisted cognitive radios for spectrum sharing and spectrum etiquette.

Guido R. Hiertz studied Electrical Engineering at RWTH Aachen University. Since April 2002, he is with the Chair of Communication Networks at RWTH Aachen University, working towards his Ph.D. His main research fields are the support for QoS in WLANs (802.11e) and protocols for Gigabit (802.11n), Mesh wireless LAN (802.11s) and PAN (802.15.5). He has contributed to many national and international research projects. He has been involved in the design of the high speed WPAN MAC protocol of WiMedia Alliance that became ECMA standard in 2005. Since 2004, he is a voting member of IEEE 802.11, where he submitted several presentations and proposals. He is charter member of Wi-Mesh Alliance that submitted a joint proposal to 802.11s. He is the inventor/co-inventor of several patents. As student member of IEEE, he has authored/co-authored several papers at IEEE conferences.

Bernhard H. Walke is running the Chair for Communication Networks at RWTH Aachen University, Germany, where about 30 researchers work on topics like air-interface design, development of tools for stochastic event driven simulation and analytical performance evaluation of services and protocols of XG wireless systems. Most of this work continuously has been funded from 3rd parties' grants. He is author of the 2002 book 'Mobile Radio Networks—Networking, Protocols and Traffic Performance' and co-author of the 2001 book UMTS—The Fundamentals and the forthcoming 2006 book 'IEEE 802 Wireless LAN/PAN/MAN Systems: Standards, Models and Traffic Performance'. He has been a board member of ITG/VDE and is Senior Member of IEEE. He has served as Program Committee and Steering Committee Chair of various conferences like the European Wireless (EW) conference that he co-founded. In 2005, he was the Scientific Chair of IEEE-PIMRC 2005, Berlin. His group has substantially contributed to the development of standards like ETSI/GPRS, ETSI/BRAN HiperLAN2, CEN TC 278 DSRC (electronic fee collection), IEEE 802.11e, 802.16 and 802.15.3. From 2001–2003, he was an elected Chair of Working Group 4 (New Technologies) of the Wireless World Research Forum. Prior to joining academia, he worked for 18 years in various industry positions at AEG Telefunken (now EADS AG). He holds a Dr (1975) degree in Information Engineering from University of Stuttgart, Germany.

