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Keywords: Coexistence in Shared Spectrum, Cognitive Medium Access, Distributed Quality of Service Support, IEEE 802.11e

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Reservation-based Spectrum Load Smoothing as Cognitive Medium Access for Spectrum Sharing Wireless Networks

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***Abstract* — This paper focuses on mitigating the coexistence problem of spectrum sharing, quality of service supporting wireless networks. The application of "waterfilling" from the information theory on the medium access of resource sharing wireless networks enables a decentralized mutual coordination and is in the following referred to as Spectrum Load Smoothing (SLS). In using SLS, the competing wireless networks aim at an equal overall smoothed utilization of the spectrum. Based on observing past usage of the spectrum or/and reservations, the wireless networks identify unused radio resources and use these opportunities for communication. In this way, the SLS is an approach to a "spectrum agile radio" that operates in spectrum originally licensed to other (incumbent, primary) radio devices: The SLS implies a search for unused spectrum, interference avoidance under coexistence in utilization of this spectrum, and a release if it is used again. SLS using radios interact and redistribute their allocations of the spectrum under consideration of their individual quality of service requirements. In this way, the SLS enables a decentralized coordination and allows an optimal usage of the frequency spectrum. In summary, the SLS realized a "cognitive medium access". This paper introduces the application of SLS in the time domain at the example of a decentralized coordination of coexisting, quality of service supporting, IEEE 802.11e wireless networks.**

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I. Introduction

The spectrum for *Wireless Local Area Networks (WLANs)* is rather limited and its utilization is under a tough competition. The popularity of WLANs is increasing while these unlicensed frequencies are shared by manifold radio systems. These radio systems are not designed for exchanging information, as for instance Wi-Fi™ (IEEE 802.11), Wi-MAX™ (IEEE 802.16) or Bluetooth™ (IEEE 802.15.1). The upcoming demand of the consumer for higher capacity and *Quality of Service (QoS)* requires in the future an intelligent and flexible spectrum usage. In face of multiple unused licensed frequencies, secondary radio devices are a solution out of this regulatory dilemma: They respect the primary (incumbent, originally licensed) radio systems and use their frequency opportunistically, i.e., only if they are vacant. The currently standardized IEEE 802.22™ is one example for a secondary radio system operating in the licensed frequencies of TV and radio broadcasts. Independent from the characterization of the shared spectrum (an unlicensed frequency band and/or opportunistic used frequencies) a decentralized coordination is necessary to support successfully QoS. Such coexistence scenarios of competing central coordinating instances are not addressed in the existing standards like IEEE 802.11(e)™ [1], [2]. For future radio networks, they are under discussion in standardization groups like the Wi-Fi™ Alliance and IEEE 802.19™. Distributed coordination to support QoS is also a key issue in *Wireless Personal Area Networks (WPANs)* as for instance IEEE 802.15.3a™ [3], where a distributed coordination of reservations is desired.

This paper introduces the *Spectrum Load Smoothing (SLS)* to coordinate and optimize the usage of radio spectrum which is shared in at least one of the following dimensions: Space, time, frequency, carrier or subcarrier, spreading code, transmission power and polarization. The rationale and algorithm of the SLS is introduced in Section II and [4]. Here, the SLS is applied in the time domain at a single fixed frequency: It is done over *Time Division Multiple Access (TDMA)*-like channels which are shared by multiple devices. A device exclusively allocates parts of the channel which is observable by all other devices. The accuracy of the SLS, especially in the case of less predictable user traffic of the devices, is improved through the usage of reservations. These reservations enable a fast coordination of the mutually agreed smoothed utilization of the radio resource. The SLS with reservations is applied in IEEE 802.11e™, as introduced in Section V. First results in terms of capability to to support QoS for this application of SLS in IEEE 802.11e™ are discussed in Section VI and concluded in Section VII.

A. Related Work

The terms "cognitive" and "smart" radios are often used in the context of intelligent spectrum usage [5], [6]. Radio systems that autonomously coordinate the flexible usage of the spectrum are also referred to as "spectrum agile radios" [7]. This paper is a first step towards the realization of such radios in applying SLS as *Medium Access Control (MAC)* layer-based approach for enabling spectrum sharing. The principle

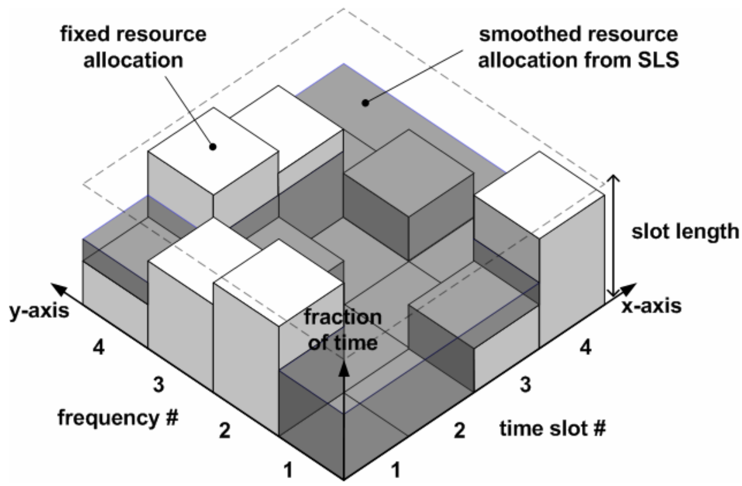

Figure 1. Spectrum Load Smoothing (SLS) in the time and frequency domain of a TDMA/FDMA system.

of SLS realizes a cognitive medium access due to its characteristic as introduced in the following section. 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 [8]. Through the application of a multi-carrier modulation, the transmission power can be adapted to the transfer function of the radio channel [9]. This view is extended by iterative waterfilling in the context of multiple access channels as analyzed in detail in [10]-[12]. This paper refers to the transfer of the waterfilling from its application in information theory to the SLS as part of a cognitive, i.e., a mutually coordinated, medium access of decentralized operating spectrum sharing devices.

II. Rationale of Spectrum Load Smoothing [4]

The SLS of allocations targets at a spectrum optimal, decentralized coordination of QoS supporting devices. This is done in distributing radio resource allocations even and regular over the available shared radio spectrum. As one benefit, the predictability of devices' allocations is improved, facilitating an aimed coordination. Furthermore, this coordination increases the overall throughput of coexisting devices and it enables at any time a high probability of a successful initial access to the shared spectrum. By this means, the coexistence within a single communication system is considered as well as the coexistence of different communication systems implying a cross-system fairness of similar and different communication systems without any direct information exchange. Moreover, spectrum opportunities are identified and used under reduction of interference. Thus, the spectral efficiency is optimized through the SLS.

Fig. 1 illustrates a potential outcome from SLS in a *TDMA / Frequency Division Multiple Access (FDMA)* system. The different time slots are on the x-axis, the frequency is on the y-axis and the relative fraction of an allocation at the total length of a time slot on the z-axis. The dark gray resource allocations result from SLS of one or multiple devices while the other allocations are not considered for SLS, as they are fixed. These fixed light gray allocations result from QoS restrictions or belong to an incumbent communication system. The level of the smoothed allocations is in the following referred to as "load level" and the allocations or empty slots, where the SLS is based on, is called "ground". The SLS consequences, under the restrictions of the devices' QoS requirements, equally distributed free quantities of the transmission medium.

The SLS mainly addresses the case of decentralized communication systems as for example IEEE 802.11™. Devices following the SLS try to achieve an equalized load level in redistributing their allocations. Thus devices with less restrictive QoS requirements may place their allocations in less allocated time slots to let other devices with strict QoS requirements access their demanded slots. Strict QoS requirements can be signaled to all devices, from one frame to another, in filling up, completely or partially, the demanded slot. Due to the SLS, all devices with allocations within a required slot will free it due to the SLS, under the restriction of their own QoS requirements. Additionally, a central instance, as for example a *Hybrid Coordinator (HC)* in IEEE 802.11e™, can coordinate the individual allocation requirements of associated devices with the help of the SLS.

III. Spectrum Load Smoothing in the Time Domain

For details on the algorithm of SLS, its convergence and duration after which a steady solution is reached as well as the specific advantages of the SLS see [4].

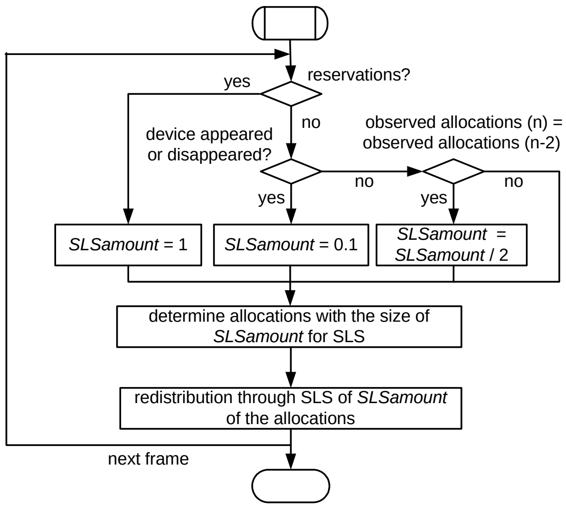

Figure 2. Iterative SLS with adaptive amount of redistributed allocations targeting on smoothed allocations [4].

A. Spectrum Load Smoothing with and without Reservations

It has to be distinguished between (I.) SLS based on the observation of past frames and (II.) SLS improved through reservations. The *SLS without reservations*, which is not considered in this paper, 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. In the case of *SLS with reservations*, i.e., a broadcasting of intended allocations for the actual frame, the SLS is done on the basis of observed allocations of the past frame actualized through the reservations of allocations for the actual frame, if available. The reservations may for instance be part of an extended IEEE 802.11e^{TM} [1] beacon as introduced in Section V. In the context of QoS support all devices prefer a steady and thus predictable outcome from the SLS. In the case of a quasi-stable overall allocation of the medium, all involved devices can be regarded as a coordinated community.

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 as well as 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. 2 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. The *SLSamount* is halved, as outlined in Fig. 2, 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]. This effect is countered in decreasing the amount of redistributed allocations. In case of a device initiating or ending transmissions the smoothed mutually agreed allocation solution is obsolete and has 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 [13].

B. Periodic Structure as Basis

Here, a periodic frame-based MAC protocol is the basis for coordination and interaction. The frame structure is later regarded as IEEE 802.11e^{TM} superframe. The decision about reallocation of resources corresponding to the SLS is done once per frame.

One device, preferably the first device that initiates a transmission, introduces a slotted time frame structure as basis for future cooperation. A slot is a time interval during which the multiple access occurs. In a distributed environment, the slot length can be identified with the help of the autocorrelation function of the observed allocations at begin of each slot [2]. This slotted structure can be changed by all devices, preferably by the first device, from one frame to another, but is assumed to be fixed here. The slotting can be based for instance on the system load, individual QoS requirements of supported applications or the protected allocations of an incumbent radio system. 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 following thereafter the intended access order of smoothed allocations.

C. Redistribution of Allocations through SLS

Fig. 3 depicts the SLS in the time domain based on a slotted, periodic frame; the definitions are used later in Section VI. Here, three decentralized devices coordinate each other and have periodically demanded allocations which do not necessarily have the same length, as for instance the demanded allocations of device 2. Each device performs SLS, i.e., distributes its demanded 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 the SLS is a multiple of the slot length, corresponding to the

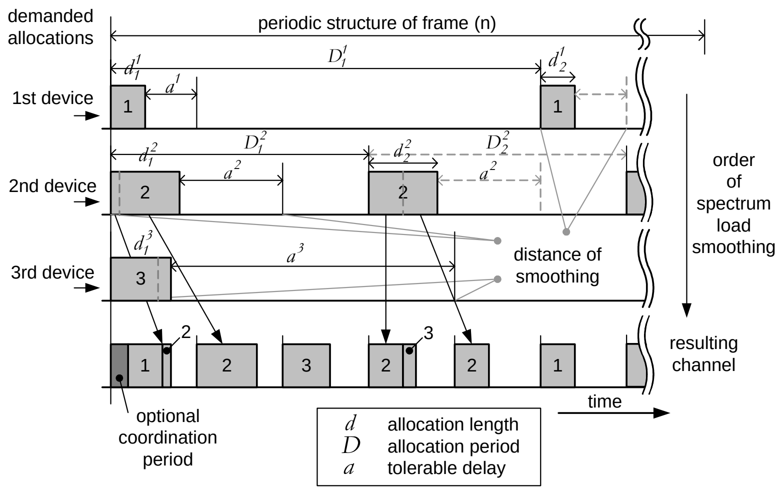

Figure 3. SLS in the time domain. Each device has an individual distance of smoothing. The periodic allocations are smoothed.

slotted structure of the frame which is introduced by device 1 here, as first device initiating a transmission. The order of SLS is given through the temporal appearance of the devices. The simultaneous SLS itself and the collision-free access to the slots is either based on observations of past frames or based on announced reservations during an optional coordination phase; see Section V for an application in IEEE 802.11e™.

In Fig. 3 the first device has the most restrictive QoS requirements, by means of a single slot length as distance of smoothing. This device 1 distributes its allocations first, here under consideration of the optional coordination phase. The smoothed allocations are placed in the first slot directly after the coordination phase and in the sixth slot of the frame. The concept of SLS is observable in focusing on the allocations of the second device, device 2: With a smoothing distance of two slots under consideration of the allocations of the first device and the optional coordination phase, device 2 places most of its demanded allocation duration in the second slot and less time in the first slot. The first and second slot have equal idle duration resulting from the SLS. Device 3 initiates as third device its transmission. After having observed at least one frame, device 3’s SLS results into a placement of its allocations into the third and fourth slot of the current frame.

IV. Overview of Quality of Service Support in IEEE 802.11e™

The main element of the enhancements to 802.11™ for the support of QoS is a central instance called *Hybrid Coordinator (HC)*. It enables a contention free access with the help of the *Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA)* to the wireless channel. The contention based access of the HCF to the channel is called *Enhanced Distributed Controlled Access (EDCA)*. For a description and evaluation of IEEE 802.11e™ see for instance [2].

V. SLS on the Basis of Reservations - Scenario of Coexisting IEEE 802.11e™ HCCA Stations

This section introduces first general terms used in the context of SLS and second outlines its application in a coexistence scenario of IEEE 802.11e™ HCCA stations – both with the help of Fig. 4. Consequently, here each device is a HC with associated stations and the allocations are *Transmission Opportunities (TXOPs)* under the control of a HC. A dedicated coordination period is used for transmitting reservations as part of sequentially sent beacons, as for instance introduced in the MultiBand OFDM Alliance™ [3].

A. *Coordination Period, Ground, Load Level and Smoothing Period*

As outlined above, a dedicated *coordination period* for the announcement of reservation, here being part of an IEEE 802.11e™ beacon, increases the accuracy of the SLS. The coordination phase is located at the beginning of a frame, as being a protected part of the first slot, see Fig. 4. A specific time interval is essentially left unused to enable the access of additional devices. The point of time where the (spectrum load) smoothed allocations begin is referred to as *ground* which is also depicted in Fig. 1. The ground is identical with the beginning of the time slot if the slot is used completely for SLS. In Fig. 4 the first slot has an increased ground, by means of that the coordination period may not be considered for SLS and is thus not subject to the coordinated access of all devices for the transmission of user data. 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 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 devices follow

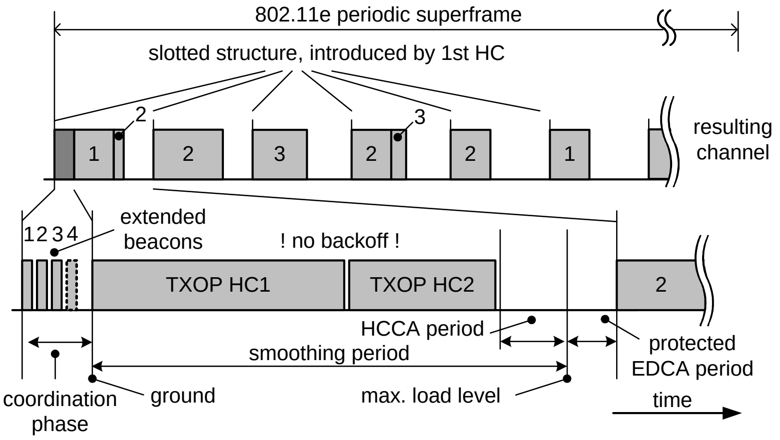

Figure 4. IEEE 802.11e™ HCCA coexistence scenario. SLS with reservations: The different HCs send their reservations within a coordination period at the beginning of the superframe.

the coordinated order of access to prevent collisions. In our application (a wireless communication system of CSMA/CA) there is the necessity of short idle times between two spectrum load smoothed allocations. 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.

B. Application of Spectrum Load Smoothing

The devices are here each a modified IEEE 802.11e™ HC with an individual HCCA mechanism, see Fig. 4. In such a scenario, standard-conform IEEE 802.11e™ WLANs are not able to support QoS [2]. The SLS is used for the decentralized coordination of coexisting HCs with the help of reservations as part of the 802.11e™ beacons, sequentially transmitted within a coordination period at the beginning of an 802.11e™ superframe: The SLS is done successively during the coordination phase. The slotted structure of the superframe is introduced by the first SLS using HC. For collision avoidance, the common access order to all slots is given through the order of initial transmission. The beacons emitted by each IEEE 802.11e™ HC are used for announcing the reserved TXOPs during the coordination phase. Within such a TXOP the HC has the right to initiate a transmission or to assign transmission periods to associated stations.

The EDCAs of all present HCs have an individual resizable period at the end of the superframe. This period is left unallocated through the SLS as it is limited by the maximum load level. The TXOP length of the EDCA traffic as well as in particular the waiting time of the EDCA before accessing the idle medium, is under the control of all HCs.

New HCs may enter the coordinated system in transmitting first their beacon together with their intended reservations in the coordination phase. Due to the SLS the allocations of the new HC are demanded in the chosen slots after the allocations of the already mutually coordinated other HCs.

VI. 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 the IEEE 802.11e™. The following definitions correspond to the ones of the game model introduced in [2] and refined in [13]. 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 a first 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. 3: (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 introduced 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

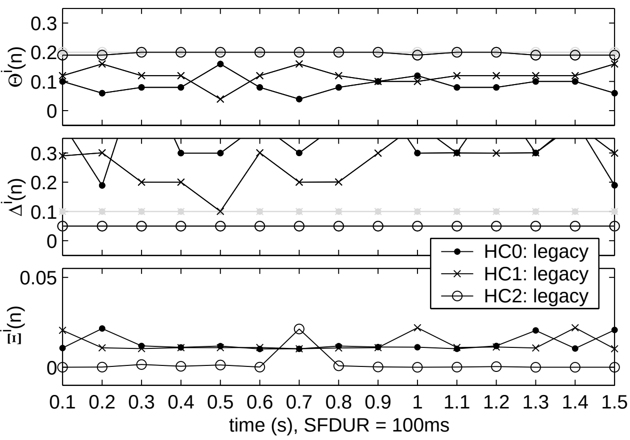

Figure 5. Legacy IEEE 802.11e™ HCCA coexistence scenario. The allocation attemps of the HCs are uncoordinated and fail in colliding. A QoS support is impossible.

$FrameLength$ 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

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

. (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 [2] and [4]. In this way, the period length is a measure for predictability and thus the success of mutual coordination (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.

B. *Coexistence of Legacy 802.11e™ Hybrid Coordinators*

Fig. 5 illustrates the QoS results, corresponding to the definitions above. Three coexisting legacy HCs (HC0, HC1 and HC2) are 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. 5 and Fig. 6 for different coexistence scenarios. 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=100ms*. The QoS requirements for the throughput and period length are marked gray. In both scenarios of this evaluation, the three 802.11e™ HCs have a 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 $\Delta^2_{req} = 0.05$. As depicted in Fig. 5, the allocations attempts of the HCs 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 HCs. This leads to unpredictable allocations of the shared medium and thus illustrates the inability of the legacy HCs to guarantee QoS.

C. *HCCA Scenario – SLS with Reservations*

A spectrum sharing scenario of one incumbent primary radio system, here HC0, and two HCs (HC1 and HC2) using SLS with reservations for mutual coordination is depicted in Fig. 6. The primary radio system is the license holder and its allocations are to be protected: The SLS using HC1 and HC2 identify free time intervals and distribute their allocations around the transmissions from the incumbent HC0. Contrary to our HC0, TV broadcast transmissions cannot be delayed but would nevertheless interfere with simultaneous allocations of HC1 and HC2, leading to the same coordination problem. The slotting for SLS is introduced by the periodic allocations of HC0. The transmission interval is observable and can be identified by HC1 and HC2 with the help of an autocorrelation function [2]. Here, the frame is divided for SLS into *40* slots and we assume that HC1 has a fixed distance of SLS (tolerable delay) of *3* slots while HC2 has a distance of SLS of *2* slots; thus $a^1 = 7.5\,ms$ and $a^2 = 5\,ms$. Corresponding to the example of Section V the reservations are successfully transmitted in a dedicated coordination phase. A coordinated allocation distribution is reached after *4* frames as the observed period length of the HCs is constant thereafter – thus the allocations are fixed and a

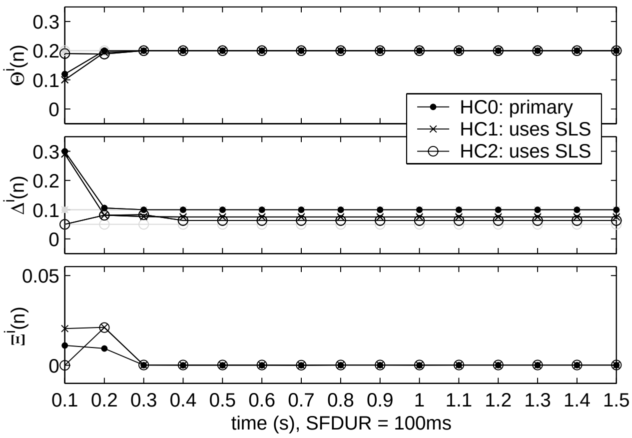

Figure 6. IEEE 802.11e™ HCCA coexistence scenario. One protected primary (incumbent) HC and two HCs using SLS with reservations. A stable coordinated allocation distribution is reached after *4* frames.

mutually coordinated solution is reached. The allocations of the incumbent HC0 are unaffected: The required throughput and period length are fulfilled and no allocations are delayed. 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 utilization of the available slots is reached. The advantages of these smoothed allocation distribution are introduced above and in [4].

VII. Conclusions

The QoS evaluations of the HCCA coexistence scenario has shown that the Spectrum Load Smoothing is a promising new approach to mitigate the problem of distributed QoS support in spectrum sharing wireless networks. A support of QoS is enabled when SLS is applied in such coexistence scenarios. Reservations help to improve the capability for distributed QoS support, especially in the case of less predictable user traffic. As shown, the SLS can be integrated into existing protocol standards. The introduced application in IEEE 802.11e™ will additionally benefit from the new protocol amendments of IEEE 802.11k™, which provide means for measuring and reporting characteristics of spectrum usage. The SLS works independent from the number of networks and accounts for both completely and partially overlapping wireless networks. The SLS enables a mutual coordination without any central organizing instance and realizes therefore a cognitive medium access. An optimum usage of the frequency spectrum resources is the outcome of the SLS and the aspect of fairness between homogeneous and heterogeneous coexisting wireless networks is considered.

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