Spectrum Load Smoothing for Optimized Spectrum Utilization - Rationale and Algorithm

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Abstract — **This paper aims at the mitigation of the destructive, mutual interference of coexisting, quality of service supporting wireless networks in a spectrum efficient way. The application of "waterfilling" from the information theory on the medium access of resource sharing wireless networks enables a decentralized coordinated, opportunistic usage of the spectrum and is in the following referred to as Spectrum Load Smoothing (SLS). In using SLS, the competing wireless networks aim simultaneously at an equal overall smoothed utilization of the spectrum. In observing the past usage of the radio resource the wireless networks interact and redistribute their allocations of the spectrum under consideration of their individual quality of service requirements. Due to the principle of SLS these allocations are redistributed to less utilized or unallocated quantities of the transmission medium. Thereby, the individual quality of service requirements of the coexisting networks are considered. Further, the SLS allows an optimized usage of the available spectrum: An operation in radio spectrum, which was originally licensed for other communication systems is facilitated, as the SLS implies a search for unused spectrum as well as a release if it is needed again. This paper introduces the rationale of SLS and outlines in detail the algorithm which enables a cognitive medium access for multiple devices in a shared spectrum.**

Keywords — Coexistence in Unlicensed Bands, Decentralized Coordination, Optimized Spectrum Utilization, Quality of Service.

I. INTRODUCTION

In practice, *Wireless Local Area Networks (WLANs)* often have to operate in problematic situations: They have to share an unlicensed frequency spectrum and thus may interfere each other severely. The increasing popularity of such WLANs and the upcoming demand for capacity combined with *Quality of Service (QoS)* make an intelligent, coordinated spectrum usage necessary to satisfy future consumer demands. Such coexistence scenarios are not addressed in the existing radio standards like IEEE 802.11(e) [1], [2]. The decentralized QoS support in operation at shared frequencies is consequently one of the key challenges for future wireless communication. This paper introduces therefore a method referred to as *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. Here, the SLS is applied in the time domain at a 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 for data transmission which can be observed by all devices. The SLS allows a centralized and - more important - a decentralized coordination of QoS supporting, coexisting wireless networks. The idea of SLS is outlined in Section II and its application in the time domain is introduced in Section III. The SLS algorithm is based on the observation of past frames and thereof derived expected allocations of the current frame. The accuracy of the SLS, especially in the case of less predictable user traffic, is improved through the usage of reservations. These reservations enable a fast coordination of the mutual agreed smoothed utilization of the radio resource. The advantage of reservations and therefore less complex interaction is illustrated simulative in Section IV.

In the context of intelligent spectrum usage, the terms "cognitive radios" and "smart radios" are often used [3]. Radio systems that autonomously coordinate the usage of the spectrum are also referred to as "spectrum agile radios" [4]. The principle of SLS is derived from the idea of waterfilling, which is well known in the field of multi-user information theory and communications engineering: In a multiple transmitter and receiver environment, waterfilling is used to solve a, necessarily arising, mutual information maximization problem based on the singular-value decomposition of a channel matrix [5]. Through the application of a multi-carrier modulation, the transmission power can be adapted to the transfer function of the radio channel [6]. This view is extended by iterative waterfilling in the context of multiple access channels as analyzed in detail in [7] - [10]. This paper refers to the transfer of the waterfilling from its application in information theory to the SLS as part of the cognitive (mutually coordinated) medium access of decentralized operating devices.

II. THE RATIONALE OF SPECTRUM LOAD SMOOTHING

Wireless networks are referred to as devices for the rest of the paper, as there is no difference from the SLS perspective, if the SLS is done by a single individual communication device or a central coordinating instance as a WLAN *Access*

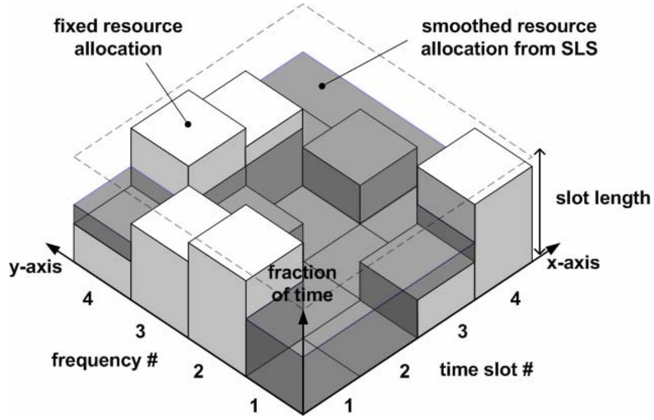


Figure 1. Spectrum Load Smoothing (SLS) in the time and frequency domain of a TDMA/FDMA system.

Point (AP) with associated stations under its control. In this case, an allocation is regarded as specific quantity of the medium which is under the exclusive control of the AP. This AP can assign parts of the allocation to associated stations.

A. The Basic Principle

The SLS of allocations targets at a spectrum optimal, decentralized coordination of QoS supporting devices 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 the 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 to other 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 two-dimensional transmission medium, here the time and frequency domain. 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. Consequently, a *Time Division Multiple Access / Frequency Division Multiple Access (TDMA/FDMA)* system is illustrated. The dark grey 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 grey allocations can be derived from QoS restrictions or belong to an incumbent, licensed 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 results, under the restrictions of the devices' QoS requirements, into equally distributed free quantities of the transmission medium.

To optimally exploit its inherent potential, SLS should be applied by all devices sharing a set of channels. Nevertheless, transmissions of incumbent, legacy or non-SLS using devices are regarded as fixed allocations and the SLS devices distribute, if possible, their allocations around them.

The SLS mainly addresses the case of decentralized communication systems as for example the ordinary decentralized architecture of IEEE 802.11, where coordination between all devices is necessary to reduce mutual interference. 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 signalled 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.

B. Predictable Allocations as Basis

Predictable allocations of a medium by a device enable an aimed interaction with other devices and may be regarded as a contribution to cooperation [2], especially in the absence of a central coordinating instance. The periodicity of resource allocations by a device can be observed and predicted by all other devices. These other devices may adapt their own resource allocations with the aim of partially or completely preventing mutual interference on the shared medium. This can be considered as a contribution to cooperation. The periodicity increases the possibility for other devices to conclude from the observed, delayed or after collisions repeated resource allocations, on the originally demanded allocations of a device. These allocations correspond to the individual traffic demands and QoS requirements. A further reduction of the period length, resulting from an increased number of equally distributed resource allocations per frame, whilst the relative proportion of the resource allocations by devices per frame remains constant, may also be considered as a contribution to cooperation [2]. The aforementioned cooperation measures imply

- Interference reduction and avoidance.
- An increased chance for other devices to reduce the delays experienced for their data packets.
- A reduced blocking probability and access time for new devices initially accessing the medium.

Periodic resource allocations may preferably be performed during unused intervals of the frame to reduce the devices' mutual interferences. Corresponding to the above introduced aspects of cooperation, a cooperating device may improve its capability to support QoS, if all other devices are cooperating as well.

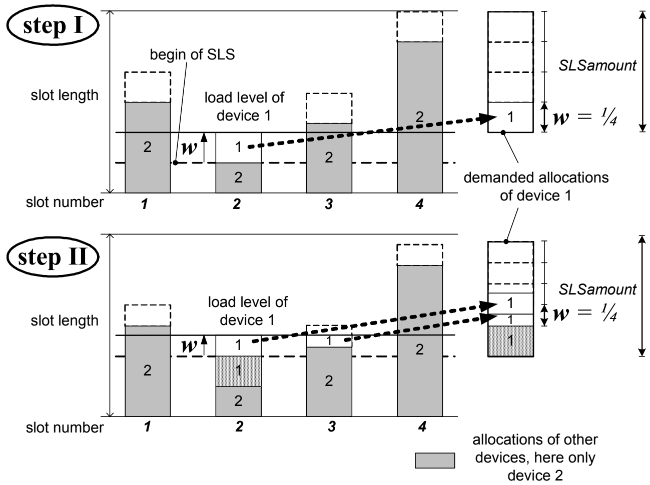


Figure 2. The principle of Spectrum Load Smoothing in the time domain over a frame divided into four slots with the same slot length. The initial two iterative steps of the SLS are depicted.

The predictability of allocations increases the accuracy of the SLS if no reservations are used. In this case the SLS has to be based on observation of past frames. The periodic allocations are the fundament for the SLS, as the SLS requires a common TDMA-like medium access in the case of multiple devices sharing one channel. In the case of a "digital" waterfilling, by means of small periods of time which may be allocated only by one device, this requirement is obsolete.

III. SPECTRUM LOAD SMOOTHING IN THE TIME DOMAIN

For a better understanding we limit the dimension of the medium under competition as depicted in Fig.1 to a single frequency for the rest of the paper without restricting the applicability of the SLS on multiple frequencies. In a first step, we assume a simplistic radio channel and ignore the hidden station problem.

A. The Algorithm

Fig. 2 describes the principle of SLS at the example of the time domain and a fixed, single frequency. We have a fixed time frame structure and the SLS is done by a device once per frame. Here, 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 allocation at begin of each slot [2]. 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 origin. 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

$$w = \frac{\textit{amount of allocations to be distributed}}{\textit{number of slots}}. \qquad (1)$$

The difference between the load level and the allocations of device 2 is filled with allocations of device 1 (see Fig. 2, step II, slot *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.

The devices' distributed allocations are placed in this example on the top - after - the allocations of the other devices. As all devices might (spectrum load) smooth their allocations simultaneously, rules for accessing a slot are necessary and a broadcast of the intended allocations through reservations is preferable to prevent collisions and delays as introduced below. The SLS implies a minimum and maximum size of an allocation after SLS, reasoned for instance in an aimed reduction of the protocol overhead or restrictions to the transmission size depending on the transmission mode of the physical layer.

B. 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 is done simultaneously at the beginning/end of a frame. To enable a mutual interaction the SLS is done in this case step wise from frame to frame in redistributing a limited amount of allocations from the previous frame: We consider therefore in the following simultaneous iterative SLS without reservations. In the case of reservations, i.e., a broadcasting of intended allocations for the actual frame, the SLS is done based on of observed allocations of the past frame actualized through the reservations for the actual frame, if available. The reservations may for instance be part of an extended 802.11e beacon [1].

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 adapted, i.e., decreased, on the way to the smoothed allocation solution. Referring to control theory, the *SLSamount* can be regarded as attenuation factor. The flow chart of Fig. 3 depicts therefore the SLS with and without reservations while the amount of redistributed allocations is flexible. Our simulations, as introduced in Section IV, have indicated that an initial value of *SLSamount=0.1* is a suitable to enable stability without reservations in an adequate time.

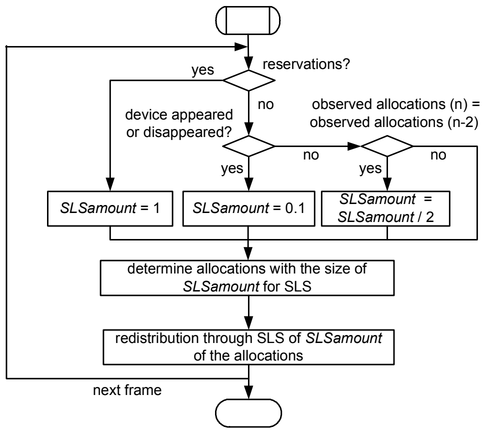


Figure 3. Iterative SLS with adaptive amount of redistributed allocations targeting on smoothed allocations.

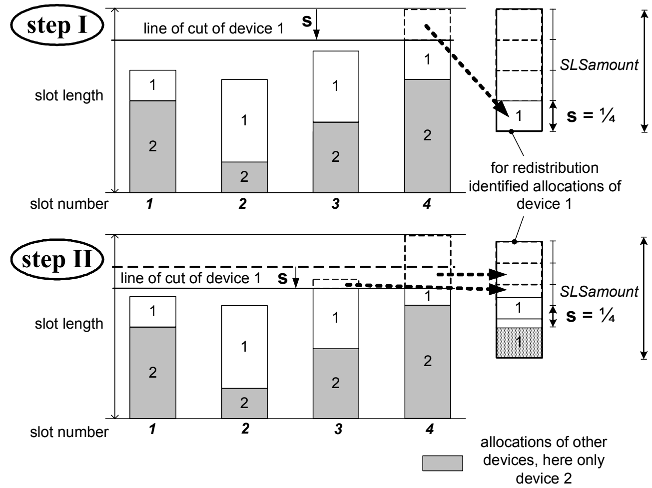


Figure 4. Determination of allcations which are to to be shifted in the SLS. The SLS from Fig. 2 is reversed and the first two steps are depicted.

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 identification of the allocations which are to be cut is introduced below. The *SLSamount* is halved, as outlined in Fig. 3 and observable in Fig. 6-8, if the overall allocations of the last but one frame equal the allocations of the present frame: In a yo-yo like manner, as depicted in Fig. 6 (d) and (e), the devices shift allocations at the same time to a less utilized slots, overload these together and shift in the consecutive frame these allocations back to the original slots. 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. Therefore the *SLSamount* is reset to *0.1*.

For better predictability we assume cooperating devices as introduced above, which change their allocation scheme less frequent during ongoing transmission to simplify the mutual coordination. This may be done for instance through an aimed buffering in the *Medium Access Control (MAC)* layer.

C. *Identification of most Destructive Allocations*

Parts of the allocations from the previous frame, which are to be redistributed within SLS, are identified in the reverse way of the SLS algorithm, as outlined for device 1 in Fig. 4: A virtual line of cut is iteratively moved down from the most utilized slot. The outstanding parts are cut and used for redistribution in the proximate SLS. The amount for cutting depicted in the upper right corner of each step, is given through the *SLSamount*. The line of cut is moved down with a step size *s* of

$$s = \frac{\text{left amount of allocations to be cut for SLS}}{\text{number of slots}}. \quad (2)$$

The allocations identified for redistribution are summed up. In subtracting these allocations from the intended amount of allocation for redistribution the remaining quantity defines the step size *s* of the next iteration corresponding to (2). The accuracy of the algorithm defines again a criterion for ending this iterative algorithm.

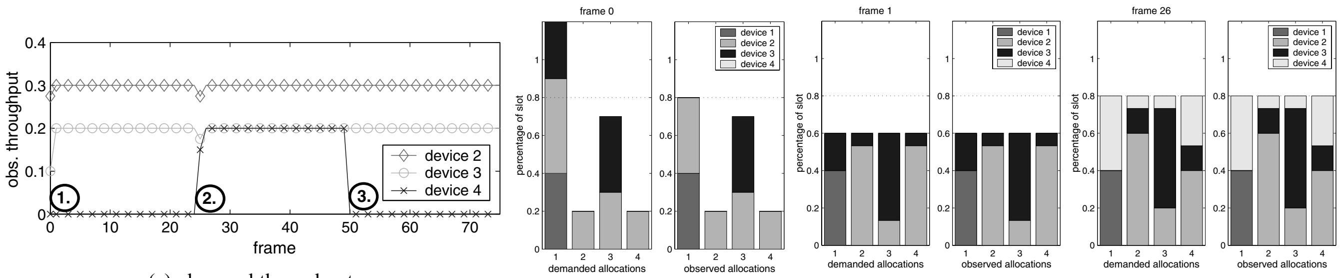
IV. Spectrum Load Smoothing – Simulative Introduction

This section introduces first the SLS on the basis of reservations and second the SLS without reservations with an adaptive amount of redistributed allocations due to less actual information about the other devices' allocations as introduced above. The SLS is performed by three devices (device 2, 3 and 4). These three devices operate at the same frequency and location together with an additional device (device 1). This device has a fixed allocation scheme: The fixed allocations may for instance result from an incumbent communication system using no SLS or from a dedicated, protected coordination phase where the reservations of the SLS-using devices are broadcasted. A frame structure of four time slots is assumed and an interaction over *75* frames is considered.

A. *SLS on the Basis of Reservations*

The SLS based on reservations can be realized within a specific coordination phase preferably to the beginning of a frame. Within this coordination, the devices use SLS and broadcast their reservations successively. The SLS considers thereby the already received reservations of the other devices if available. Otherwise the observed and therefore less actual allocations of the last frame are taken into account.

Fig. 5 (a) depicts the observed normalized throughput of the three SLS using devices over time. Initially, device 2 has a demanded normalized share of capacity of *0.3*, while device 3 demands *0.2*. Specific events in the route of interaction are



(a) observed throughput.

(b) frame *0*.

(c) frame *1*.

(d) frame *26*.

Figure 5. Observed throughput (a) and allocations during the SLS (b)-(d). Device 1 has fixed allocations. The SLS is done by the devices 2, 3 and 4. Device 4 initiates transmission in frame *25*. All allocations can be redistributed by the devices from frame to frame (*SLSamount=1*).

marked with numbers and the corresponding allocation situations are depicted in Fig. 5 (b) to (d): These figures outline the demanded and observed allocations of the four time slots per frame. For the SLS, we assume a maximum load level of a time slot, i.e., considered maximal capacity, of *0.8*. The remaining capacity is essentially left unallocated to enable for instance the access of additional SLS using devices or legacy devices. The maximum load level is respected by all devices and they abort their allocations if it is reached. The SLS is done over the complete frame.

At the initial frame *0*, marked through ① in Fig. 5 (a) and depicted in Fig. 5 (b), device 1,2 and 3 share the medium and their demanded allocations are uncoordinated: They overload the first time slot leading to a shortened observed allocation for device 2 and no allocation for device 3 in this slot implying less observed throughput as demanded. The SLS leads already in frame *1* to a mutually coordinated demand of allocations implying a fulfilled demanded throughput for both devices as depicted in Fig. 5 (c). The devices may redistribute all (*SLSamount=1*) of their allocations simultaneously per frame corresponding to the above introduced SLS with reservations algorithm.

A fourth device initiates transmission in frame *25*, demanding *0.2* as share of capacity and initiates its allocations at frame *25*, see Fig. 5 (a) ②, leading again to an uncoordinated allocation distribution and an overloading of some slots leading to reduced observed throughput. As all devices follow the SLS, device 2 and 3 as well as 4 redistribute their allocations. The emerging outcome of SLS in frame *26* is depicted Fig. 5 (d). At frame *50,* device 4 terminates its transmissions ③, resulting in a redistribution of the allocations of the remaining devices similar to Fig. 5 (c).

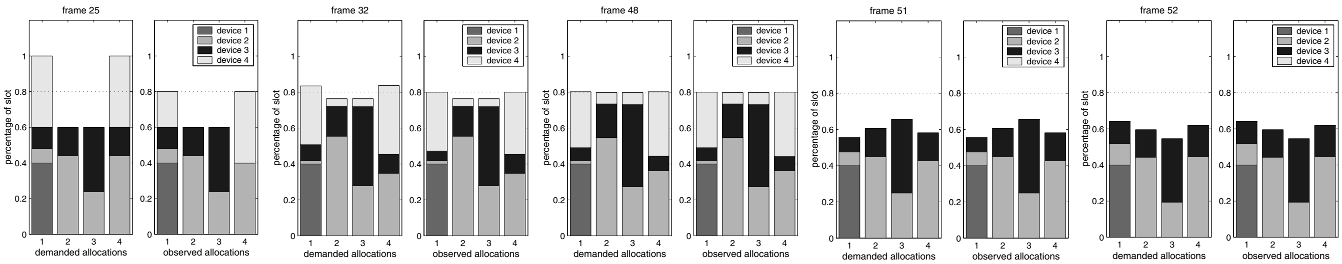
The emerging steady point of interaction can be regarded as *Nash Equilibrium* from the perspective of game theory. In focusing on the throughput no device can gain a higher throughput in deviating from this solution [11]: Although the devices still redistribute their allocations due to the SLS the resulting allocation outcome is fixed and stable.

B. *SLS without Reservations*

Without reservations the SLS has to be based on less accurate information: The observed allocations of past frames are considered for determining the expected other devices' allocations of the current frame. These observed allocations form a basis for the simultaneous SLS, done preferably at the beginning/end of the actual frame. To enable nevertheless coordination the redistribution process of allocations due to the SLS has to be slowed down for signaling purposes, as introduced above.

Fig. 6 and 7 depict analogous to Fig. 5 the observed throughput and corresponding allocations during the interaction. Contrary to Fig. 5, the amount of allocations is here adapted during the course of interaction following the SLS algorithm as introduced in the flow chart of Fig. 3: The amount of allocations which are redistributed during one frame is decisive for the smoothness of the stable allocation scheme resulting from SLS. Therefore, Fig. 8 depicts the amount of shifted allocations per frame: All devices initiate their *SLSamount* with *0.1* and reset to this value if any device appears ①, disappears ④ or rapidly changes its demanded allocations. The influence of the adaptive *SLSamount* is illustrated in Fig. 6 (a) – (c): The appearance of device 4 in frame *25*, Fig. 6 (a) and ①, leads to an uncoordinated allocation distribution over the frame. The three devices stepwise shift *10* percent (*SLSamount=0.1*) of their allocations leading to Fig. 6 (b) and ②. Thereafter, the *SLSamount* is halved until a predefined minimum, here *0.001*, is reached leading to nearly ideal smoothed allocations in frame *48*, Fig. 6 (c) and ③. The above mentioned yo-yo like shifting of allocations which motivates the adaptive *SLSamount* is outlined in Fig. 6 (d) and (e): The devices' distribution of allocations in frame *51* and *53* is equal and triggers a reduction of *SLSamount*, as depicted in Fig. 8.

In summary, the introduction of the adaptive amount of redistributed allocations during the simultaneous, iterative SLS moderates the inaccuracy of the SLS resulting from the missing reservation information. Nevertheless, it takes more time, compared to SLS with reservations, until a coordinated solution is reached: see therefore Fig. 5 and 7.



(a) frame *25*. (b) frame *32*. (c) frame *48*. (d) frame *51* and *53*. (e) frame *52*.

Figure 6. Allocations during the SLS. The amount of the allocations which is redistributed per frame is adapted as depicted in Fig. 8.

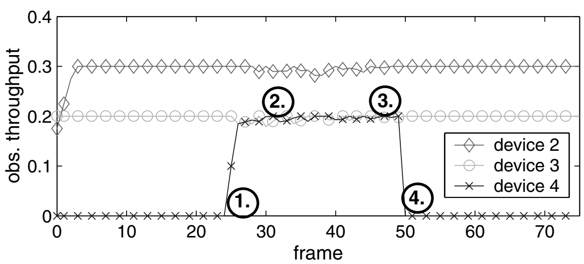


Figure 7. The observed throughput of SLS, done by three devices, with adaptive amount of redistributed allocations from frame to frame.

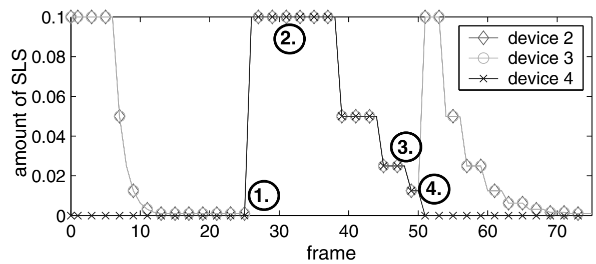


Figure 8. The amount of allocation, redistributed in the SLS is adapted by the devices.

V. CONCLUSIONS

The introduced SLS is a new universal approach to enable QoS support in coexisting wireless networks. It can be integrated into existing protocol standards through minor extensions. The envisaged application in 802.11e benefits from the new protocol amendments of 802.11k [12] which provides means for measurement, reporting, estimation and identification of spectrum allocations. The SLS is independent of the number of networks and accounts for both completely and partially overlapping wireless networks. The SLS enables a decentralized mutual coordination based on a cognitive medium access. An optimal opportunistic usage of all available radio resources is the outcome of the SLS.

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