

# Hybrid Spectrum Sharing for Cognitive Small Cells

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**Abstract**—Conventional overlay and underlay spectrum sharing strategies enable the cognitive Small Cells (SCeNBs) to access a spectrum of macrocells. The problem of the overlay approach is strong dependency of its efficiency on an activity of macrocell users. Thus, not enough resources remain for the SCeNB users if the macrocell is loaded heavily. The main weakness of the underlay approach is that it can result in a low transmission efficiency because the transmission power level of the SCeNBs is restricted. To overcome the above-mentioned problems of both spectrum sharing strategies, a hybrid spectrum sharing combining both overlay and underlay has been introduced in literature. In this paper, we propose a new distributed resource allocation algorithm for hybrid spectrum sharing tailored for realistic scenarios considering varying channel quality over individual resource blocks. The algorithm considers the buffer state at the SCeNBs, ratio of the resources available in the overlay and underlay modes, and channel quality experienced by the users at individual resource blocks. The proposed scheme increases the amount of traffic served for SCeNB users by 22.7% and reduces the packet delay by 27.1% for heavy loaded network comparing to existing schemes.

**Keywords**—cognitive small cells, hybrid spectrum sharing, mobile networks, resource allocation.

## I. INTRODUCTION

One of the key technological concepts enabling huge data rate transmissions in 5G networks is the extremely dense deployment of small cells (SCeNBs) [1]. A densification of the SCeNBs deployment can, however, result in severe interference to macrocells (eNBs) if a co-channel deployment of the SCeNBs is considered [2]. A promising alternative for interference mitigation is to equip the SCeNBs with cognitive capabilities towards “cognitive SCeNBs” [3]. These cognitive SCeNBs access the frequency spectrum as secondary users with a lower priority than the eNBs, which are seen as the primary users in the system.

The cognitive SCeNBs access the spectrum in either an underlay or an overlay sharing mode [4][5]. In the underlay mode, the SCeNBs can use the same radio resources as the eNB provided that the interference to the eNB is kept under a predefined threshold. The interference level is controlled by adjusting the transmission power of the SCeNBs (see, e.g., [6]-[13]). In the case of overlay mode, the SCeNBs only access the radio resources not currently being utilized by the eNB (as considered, for example in [14]-[20]). The most notable drawback of the underlay mode is that small cell users may not be able to attach themselves to the SCeNB since its coverage is very limited due to restricted transmission power. In addition, low transmission power can result in use of a less effective modulation and coding scheme. The main disadvantage of the overlay mode is that the amount of resources available to the SCeNBs is strongly dependent on the activity of users attached to the eNB. In the worst

case scenario, there can even be no resources available to the SCeNBs if the eNB is fully loaded.

To remedy the drawbacks of both the overlay and the underlay modes, a hybrid spectrum sharing mode for the cognitive SCeNBs is suggested in the literature (see, [21]-[24]). In [21], we propose a hybrid spectrum sharing dynamically selecting the mode (i.e., the underlay or the overlay) that currently provides higher throughput. The selection is based on the amount of resources available in each mode and on the data transmission efficiency experienced by the user equipments (UEs). This work is extended in [22], where the selection is based not only on the transmission efficiency, but also on the energy consumption of the SCeNBs.

Contrary to [21] and [22], where only a single mode is used at one time, the authors in [23] propose a game theoretic-based hybrid mode exploiting the underlay and the overlay modes simultaneously. The SCeNBs primarily allocate the resources in the overlay mode. The resources in the underlay mode (occupied by the eNB at the same time) are exploited by the SCeNBs only if the resources in overlay mode are not sufficient. In [24], we have proposed a buffer state-based hybrid resource allocation scheme where the SCeNBs primarily operate in the underlay mode instead of the overlay mode. We have demonstrated that the capacity of the system can be improved with respect to [23]. This is because all SCeNBs can use the underlay mode whereas the resources in the overlay mode are shared with neighboring SCeNBs to avoid interference. Consequently, some SCeNBs exploit only resources in the underlay mode whereas more resources in the overlay mode are available for the highly loaded SCeNBs. However, the scheme proposed in [24] is not suitable for cases where channel fading is varying across different resource blocks (RBs) since the scheme does not allocate the RBs according to Signal to Interference plus Noise Ratio (SINR) and only information on a buffer state is exploited.

In this paper, we propose a novel distributed radio resource allocation algorithm managing the whole process of resource allocation for individual SCeNBs. The work is based on our hybrid spectrum sharing algorithm proposed in [24], but we significantly extend the original work towards its suitability for realistic scenarios with the varying channel quality over individual RBs. To this end, the proposed algorithm selects overlay/underlay mode based on enhanced set of criteria mixed together in order to maximize ratio of data served to the UEs. Like in [24], the first criterion is buffer status. Then, two new criteria are introduced in this paper. The first new criterion is the ratio of RBs available in the overlay mode to that in the underlay mode since it impacts the allocation in the underlay mode. The second criterion is the SINR experienced by the UEs at individual RBs. We demonstrate that the proposed hybrid spectrum sharing



assume FIFO (First In First Out) buffer queuing model where the oldest data packet is served the first. In case that the data packet is stored in the buffer longer than a maximal allowable delay ( $\delta_{max}$ ), the data packet is discarded and removed from the buffer. To that end, the SCeNB keeps awareness of the buffer state for each UE represented by an amount of data waiting in the buffer ( $b$ ) and a packet delay ( $\delta$ ) for all data packets stored in the buffer.

### III. ALLOCATION OF RESOURCES ACCORDING TO THE CONVENTIONAL HYBRID MODE

This section describes the hybrid spectrum sharing mode allocation process in our previous work proposed in [24] (labeled hereafter HSS-con). Before the allocation process itself, the SCeNB classifies the RBs into three groups; 1) RBs in underlay mode (occupied by the eNB), 2) RBs in overlay mode (RBs not occupied by the eNB), and 3) RBs in overlay mode allocated to the direct neighbors (i.e., RBs not available to the given SCeNB). The classification of the RBs can be done, e.g., by means of a sensing procedure [14] and/or eavesdropping of the eNBs transmission [16].

The allocation process according to the HSS-con is divided into two phases: the allocation of the RBs in underlay mode (first phase) and the allocation of the RBs in overlay mode (second phase). The RBs in underlay mode are assigned first because all the SCeNBs can use these RBs given restricted transmission power in the underlay mode. However, if the SCeNB is not able to serve its UEs solely within the RBs in underlay mode, the SCeNB also exploits the RBs in overlay mode. These RBs are allocated to the UEs in the second phase. By contrast, if the number of RBs in underlay mode is sufficient to serve all the active UEs of the SCeNB, the direct neighbors may borrow all the RBs in overlay mode allocated by default to the SCeNB. Note that the number of RBs assigned by default to each SCeNBs depends on how many direct neighbors,  $n_A$  (see (1)), it has.

The allocation of RBs is done in a sequential manner by considering the estimated amount of data waiting in the buffer ( $b^*$ ) represented by a difference between the amount of data waiting in the buffer at the beginning of allocation ( $b$ ) and the estimated amount of data to be sent in the next allocation interval. The estimation of the amount of data to be sent in the RB is based on known SINR at this RB. In other words, the RB is always allocated to the UE with the highest  $b^*$ . Note that  $b^*$  decreases during the allocation process as the RBs are step-by-step assigned to individual UEs during one allocation interval whereas  $b$  is fixed as it indicates initial state of buffer and no arrival of new data is assumed during

one allocation interval. Note that the allocation interval can be represented, for example, by the transmission time interval in LTE.

An example of the allocation process for one allocation interval is illustrated in Fig. 2. While Fig. 2a depicts SINR values for two active UEs attached to the SCeNBs, Fig. 2b shows how the RBs are step-by-step assigned to these UEs. As explained above, the SCeNB assigns RBs in the underlay mode in the first allocation phase. Thus, the RB “1” is allocated to the UE1 since  $b_{UE1}^* > b_{UE2}^*$ . After that the rest of the RBs in underlay mode is assigned to the UE2 because  $b_{UE2}^* > b_{UE1}^*$ . In the second phase, the SCeNB allocates the RBs in overlay mode in the same way as in underlay mode (the RB “2” is assigned to the UE2 and the RB “5” is assigned to the UE1 for transmission of data).

Although the sequential allocation of the RBs considering only  $b^*$  can be justified if the SINR is the same over all RBs, this approach is not very effective if the SINR varies among individual RBs. This situation is depicted in Fig. 2b where most of the RBs in underlay mode are allocated to the UE2, which experiences a very low SINR on these RBs.

### IV. PROPOSED HYBRID SPECTRUM SHARING MODE FOR ALLOCATION OF RESOURCES

This section describes the proposed hybrid spectrum sharing mode (labeled HSS-pro) for the allocation of resources to the cognitive SCeNB. The objective of the proposed HSS-pro is to overcome the main weakness of the HSS-con, i.e., the problem for scenarios with varying SINR over individual RBs and, thus, to further increase the amount of data served for SCeNB UEs. While in the case of the HSS-con, the allocation of RBs is done solely according to  $b^*$ , the HSS-pro considers two additional decision criteria: 1) the ratio of RBs available in the overlay mode to the underlay mode (i.e.,  $n_{RB}^O/n_{RB}^U$ ) and 2) the SINR experienced by the UEs at individual RBs.

The allocation process itself is divided into two phases analogously to the HSS-con. In the first allocation phase, the SCeNB assigns the RBs in underlay mode. However, when compared to the HSS-con, the allocation in the underlay mode depends on the  $n_{RB}^O/n_{RB}^U$  ratio.

If there are enough RBs in overlay mode (i.e., if  $n_{RB}^O/n_{RB}^U > \tau$  where  $\tau$  is the threshold defining the required ratio of the RBs in overlay and underlay modes), the allocation of the RBs in underlay mode is done solely according to the SINR while disregarding  $b^*$ . This way, the HSS-pro is able to maximize the amount of data to be sent in the underlay mode, since the RBs in underlay mode are assigned to the UEs experiencing a good channel quality.

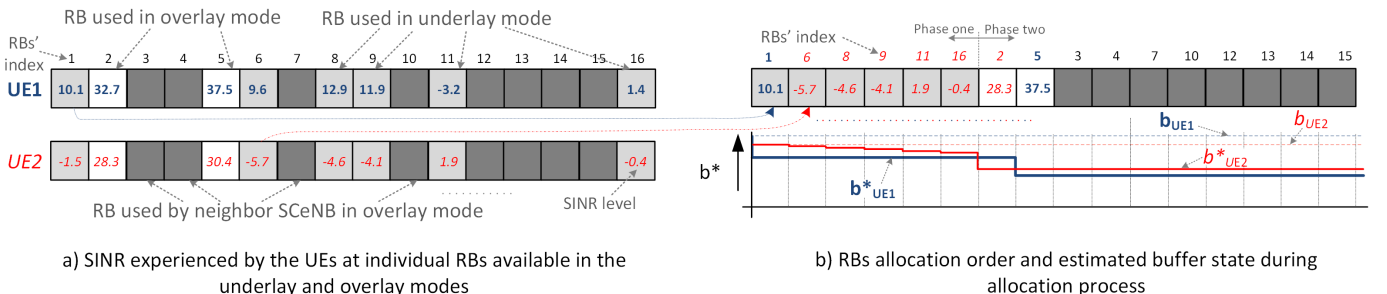


Fig. 2: An example of allocation of RBs to the UEs according to HSS-con in one allocation interval.

**Algorithm 1** : Allocation of RBs according to HSS-pro.

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1: Derive  $n_{RB}^U, n_{RB}^O, \Gamma_i^U, \Gamma_i^O$ 
2:  $n_{RB,f}^U = n_{RB}^U, n_{RB,f}^O = n_{RB}^O, b_s^* = b_s \forall s$ 
3: if ( $n_{RB}^O/n_{RB}^U > \tau$ ) then
4:   while ( $n_{RB,f}^U > 0$  and  $\sum_{s=1}^a b_s^* > 0$ ) do
5:     find  $\max(\gamma_{r,s,i}^U \in \Gamma_i^U)$ 
6:     allocate  $r$ -th RB to  $s$ -th UE in underlay mode
7:     update  $b_s^*$ 
8:     remove  $r$ -th col. from  $\Gamma_i^U, n_{RB,f}^U = n_{RB,f}^U - 1$ 
9:   end while
10: else
11:   while ( $n_{RB,f}^U > 0$  and  $\sum_{s=1}^a b_s^* > 0$ ) do
12:     find  $\max(\gamma_{r,s,i}^U \in \Gamma_i^U)$  for UE with  $\max(b_s^*)$ 
13:     allocate  $r$ -th RB to  $s$ -th UE in underlay mode
14:     update  $b_s^*$ 
15:     remove  $r$ -th col. from  $\Gamma_i^U, n_{RB,f}^U = n_{RB,f}^U - 1$ 
16:   end while
17: end if
18: while ( $n_{RB,f}^O > 0$  and  $\sum_{s=1}^a b_s^* > 0$ ) do
19:   find  $\max(\gamma_{r,s,i}^O \in \Gamma_i^O)$  for UE with  $\max(b_s^*)$ 
20:   allocate  $r$ -th RB to  $s$ -th UE in overlay mode
21:   update  $b_s^*$ 
22:   remove  $r$ -th column from  $\Gamma_i^O, n_{RB,f}^O = n_{RB,f}^O - 1$ 
23: end while
    
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The UEs experiencing the low channel quality in underlay mode can use the RBs in overlay mode instead, because a good channel quality is guaranteed in overlay mode due to low interference from the neighboring SCeNBs and the transmission power set to  $P_{max}$ .

If there are not enough RBs in overlay mode (i.e.,  $n_{RB}^O/n_{RB}^U \leq \tau$ ), the allocation of the RBs in underlay mode is based primarily on  $b^*$  whereas SINR is a secondary criterion. This means that SCeNB first selects which UE will be assigned with an RB (i.e., the UE with the highest  $b^*$ ). After that, the RB with the highest SINR for this particular UE is allocated to the UE. The reason why the allocation in the underlay mode is done primarily according to SINR if  $n_{RB}^O/n_{RB}^U \leq \tau$  is that, the UEs with a low channel quality would have low capacity if the SINR would not be considered (e.g., as in [24]).

If the number of RBs in underlay mode is not sufficient for transmission of all the data to the UEs, the SCeNB allocates the RBs in overlay mode in the second phase. Note that the allocation of the RBs in overlay mode is done

primarily according to  $b^*$  whereas the SINR is a secondary decision parameter. Consequently, the SCeNB first decides which UE will be granted with an RB. Then, the SCeNB assigns the UE with the RB at which the UE experiences the maximum SINR out of all the available RBs in overlay mode.

The proposed resource allocation for hybrid spectrum sharing is described in Algorithm 1. At the beginning, the SCeNB derives the number of available RBs both in underlay ( $n_{RB}^U$ ) and overlay ( $n_{RB}^O$ ) modes, and determines the set of SINRs for all active UEs over all RBs that can be used by the  $i$ -th SCeNB in underlay mode ( $\Gamma_i^U$ ) and overlay mode ( $\Gamma_i^O$ ) (see line 1 in Algorithm 1). In the next step, the SCeNB initiates the values of the number of free RBs in underlay and overlay modes ( $n_{RB,f}^U$  and  $n_{RB,f}^O$ ) and sets  $b_s^* = b_s$  for all active UEs. Then, depending on the ratio of the number of RBs in the overlay to underlay mode, the RBs in underlay mode are assigned as follows.

If  $n_{RB}^O/n_{RB}^U > \tau$ , the SCeNB follows steps 4 to 9 as long as  $n_{RB,f}^U > 0$  and the SCeNB still has some data in the buffer (i.e., if  $\sum_{s=1}^a b_s^* > 0$ ). In these steps, the SCeNB finds the maximal value of the SINR stored in  $\Gamma_i^U$  (line 5) and allocates the RB to the  $s$ -th UE, which experiences the highest SINR for this particular RB (line 6). Then, the SCeNB updates the estimated buffer size ( $b_s^*$ ) (line 7), removes the  $r$ -th column from  $\Gamma_i^U$  and decreases  $n_{RB,f}^U$  by 1 (line 8).

If  $n_{RB}^O/n_{RB}^U \leq \tau$  (lines 11-16), the SCeNB selects the UE with the maximal  $b_s^*$ . For this  $s$ -th UE, the SCeNB finds the RBs for which the  $s$ -th UE experiences the highest SINR (line 12). After that, the allocation process follows the same steps as in the case when  $n_{RB}^O/n_{RB}^U > \tau$  (lines 13-15).

If the SCeNB allocates all available RBs in underlay mode and still has some data to be sent, the RBs in overlay mode are exploited as shown in Algorithm 1, lines 18–23. The allocation of the RBs in overlay mode follows the same principle as the assignment of the RBs in underlay mode for  $n_{RB}^O/n_{RB}^U \leq \tau$ . This means the RBs in overlay mode are granted to the UEs according to the estimated buffer state  $b_s^*$  (see line 19).

An example of RB allocation according to the proposed hybrid mode algorithm is depicted in Fig. 3, where we consider the case if  $n_{RB}^O/n_{RB}^U > \tau$ . Thus, the allocation in the underlay mode is only done according to the SINR. Hence, the SCeNB subsequently allocates the RBs “8”, “9”, “1”, and “6” to the UE1, then the RB “11” is assigned to the UE2, and the last RB available in underlay mode, the RB “16”, is given to the UE1 (Fig. 3b). Only one RB is granted to the UE2 in the underlay mode, because

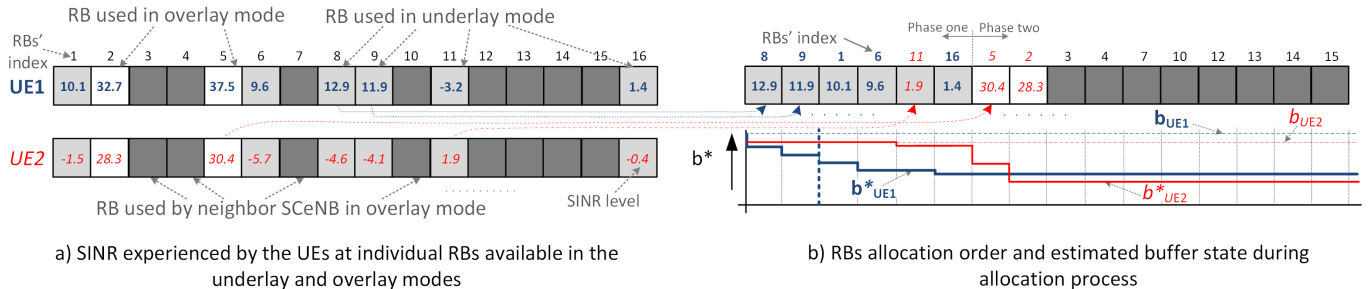


Fig. 3: An example of allocation of RBs to the UEs according to HSS-pro in one allocation interval.

the UE2 experiences low channel quality from the SCeNB thus making the underlay mode not feasible for most of the available RBs. The SCeNB assigns the RBs to the active UEs, which experience high SINR values for these particular RBs. This minimizes the number of RBs necessary for data transmission and consequently maximizes the amount of data served in the underlay mode. Then, the allocation of the RBs in overlay mode is performed primarily according to  $b^*$ . Hence, the SCeNB allocates both RBs in overlay mode to the UE2, since  $b_{UE2}^* > b_{UE1}^*$ .

## V. PERFORMANCE EVALUATION

This section first describes the simulation scenario and parameters, the performance metrics, and competitive algorithms selected for performance comparison. Then, it assess the performance of the HSS-pro and compare it to other competitive algorithms for cognitive small cells.

### A. Simulation scenario and performance metrics

We conduct the evaluations in MATLAB following FDD LTE-A release 12 with system parameters setup according to the Small cell forum as summarized in Table I. We assume 20 SCeNBs randomly placed in a dual strip model consisting of 40 apartments [26] and 40 UEs moving according to the mobility model specified in [27]. To each SCeNB, two UEs are always attached. The UEs activity/inactivity is generated according to FTP model defined in [28]. Besides the UEs connected to the SCeNBs, we assume 40 UEs attached to the eNB moving on the sidewalk in vicinity of SCeNBs. These UEs implies restrictions on the transmission power in underlay mode as described in the system model.

The performance of our proposed scheme is assessed in terms of the amount of data served by the SCeNB to the UE in downlink and the average packet delay experienced by these UEs. The first metric defines the ratio of data that the UEs receive with respect to the amount of data received at the SCeNBs from the network. The second performance metric represents the packet delay consisting of a waiting of the data packet in the SCeNB's buffer and the transmission delay from the SCeNB to the UEs. Note that data packets discarded due to exceeding maximal allowable packet delay (in our simulation set to 1000 ms) are not considered in delay calculation.

The performance of the proposed HSS-pro is compared to two existing hybrid spectrum sharing schemes for cognitive small cells. The first scheme, labeled as HSS-con, is the

scheme proposed by us in [24]. The second scheme, presented in [23], is based on a game theoretic approach for resource allocation for cognitive SCeNBs and we label it herein as HSS-GT. We have selected only [24][23] for comparison to our scheme as these are the only ones allowing to use underlay and overlay resources simultaneously.

### B. Simulation results

Fig. 4a and Fig. 4b illustrates the amount of data served by the SCeNBs depending on the load of the SCeNBs and the load of the eNB, respectively. The proposed HSS-pro significantly outperforms both HSS-GT and HSS-con in terms of the served data. The gain increases with SCeNB load as can be seen in Fig. 4a (note that the eNB load is set to 50% in Fig. 4a). The HSS-pro outperforms HSS-GT by 21.7% and HSS-con by 11.8% for a high load of the SCeNBs. The reason why HSS-pro performs better than HSS-GT is that all SCeNBs can use the underlay mode while the resources in the overlay mode are shared with neighboring SCeNBs to avoid interference. Thus, some SCeNBs exploit only resources in the underlay mode whereas more resources in the overlay mode are available for the highly loaded SCeNBs. Moreover, the performance gap between HSS-pro and HSS-con reflects the fact that the allocation of RBs is not done solely according to buffer state (like in HSS-con), but also new criteria are considered for the proposed resource allocation algorithm.

Fig. 4b depicts the performance of the HSS-pro when the SCeNB load remains constant (set to 16 Mbit/s) and the mean eNB load varies between 0% and 100%. The performance gap between the proposed HSS-pro and HSS-GT and HSS-con is up to 22.7% and 12.7%, respectively. Fig. 4b shows that the highest performance gain is achieved by the HSS-pro for a mean eNB load between 60% and 100%, i.e., the load at which the eNB should be operating most of the time if the network is planned effectively.

The average packet delay depending on SCeNB load is depicted in Fig. 5a. As can be observed the packet delay is increasing with the SCeNB load since the buffer is significantly more loaded at higher loads. Similarly as in Fig. 5a, the HSS-pro outperforms both competitive schemes in terms of average packet delay. More specifically, the use of HSS-pro reduces average packet delays by 27.1 % (with respect to HSS-GT) and by 19.2 % (with respect to HSS-con) at heavy SCeNB load. The packet delay reduction is a consequence of the higher throughput introduced by the HSS-pro that reduces waiting time in the buffer.

TABLE I: Parameters and settings for simulations

Parameter	Value
Carrier frequency $f$ [GHz]	2.0
Channel bandwidth $BW$ [MHz]	20
Max./min. SCeNB transmission power $P_{max} / P_{min}$ [dBm]	10/-20
eNB transmission power [dBm]	43
Noise [dBm/Hz]	BW4pW/GHz
Number of SCeNBs/SUEs [-]	20/40
Loss of internal wall, external wall, window [dB]	5, 10, 3
$\gamma_{min}$ [dB]	-9.478 [28]
$\kappa_n$ [-], $\tau$ [-]	10, 0.1
Buffer size $B$ [Mbits]	1
Maximum allowable packet delay $\delta$ [ms]	1000
Indoor path loss model	ITU-RP.1238 [29]
Outdoor path loss model	COST 231 [29]
Simulation time[s]/Number of drops	10 000/10

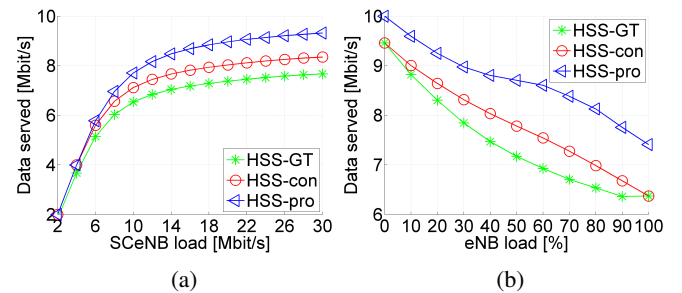


Fig. 4: The amount of data served by the SCeNBs in DL while MBS load is fixed at 50% (a) or SCeNB load is fixed at 16 Mbit/s (b).

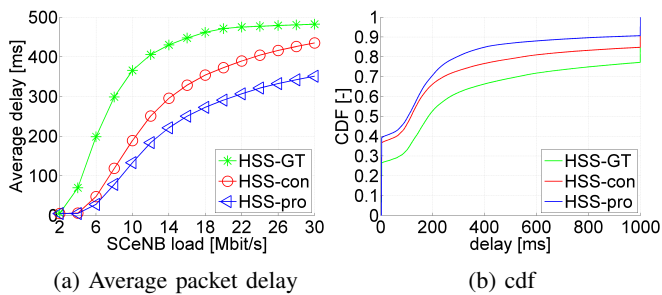


Fig. 5: Packet delay depending on the SCellNB load.

Fig. 5b more deeply analyzes a distribution of packet delay over all loads of the SCellNBs. The figure shows that in one extreme, a specific amount of data packets are received at the UEs with negligible delay. To be more precise, the UEs are able to receive 39.2 % of all packets with delay up to 5 ms if HSS-pro is implemented, while only 36.6 % and 26.4 % of packets with delay up to 5 ms are observed for the HSS-con and HSS-GT, respectively. In these cases, the buffer of individual SCellNBs is empty and only processing/scheduling delay affects the overall delay. Contrary, if the buffer is fully loaded the data packets may be waiting in the buffer for maximum tolerable delay before the SCellNB sends them to the UEs. In case of the HSS-pro, only 9.3 % of the packets wait in the buffer for 1000 ms while 15.2 % (22.8 %) of the packets wait for 1000ms in case of the HSS-con (HSS-GT).

## VI. CONCLUSIONS

In this paper, we have proposed a new algorithm for allocation of resources for cognitive SCellNBs based on hybrid spectrum sharing for channel with varying channel quality over RBs. The proposed algorithm maximizes the amount of data served in the underlay mode so that the overlay mode can be exploited by highly overloaded SCellNBs. The simulation results demonstrate that the proposed scheme is able to significantly outperform other competitive schemes in terms of both the amount of data served to the users and the packet delay. The gain in the amount of served data introduced by the proposed algorithm exceeds 22% for highly loaded SCellNBs and eNB. Moreover, the average packet delay is reduced by more than 27% for highly loaded SCellNBs. Future research direction includes analytical analysis and extension of the algorithm with energy consumption as a part of the decision metrics for the selection of the underlay/overlay mode.

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