Hybrid Spectrum Sharing Through Adaptive Spectrum Handoff for Cognitive Radio Networks

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***Abstract*—Sharing available resources in cognitive radio networks can benefit from spectrum handoff to enhance the rate performance by switching from current unavailable channels to the available ones. However, spectrum handoff can cause transmission interruptions leading to the degradation of services. In this work, we aim to balance the tradeoff between benefits of spectrum handoff and their negative impacts on spectrum sharing. Therefore, we develop an adaptive hybrid strategy that includes novel static and dynamic spectrum sharing based essentially on a rate compensation concept. The former is suitable when spectrum handoff is not necessary. The latter allows performing spectrum handoff to compensate the lost rate from the unavailable periods and improve the rate performance. We compare our hybrid strategy with a fully dynamic one and an optimization framework. Through simulations, we show that our strategy reduces the number of handoffs significantly while the achieved rate is fulfilling compared to the optimal.**

I. Introduction

The significant underutilization of the licensed spectrum is posing new challenges related to the design of new network paradigms for wireless communication. As a consequence, Cognitive Radio Networks (CRNs) is proposed in order to improve the spectrum utilization by allowing secondary users (SUs) temporarily occupy the unused spectrum bands that are unused by primary users (PUs). One of the challenges in CRNs is related to high fluctuations in the available spectrum so that the service requirement of SUs is hard to achieve, especially when multiple SUs must compete to share the limited spectrum bands. Therefore, efficient spectrum sharing is necessary to provide fairness allocation as well as service satisfaction across multiple users while maximizing the utilization of the total available bandwidth

These goals are achieved concretely through spectrum handoff and spectrum selection functions while applying a given sharing strategy. The first possible strategy refers to static spectrum sharing where no handoff is performed during the transmission of a SU. Concretely, this means that the spectrum allocation is done only once, for instance, before starting the transmission. The second strategy refers to dynamic spectrum sharing where the rate allocation of SUs is recomputed instantaneously regarding PUs activities, for instance, when a frequency channel becomes unavailable [1].

Generally, dynamic spectrum sharing can benefit from spectrum handoff to enhance the rate performance by switching from the unavailable channels to the available ones. However, *spectrum handoff delay* may cause a significant latency before transmitting packets which can reduce the service satisfaction of SUs [2]. Furthermore, a large number of spectrum handoffs also increases the channel contention and collision among SUs, since they may handoff and select the same channels simultaneously [3]. On the other hand, static spectrum sharing can avoid the impacts of spectrum handoff delay by allowing SUs to backoff and wait if any of PUs is using the same channel. Typically, if PUs occupy the channel for long periods, SUs would suffer for the long waiting delay leading to service degradations. In our previous work [4], we found analytically optimal rates for SUs through the formulation of a global spectrum sharing (GSH) where the complete information of future PUs activities are taken into account. Since the optimization is global, spectrum handoffs are performed as required so that the achieved rates are optimized and the number of spectrum handoffs is reduced compared to dynamic sharing with instantaneous handoff.

Nevertheless, optimizing in the same formulation the number of handoffs and the achieved rates is not straightforward. The optimization problem becomes too complex to be solved exactly. Besides, it is not always convenient to obtain complete long-term future PUs activities in advance. Moreover, the centralized optimization considered in GSH can be complex and not scalable with the number of users. More importantly, the allocation and the spectrum handoff sequence provided by the solver software can not be converted easily to a distributed solution of the dynamic spectrum sharing problem. Therefore in this work, we aim to design a heuristic for centralized spectrum sharing that exploits short-term future information of PUs activities when they are provided. The main objective is to consider carefully the impact of spectrum handoff while trying to maximize user satisfactions in terms of achieved rates. We still consider the GSH strategy as a benchmark for the rate performance. Our heuristic is derived from the more practical static and dynamic spectrum sharing strategies in a hybrid manner. It balances adequately the tradeoff between benefits of spectrum handoff and the necessity of reducing their number. It maximizes the utilization of the network capacity and the achieved rates of SUs. This is done by modifying and adapting renowned Best Fit algorithms which are commonly applied for the bin packing problem [5], so that we consider originally

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multi-channel communications and spectrum handoff reduction. Fairness is also considered in our proposed strategy. We apply a *two step allocation* mechanism to the static spectrum sharing scheme to guarantee that the allocation can be satisfied for all SUs. For the dynamic spectrum sharing scheme, a priority channel selection is introduced to compensate lost rates in turns and achieve fairness on the long term.

II. Related Work

Most of the research works on centralized spectrum sharing in CRNs have a main objective on maximizing the utilization of the total available bandwidth. A linear-integer optimization method has been widely used in the literature (e.g., [1], [6], [7]). This optimization problem is quite suitable for the centralized architecture where a CR base station has global information of the network and decides optimally on the resource allocation for all SUs. The bi-objective optimization framework is proposed to deal with the QoS and power control simultaneously [6]. Firstly, the achieved rate of SUs is maximized according to a service requirement constraint. Since, the *common use* model [8] is considered in this work where multiple SUs can access the same channel simultaneously, the second objective is to minimize the transmitting power to avoid collisions among SUs in a single channel. Nevertheless, the fairness issue is not considered in this work. To achieve a fair allocation, a two-step optimization problem is formulated and proposed in [7]. At the first step, the objective is to maximize the minimum service satisfaction ratio of SU. As a consequence, a value of service satisfaction from the first step is fed as a constraint in the second step while maximizing the total achieved rate. Thus, the optimization in the second step can fulfill the utilization of total capacity from the first step. A different method called proportional fairness is also commonly applied in optimization framework for spectrum sharing which is regarded as a compromise between max-min fairness and maximum throughput scheduling [9], [10], [11]. In [11], the proportional fair scheduling algorithm is addressed while considering the achieved rate and the interruption due to PUs appearance. Nevertheless, these works consider only a static sharing where the allocation is done only once, for instance, before starting transmissions. In other words, the possible benefit from spectrum handoff is not considered.

A dynamic allocation is addressed in [1], where the objective is to maximize the utilization of the spectrum. The user allocations are recomputed dynamically each time activities of PUs change the status of the spectrum. In [12], the channel reconfiguration algorithm based on the knapsack problem is introduced to optimize the number of SUs added in each time slot. The assigned time slot for SUs can be rearranged when the status of the spectrum is changed regarding the PUs activities, and thus the global utilization can be maximized. However, these works do not contain any condition for controlling the number of spectrum handoff. Therefore, it is expected that a large number of spectrum handoff can be generated which possibly impacts the rate performance, especially if a large spectrum handoff delay is considered. Besides, fairness is not considered in these works.

III. Spectrum Sharing Model in Cognitive Radio Networks

We consider an infrastructure-based CRN with a total of N secondary users (SUs) and M licensed channels available for opportunistic spectrum access. Each SU is equipped with n wireless interfaces. A single SU can use multiple channels simultaneously through multiple wireless interfaces and each channel can be used by several SUs at the same time. The latter capability is managed at the MAC layer of cognitive radio devices through various multiple spectrum access techniques such as random or time division access [13]. The available capacity of channel i is denoted by c^i. Each user j has a different rate requirement r_j, which can be considered also as the user weight for sharing the available bandwidth. The sharing among SUs can be controlled through a CR base station that is responsible of protecting the primary network from possible interferences and degradations. When PUs appear in the licensed channel, the SUs' transmissions must stop or handoff to other available channels. If SUs stay on the interrupted channel, they continue transmission when PUs leave the channel. At a given time and according to some sharing criteria, each SU is allocated a bandwidth from each channel. Denotes by b_j^i the allocated bandwidth for SU_j over channel i, where $b_j^i \in \mathbb{R}; 0 \leq b_j^i \leq c^i$. If $b_j^i = 0$, then SU_j is not tuned to channel i and thus is not transmitting over this channel.

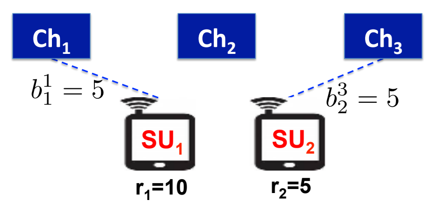


Fig. 1. Spectrum sharing example with limited wireless interfaces

Fig. 1 shows an example that highlights the impact of the number of wireless interfaces and also the limitation of classic weighted fair sharing algorithms. It considers a scenario where two SUs compete to access three licensed channels and each SU has only one wireless interface, $n = 1$. The rate requirements of SU_1 and SU_2 are set to 10 and 5 respectively. The average available bandwidth of each licensed channel is fixed to 5 and thus total available bandwidth is 15. Considering the weighted fair sharing method, the allocated bandwidth of SUs can be weighted as their rate requirement. Thus, SU_1 and SU_2 should be allocated the rates 10 and 5 respectively. Even though, the total available bandwidth is adequate compared to the total rate requirement of all users, SU_1 achieves only a rate of 5. This is because the transmission of SU_1 is limited to one channel. Therefore, the bandwidth should be shared fairly among all SUs with respect to their different service satisfactions and also capabilities in terms of number of wireless interfaces for instance.

The challenge is then to maintain the service satisfaction for all SUs by applying an effective spectrum sharing strategy.

IV. Hybrid Spectrum Sharing Design

To determine how spectrum handoff should be performed adequately while achieving the optimal spectrum sharing, we consider two schemes of operation. The first scheme is called Static Spectrum Sharing (SSS) which corresponds to a long-term allocation (i.e., the allocation is used for a long period of transmission). The second scheme is called Dynamic Spectrum Sharing (DSS), in which the allocation is recomputed periodically.

A. Static Spectrum Sharing

The objective of Static Spectrum Sharing (SSS) is to satisfy the rate requirement of SUs for the long-term communication without an attempt to perform spectrum handoff. Here, the CR base station determines the average total available bandwidth of selected channels to satisfy the constraint of the rate requirement r_j. To allocate the bandwidth properly, first we compute the average total available bandwidth based on the long-term availability ratio $\beta^i = \frac{E[T^i_{av}]}{E[T^i_{av}]+E[T^i_{un}]}$ on each channel i, where $E[T^i_{av}]$ and $E[T^i_{un}]$ are the average of availability and unavailability periods of channel i respectively. These values are obtained through long-term observations for each channel i. Then, the average total available bandwidth can be computed as $c^i = \beta^i \cdot bw^i$, where bw^i is the link bandwidth of channel i. However, when we switch to this scheme, some SUs may not achieve sufficient rate from the prior allocation which can be reflected by the number of packets in their transmission queue $q_j(t)$. To take into account these packets in the queue, a new rate requirement r^q_j is computed as follows:

$$r^q_j = r_j + \frac{q_j(t)}{T_{comp}} \tag{1}$$

where T_{comp} is a compensation period during which packets from the queue shall be sent. We call it a compensation period because these packets correspond to a period where the allocated rate is lower than the requirement, and thus the lost rate must be compensated. Intuitively, the value of T_{comp} should be large, since the SSS is suitable for the long-term communication without spectrum handoff.

To design an efficient heuristic algorithm for SSS, we are inspired by the Best Fit Decreasing (BFD) algorithm, which is frequently applied to solve the classic bin packing problem [5]. In this problem, a finite set of items must be packed to an infinite set of bins. Accordingly, in our spectrum sharing problem, a finite set of items is equivalent to a set of SUs denoted by S. As for a set of bins, it is equivalent to a set of channels denoted by Ω, but in our case this set is finite.

Furthermore, there are also other variations between the classic bin packing problem and our problem. First, in our case, the capacity of channels are not homogeneous which means the capacity of the bins are not the same as in the classic problem. Second, unlike the bin packing problem, we do not consider minimizing cost incurred for channel or bin selection but instead we aim at maximizing the number of packed items in a finite number of bins (channels). This corresponds to maximize the achieved rate with the difference that even if the item does not fit to any bin, some part of the item can be packed in the bin. Finally, to consider the multi-channel communications, the volume of items or rate requirement of user r^q_j can be divided into n_j fragments which corresponds to the number of antennas.

Regarding these variations, we adapt the BFD algorithm and propose *Best Fit selection with Multi-channel constraint for Static spectrum sharing (BFM-S)* heuristic to solve the spectrum sharing problem in hand. A pseudo code for the BFM-S algorithm is depicted in Algorithm 1. The details of the BFM-S algorithm are described as follows:

Multi-Channel Selection: From the point of view of utilization and fairness, the capacity of the selected channels should fit exactly the rate requirement r^q_j. Otherwise, if this channel selection condition is not considered, any small value of r^q_j can reserve a large capacity channel.

To select the eligible channels for each SU, we first sort channels in Ω according to a non-decreasing order of their average total available bandwidth c^i. Second, we sort SUs in S in a non-increasing order regarding their rate requirement r^q_j. Accordingly, the BFM-S algorithm starts channel selection from the SU who has the maximum r^q_j. Fig. 2 illustrates the channel selection process for an SU. Here, the number of candidate channels in each iteration is restricted to the number of wireless interfaces n_j. Let C_l be the total capacity of a set of candidate channels at the l^{th} iteration, $C_l = \sum_{i=l}^{l+n_j-1} c^i$ (line 9:). If the total capacity of candidate channels fits to the rate requirement r^q_j, the iteration is broken and then the channels at this iteration are chosen for SU_j. A set of chosen channels for SU_j is denoted by CH_j. This condition corresponds to $C_l \geq r^q_j$ (line 8:). Note that, the number of channels in our problem is finite and is denoted by M. Therefore, the number of iterations in the multi-channel selection is also finite and is calculated based on the number of antennas n_j and the number of channels M. It is equal to $l^{max} = 1 + (M - n_j)$. As a consequence, if an iteration runs until l^{max} and the rate requirement r^q_j is larger than the total capacity of candidate channels C_l, a set of channels at l^{max} iteration will be selected for SU_j.

Intra Channel Allocation: In this step, an SU is allocated a rate from each selected channel in CH_j which is obtained from the previous step. To allocate the bandwidth properly, first, the BFM-S algorithm assigns the channel that has the minimum remaining capacity to allocate the rate to SU_j. Consequently, the allocated rate for SU_j over a selected channel i is computed as: $b^i_j = min(r^q_j, c^i), i \in CH_j$ (line 14:). If the channel does not have enough capacity to fit the r^q_j, the remaining rate requirement $(r^q_j - b^i_j)$ will be assigned to the next larger capacity channel in CH_j (line 15:). Thus, multi-channel communication is used only when required. Finally, we update the capacity of the channels to the remaining capacity of the selected channels according to the allocated bandwidth b^i_j (line 16:).

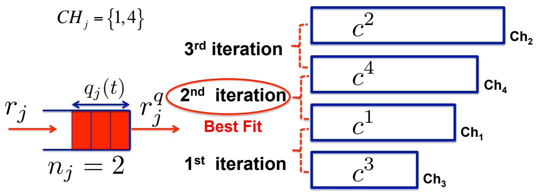


Fig. 2. An example of BFM-S algorithm, SU equips with two antennas

Now, the achieved rate of SU_j can be computed as $a_j = \sum_{i=1}^{M} b_j^i$. This procedure is repeated for all users in the set S. Note that, when the algorithm starts processing the next user, the set of channels Ω needs to be sorted again because the capacity of some channels were changed after allocation of previous SUs.

On the other hand, when the total demand bandwidth of SUs is larger than the network capacity (overloaded state), the resource allocation may not be fair for all SUs. Since, some SUs may occupy all available bandwidth and the others will not be able to obtain any rate from the network, especially last ones in the set S. Moreover, the allocation in SSS is applied for the long-term transmission, as a consequence SU who cannot satisfy the allocated rate will suffer from this insufficient rate allocation for a long period. Thus, the *second step BFM-S* is proposed to alleviate this unfairness problem. Note that, this step is only applied in the case where at least one SU is not satisfied with its achieved rate ($a_j < r_j^q, \forall j \in \{1, 2, ...N\}$). In this step, the rate requirement r_j^q is recomputed based on the total amount of allocated rate from the first step allocation, denoted by $A^{1st} = \sum_{j=1}^{N} a_j$. This amount represents somewhat the effective maximum capacity of the channels. Accordingly, rate requirements of SUs in the second step can be computed as follows:

$$r_j^{q^{2nd}} = \frac{r_j^q}{\sum_{j=1}^{N} r_j^q} \cdot A^{1st} \tag{2}$$

Consequently, the BFM-S is recalled by applying the second step rate requirement $r_j^{q^{2nd}}$. On the contrary, this unfairness problem cannot be solved at the first step of BFM-S through the classic weighted fair sharing method , due to the fact that the efficiency of the algorithm itself is also dependent on the number of wireless interfaces of each SU. Specifically, even in the underloaded state, rate requirement of SUs cannot be guaranteed because of the limitation of wireless interfaces, as described in Section III and thus the first step is necessary. Intuitively, the second step BFM-S enhances the fairness allocation, but it possibly decreases the utilization of channel capacity. Since, the maximum achieved rate is limited to the $r_j^{q^{2nd}}$. Therefore, we evaluate the first step and the second step BFM-S through the average service satisfaction, denoted by $E[\alpha_j] = \frac{\sum_{j=1}^{N} a_j/r_j}{N}$. If $E[\alpha_j]$ of the first step is larger than the second step, the allocation applies the solution from the first step BFM-S. Recall that, if all SUs can satisfy the rate requirement at the first step, the second step BFM-S is not necessary.

Algorithm 1 BFM-S

Input Ω: Set of channels, S: Set of SUs, n_j: Number of wireless interfaces of SU_j, M: Number of channels, r_j^q: Rate requirement of SU_j.
Output CH_j: Set of selected channels for SU_j, b_j^i: Allocated bandwidth for SU_j over channel i.
Sort the SUs in S according to non-increasing order of their rate requirement r_j^q
for $j = 1 : |S|$ **do**
  $CH_j = \emptyset$
  Sort the channels in Ω according to non-decreasing order of their capacity c^i
  $l = 1$, $l_{max} = 1 + (M - n_j)$
  while $C_l < r_j^q$ **and** $l \leq l_{max}$ **do**
    $C_l = \sum_{i=l}^{l+n_j-1} c^i$ // Multi-Channel Selection
    $CH_j \leftarrow$ a set of channels at l^{th} iteration
    $l = l + 1$ // Search for the best fit
  end while
  for $k = 1 : n_j$ **do**
    $b_j^{CH_j(k)} = min(r_j^q, c^{CH_j(k)})$ // Intra Channel Allocation
    $r_j^q = r_j^q - b_j^{CH_j(k)}$
    $c^{CH_j(k)} = c^{CH_j(k)} - b_j^{CH_j(k)}$ // Updating capacity
  end for
end for

B. Dynamic Spectrum Sharing

Intuitively, when the rate requirement is larger than the available bandwidth of the channel, spectrum handoff is necessary by switching from current unavailable channels to the available ones. However, in the DSS scheme, waiting at the current unavailable channel in an attempt to compensate later the lost rate is also useful since it reduces the number of spectrum handoffs, which in turn can increase the achieved rate. To balance this tradeoff, the DSS scheme uses a *rate compensation* approach by introducing a reservation period, denoted by T_r. A fixed allocation will be applied during this period without any handoff. If some SUs do not achieve their rate, they can compensate in the next reservation period by allocating to them a larger rate so that the average rate at the end of their connection meets the requirement. The allocation can change only at the end of each period as illustrated in Fig. 3. Thus, during unavailable periods inside T_r, spectrum handoffs are not performed.

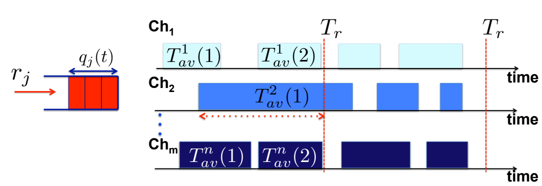


Fig. 3. The reservation period in dynamic spectrum sharing strategy

At the end of T_r, some SUs may not receive sufficient bandwidth to send all their packets. This is reflected in their transmission queue $q_j(t)$. Thus, the requirement of SUs should be related to the number of packets in the queue in order to compensate the lost rate during the former T_r. The total quantity of data to be sent in the next period T_r can be obtained as follows:

$$p_j = r_j \cdot T_r + \sum_{q=1}^{q_j(t)} size(q) \tag{3}$$

where $q_j(t)$ is the number of packets in the transmission queue and $size(q)$ is the size of the q^{th} packet in the queue. ***Unlike SSS, here the total capacity c^i is computed through the quantity of data that the channel i can "contain" in the next period T_r***, which is expressed as follows:

$$c^i = \sum_{l=1}^{k} T^i_{av}(l) \cdot bw^i, \forall i \in \{1, 2, ...M\} \tag{4}$$

where $T^i_{av}(l)$ is the l^{th} available period of channel i in T_r, k is the number of available periods in T_r and bw^i is the link bandwidth of channel i. To consider the overhead of spectrum handoff, the handoff delay HO_{delay} is included if a channel was not selected in the former period. Thus, the capacity of channel i, when it is selected to SU_j can be updated as follows:

$$c^i_j = c^i - \left(\frac{\sum_{l=1}^{k} T^i_{av}(l)}{\sum_{l=1}^{h} T^i_{av}(l)} \cdot c^i \right), \text{if } i \notin CH^f_j \tag{5}$$

where h is the number of available periods during the handoff (HO_{delay}) and CH^f_j is a set of selected channel in the former period. The last term on the right in the formula represents the fraction of quantity of data that is not used during the handoff. Notice that, if SU_j selects the same channel from the former period, i.e. $i \in CH^f_j$, the handoff delay is not counted for the channel capacity and $c^i_j = c^i$.

Similar to SSS, the BFM algorithm is also applied in DSS with some modifications, called *Best Fit selection with Multi-channel constraint for Dynamic spectrum sharing (BFM-D)*. A pseudo code for the BFM-D algorithm and its complexity analysis are available in [14]. Besides, we deliberate to explain the BFM-D algorithm compared with BFM-S by discussing the details of modifications as following. BFM-D is applied at the end of every T_r period using p_j and c^i computed for the next T_r period. To alleviate the unfairness problem, the service satisfaction α_j is measured as the ratio between the achieved rate a_j and the rate requirement r_j, which can be expressed as $\alpha_j = \frac{a_j}{r_j}, \forall j \in \{1, 2, ...N\}$. Consequently, SU who has the lowest satisfaction ratio would have the *priority* to select the channels to use in the next T_r period in order to compensate from insufficient allocated rate from the previous period. Unlike BFM-S, we sort SUs in S in a non-decreasing order regarding their service satisfaction α_j. Accordingly, the BFM-D algorithm starts *Multi-Channel Selection* from the SU who has the minimum α_j.

The capacity of channel c^i must be updated according to the quantity of data that is allocated to the prior SUs. This updated capacity is called the remaining capacity of channel, denoted by c^i_r. In addition, BFM-D also needs to determine the handoff delay for each SU *individually* as mentioned in Eq. 5. However, the total channel capacity c^i in the formula must be replaced by the remaining capacity c^i_r due to the channel capacity can be allocated to the higher priority SUs. Hence, before starting the selection for each SU, the set of Ω is sorted in a non-decreasing order according to the remaining capacity c^i_j which also includes the overhead of handoff delay. Unlike BFM-S, BFM-D algorithm uses the total quantity of data p_j instead of the rate requirement r^q_j. Thus, the best fit condition in BFM-D is changed by considering $C_l \geq p_j$.

To avoid generating unnecessary spectrum handoff at the end of the reservation period and thus reducing more the number of spectrum handoff,[1] we incorporate two new mechanisms in the BFM-D algorithm as follows:

Reserving the same channels: During the multi-channel selection of BFM-D when the turn of SU_j comes, then if the set of current channels CH_j used by SU_j has sufficient capacity compared to p_j, the same set of channels is assigned to SU_j as the former period, i.e. $CH_j = CH^f_j$. Of course, if these channels were allocated to a previous user in the previous iterations, then SU_j cannot keep the same channels. This is coherent with the fact that in the previous iterations higher priority (lower satisfaction) users were served first.

Avoiding to take an occupied channel by other SUs: When the best fit is found at some iteration (see Fig. 4), the set of candidate channels CH_j would be preferably free from other SUs during the former period. Because in this case other SUs may continue to use the same channels, spectrum handoff operation can be reduced globally. Therefore, the iteration is continued to search for a new channel to replace an occupied channel in the best fit iteration. Clearly, the new replaced channel must be unoccupied by any SUs from the previous period. In addition, the capacity of this channel cannot be much larger than the one in the best fit iteration. Regarding the utilization aspect, SU should be assigned to the first channel which fits its request. Otherwise, if SU moves to the upper channel which has very large capacity, other SU who has larger requirement will not be able to find any channel to fit its request. The criterion for selecting a new channel in next step iteration to be replaced a best-fit one can be expressed as $c^\tau \leq c^\chi + \Delta$, where χ is an occupied channel found at the best fit iteration, c^χ is the capacity of channel χ, Δ is a maximum bound capacity and τ is a free candidate channel from next iterations that can replace the occupied channel in the best fit iteration. Here, Δ is chosen to be small for the reason explained above which is not affecting the best-fit principle.

Since p_j is used instead of r^q_j, we then compute the quantity of data of SU_j to be sent over channel i, which can be expressed as follows: $d^i_j = min(p_j, c^i_j), \forall i \in CH_j$. Here, the allocated bandwidth b^i_j is calculated by dividing d^i_j by the total used available periods in the next T_r. Consequently, the

[1]Recall that inside the reservation period T_r, spectrum handoffs are expected to be reduced since during unavailable periods the allocated channels are not changed.

BFM-D algorithm also updates the capacity of the channels to the remaining capacity of the selected channels regarding the quantity of data d_j^i, which can be calculated as; $c_r^i = c_r^i - d_j^i, \forall i \in CH_j$. This refers to the *intra channel allocation*.

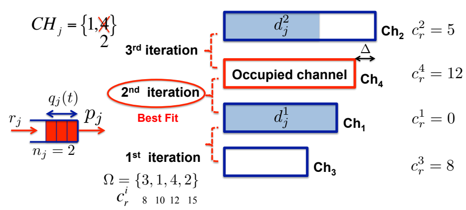


Fig. 4. An example of BFM-D algorithm, SU equips with two antennas

Fig. 4 illustrates the multi-channel selection and intra channel allocation procedures in BFM-D algorithm. The channels in Ω are sorted in a non-decreasing order according to their capacity c_j^i. Here, the best fit is found at the 2^{nd} iteration which contains channel 1 and 4. However, channel 4 was occupied by the other SUs in the previous T_r period ($\chi = 4$), hence the iteration is continued to search for an appropriate channel (τ). At the next iteration, there is channel 2 which was not occupied by any SU from the previous T_r. Besides, its capacity is also not much larger than channel 4 ($c_r^2 \leq c^\chi + \Delta$). As a consequence, channel 2 is chosen instead of channel 4 (i.e. $CH_j = \{1, 2\}$). Finally, BFM-D allocates the quantity of data d_j^1 and d_j^2 over channel 1 and 2 respectively.

C. Hybrid Spectrum Sharing Decision

According to the dynamic PU activities, the environment of CR networks varies over time, which makes it more difficult to decide on spectrum sharing scheme while maintaining the service requirements and reducing the number of spectrum handoffs. Therefore, it is preferable to apply a *hybrid decision* in which the mode of spectrum sharing can be interchangeable between SSS and DSS. The state diagram for the hybrid decision is shown in Fig. 5.

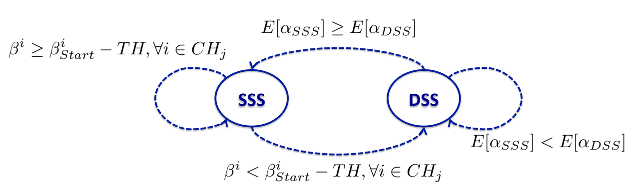


Fig. 5. The two modes of the hybrid spectrum sharing

Clearly, SSS is more suitable for the underloaded state where the rate requirements are less than the capacities of the channels. However, it is not sufficient to choose SSS based solely on this condition. Due to the fact that, the limitation of the number of wireless interfaces, all SUs may not satisfy their rate requirement even though the network is classified as underloaded. On the other hand, applying only the DSS to achieve more rate may not be necessary, since a lot of spectrum handoff would be performed. To make the right decision between SSS and DSS, at the beginning of each T_r period, we apply the following procedures and rules:

Current spectrum sharing is DSS: Firstly, SSS is run to find a solution for resource allocation and to estimate the average satisfaction, $E[\alpha_{SSS}]$. Secondly, the average satisfaction of SSS is compared to the current measured one, $E[\alpha_{DSS}]$. Finally, if the satisfaction from SSS is better than the current one (DSS), the spectrum sharing is switched to SSS. Otherwise, spectrum sharing is still in DSS scheme and BFM-D is called to find a solution for spectrum sharing in the next T_r period.

Current spectrum sharing is SSS: The achieved rate of SUs are sensitive to the availability ratio of channel, denoted by β^i. Since the BFM-S algorithm requires this ratio to estimate the capacity of channels, it is important to observe the characteristic of channels regularly. Moreover, if this characteristic is fluctuating over some acceptable limit, the spectrum sharing should reallocate again due to the fact that the initial allocation of SSS cannot provide the guaranteed service satisfaction to all SUs. The initial availability ratio of channel, denoted by β^i_{Start}, is recorded when spectrum sharing is switched from DSS to SSS. Consequently, β^i is computed at the beginning of each T_r based on the average of the available and unavailable periods from the long-term observation. Finally, if at least one active channel (a channel used by SU) has β^i below the β^i_{Start}, the spectrum sharing will switch to DSS and the BFM-D is called to find a solution for spectrum sharing in the next T_r period. The exact condition to move from SSS to DSS is if $i \in CH_j$ such that $\beta^i < \beta^i_{Start} - TH$. TH is the acceptable limit which should be small. Besides, the value TH can be guided by the application, for instance the file transfer protocol may accept a small tolerance allowing a reduction in the sending rate which can be related to the acceptable limit of the availability ratio.

V. Performance Evaluation

In this section, we analyze the performance of our proposed hybrid spectrum sharing strategy using OMNeT++ [15]. The performance of our strategy is compared to the dynamic spectrum sharing where the spectrum sharing is based solely on DSS. Furthermore, we also compare our hybrid strategy with the Global Spectrum Sharing (GSH) [4]. In this model, the global knowledge of PU activities is assumed to be known in advance. Then, the optimization problem in GSH is solved by programming using CPLEX 12.4 [16]. The simulation is repeated 20 times or 30 if confidence intervals are very large. Averages along with 95% confidence intervals computed with the t-distribution are shown in all plots. In addition, the simulation time is fixed to 500 time units.

A. Simulation Setup and Performance Metrics

We simulate an infrastructure-based CRN with $M = 12$ licensed channels and total of $N = 4$ secondary users. Without loss of generality, each channel has a fixed bandwidth of 10 packets/time unit ($bw^i = 10$) and the size of transmission packet is fixed as 1 unit for all SUs. To take into account the primary user activities, we simulate channels that are switching between available and unavailable periods with a duration exponentially distributed. The means of these durations denoted by $E[T_{av}]$ and $E[T_{un}]$ are generated between $\{0.33, 4.5\}$ time units in order to create 12 channels with different properties (Table I). We compare the performance of the spectrum sharing strategies while increasing the SU's rate requirement. At the first step, 4 SUs have different rate requirements equal to 1, 2, 3 and 4 respectively, hence the total rate requirement (R) is equal to 10. Then, we increase the rate requirement of each SU from the first step by $\{2, 3, 4, 5, 6, 7, 8, 9, 10\}$ times, thus the total rate requirement is varied as follows 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 successively.

TABLE I
CHANNEL CONFIGURATION WITH EXPONENTIAL DISTRIBUTION

Ch	$E[T_{av}]$	$E[T_{un}]$	β^i	Ch	$E[T_{av}]$	$E[T_{un}]$	β^i
0	1	3	0.25	6	1.5	1.5	0.5
1	1.5	4.5	0.25	7	2	2	0.5
2	2	6	0.25	8	1	0.33	0.75
3	4	12	0.25	9	1.5	0.5	0.75
4	0.5	0.5	0.5	10	2	0.67	0.75
5	1	1	0.5	11	4	1.33	0.75

To analyze the performance of the hybrid spectrum sharing strategy, we base our evaluation on total achieved rate, performed number of spectrum handoff and the degree of fairness. Regarding the objective of achieving a fair spectrum sharing, the Jain's fairness index [17] is computed and compared with different total rate requirements R. So far, in our hybrid spectrum sharing, some input parameters are required in the configuration, consisting of the compensation period T_{comp}, maximum bound capacity Δ, threshold of channel fluctuation TH and the reservation period T_r. Clearly, the value of T_{comp} should be large regarding the long-term communication in SSS. Thus, we set $T_{comp} = 100$ time units and applied it for all scenarios. For the Δ parameter, clearly this value should be small due to the fact that we want to maximize the utilization of resource allocation as we discussed in the detail of BFM-D algorithm. Hence, we applied the value of 0.05 for Δ. Similarly for the parameter TH, this value should be small as well, so spectrum sharing can switch to DSS faster. Hence, the value of TH is set to 0.1. The impact of the reservation period T_r is crucial for our strategy, hence we study this factor precisely in the following section. In addition, we first omit the impact of handoff delay by setting $HO_{delay} = 0$ in order to understand clearly the performance of hybrid spectrum sharing strategy. Then, we investigate this factor closely through section V-F.

B. Impact of Reservation Period

We investigate first what would be the impact of the reservation period (T_r). Fig. 6 plots the total achieved rates at the receivers, the number of performed handoff during the simulation and fairness index of allocation while varying the value of T_r and the total rate requirement of SUs, $R = \{20, 40, 60, 80, 100\}$. As mentioned before, the number of spectrum handoff and the ability of rate compensation can be controlled through T_r. The results show that when T_r is increased, the allocation is more close to the static allocation where the number of channel handoffs is significantly decreased. However, the total achieved rate is also decreased when T_r is large, since SU cannot enhance the achieved rate by performing spectrum handoffs. On the contrary, the small reservation period ($T_r = 0.25, 0.5, 1$) also cannot enhance the achieved rates due to the fact that it is too short to allow a rate compensation to be set up. Indeed, in this case we approach a sharing with instantaneous handoffs without rate compensation. Furthermore, the unnecessary handoffs are performed, since new allocation is recomputed periodically in each T_r period. According to the figure, a value of reservation period equals to 2 units of time achieves the best performance in terms of achieved rate and fairness with a low number of channel handoffs. Therefore, for the next simulations, we fix the reservation period to 2 units of time.

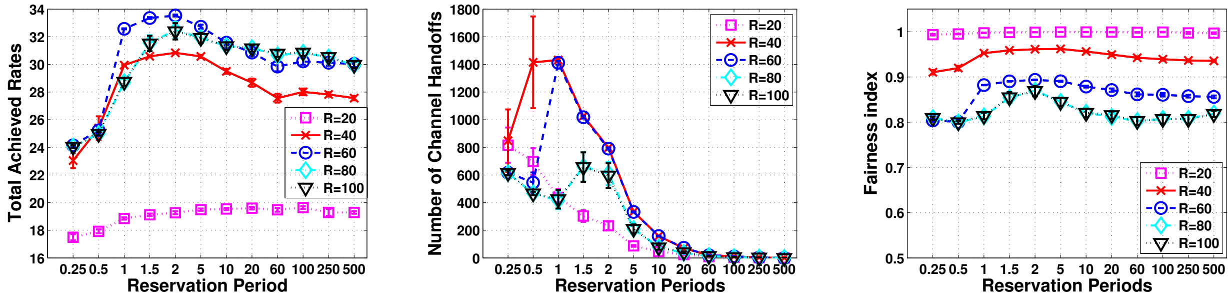
C. Achieved Rates vs. Number of Handoffs

In this section, the performance of hybrid spectrum sharing is studied and compared to the dynamic spectrum sharing and GSH while varying the total rate requirements (R) from 10 to 100. Fig. 7 shows the summation of achieved rates for all SUs and compares it to the number of channel handoffs. Generally, GSH obtains *slightly* higher achieved rates compared to the hybrid and dynamic strategies (see Fig. 7(a)). However, the GSH method performs excessively more handoffs than the others which is not efficient compared to its small gain of the achieved rate (see Fig. 7(b)). This shows the efficiency of both BFM-S and BFM-D heuristics for the rate allocation. The reason is that the hybrid and dynamic strategies integrate many features to prevent the unnecessary handoffs consisting of: reserving the same channel, avoiding to take occupied channels by other SUs, and not performing handoffs inside a reservation period.

Specifically, both hybrid and dynamic strategies provide similar performance in terms of total achieved rates. However, in the underloaded state, i.e., when all SUs can satisfy their rate requirement ($R = 10$ and 20), the hybrid strategy shows lower number of channel handoffs (see Fig. 7(b)). This is because the hybrid strategy switches to the SSS scheme where SUs can satisfy their allocation without any attempt to perform handoffs. On the other hand, in the very high load state ($R = 70$ onwards), the hybrid strategy efficiently perform handoffs leading to lower number of channel handoffs, while it achieves almost the same total achieved rate as the dynamic strategy. Through spectrum sharing decision, it is sufficient to apply the static allocation in this environment, since the available bandwidth is rare compared to the rate requirement. Thus, spectrum handoff is less necessary in this scenario. Nevertheless, even the average available bandwidth is 60, all strategies (GSH, hybrid and dynamic) still cannot satisfy the total rate requirement when it is larger than 20. The reason is the limitations of the number of wireless interfaces as discussed in Section III.

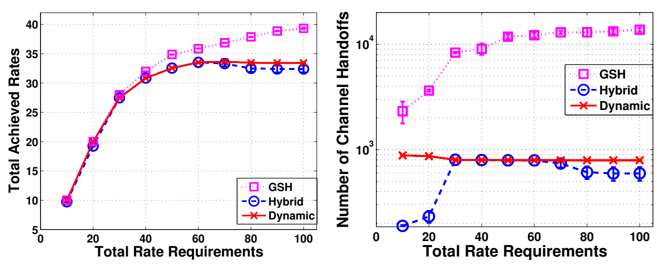
D. Multi-Channel Benefits for Hybrid Sharing

According to the limitation on the number of wireless interfaces, SUs may not be able to achieve their rate requirement Here, we consider that all SUs are equipped with the same



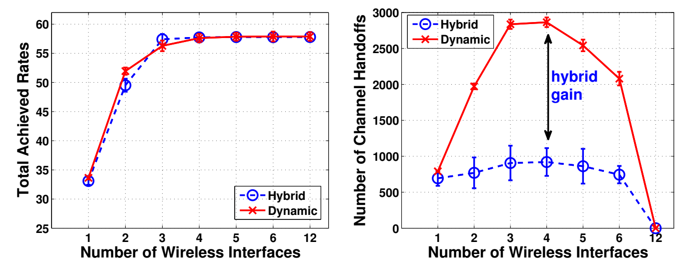
(a) Total achieved rates (b) Number of channel handoffs (c) Fairness index

Fig. 6. Impact of reservation period



(a) Total achieved rates (b) Number of channel handoffs

Fig. 7. Performance for different spectrum sharing strategies



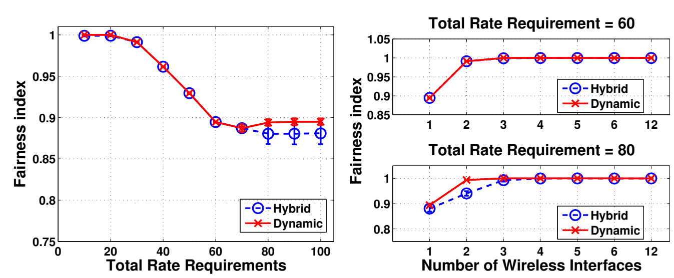
(a) Total achieved rates (b) Number of channel handoffs

Fig. 8. Impact of multi-channel communications

number of wireless interfaces n_j and the total rate requirement is set to $R = 80$. Fig. 8(a) shows the total achieved rate while the number of interfaces is varied from 1, to 12. Using three wireless interfaces, the achieved rates can reach to the maximum utilization. As for the number of handoffs (Fig. 8(b)), using $n_j = 1, 2$ wireless interfaces is not sufficient for having more transmission opportunities to increase all users satisfactions. Hence, by increasing the number of wireless interfaces, spectrum handoff is more useful to have more satisfaction beyond the achieved rate. Consequently, number of channel handoffs is significantly increased when a wireless interface is added, especially for the dynamic spectrum sharing. On the other hand, when $n_j = 3$ onwards, spectrum handoff is reduced gradually showing that the limitation of the number of wireless interfaces is released, as a matter of fact, the total number of wireless interfaces in the network equals to the total number of channels $(4 \times 3 = 12)$. Intuitively, hybrid spectrum sharing strategy can reduce the number of channel handoffs significantly compared to the dynamic approach, since the former can switch to static mode which is very useful to avoid performing unnecessary spectrum handoff.

E. Impact on Fairness

In this section, the Jain's fairness index [17] is computed and compared with different total rate requirements R by fixing $n_j = 1$ (see Fig. 9(a)). Apparently, the maximum fairness cannot be achieved from 20 onwards, because the available bandwidth can be supplied only to some SUs and not for all. Thus, the service satisfaction can be different among SUs, but the utilization is increased reasonably. However, when $R > 60$, the fairness of dynamic strategy is slightly improved. This is because system turns to the overloaded state and all SUs cannot satisfy the service satisfactions, leading to the global increase in the fairness. Besides, the priority channel selection in dynamic strategy (DSS scheme) allows SUs who achieve low service satisfaction to benefit from the higher priority to compensate lost rates in turns and achieve fairness on the long term. On the contrary the hybrid strategy shows lower fairness because it prefers to apply the static allocation (SSS scheme) to avoid performing a large number of spectrum handoff. Concurrently, if some SUs cannot satisfy their requirement, they will not be able to achieve their satisfaction. Furthermore, multi channel communications also improve fairness as shown in Fig. 9(b). The larger the number of wireless interfaces, the better the tradeoff between fairness and utilization. As a result, when the limitation of number of wireless interfaces is released ($n_j = 3$), the maximum fair allocation is found.

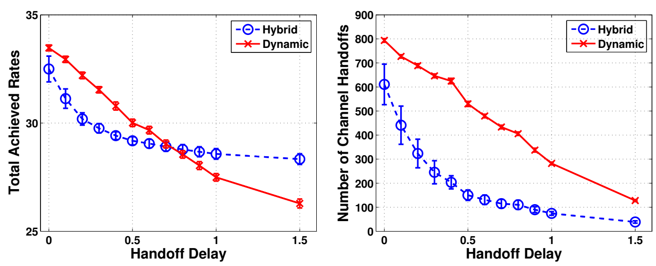


(a) Varying rate requirement (b) Varying number of wireless interfaces

Fig. 9. Jain's fairness index for hybrid and dynamic sharing strategy

F. Impact of Handoff Delay

In this section, we vary the handoff delay from 0 to 1.5 units of time while the total rate requirement is set to $R = 80$. In Fig. 10(a), we show that increasing handoff delay causes an adverse influence on the total achieved rate in both hybrid and dynamic strategies. Generally, the dynamic strategy can achieve better performance in terms of total achieved rate, but the number of channel handoffs is significantly increased (see Fig. 10(b)). On the contrary, when handoff delay is increased, the hybrid strategy achieves better rate than the dynamic one. Due to the fact that, the hybrid strategy decides effectively to apply the SSS scheme where the allocated channels are not changed. As a result, the handoff cost can be alleviated and the total achieved rate is also enhanced. Besides, the capacity of new target channels is reduced by the handoff delay, (Eq. 5) causing a reduction in the average satisfaction ratio of DSS, so that SSS becomes a better choice.



(a) Total achieved rates (b) Number of channel handoffs

Fig. 10. Impact of handoff delay

VI. Conclusion

In this work, we have proposed a hybrid spectrum sharing strategy which includes two heuristic algorithms: *static spectrum sharing* and *dynamic spectrum sharing*. It is an attempt to reach the optimal rate performance while implementing a practical sharing strategy that reduces as required spectrum handoffs. These two sharing algorithms are selected adaptively depending on the current network status. We compare the performance of the hybrid strategy to the dynamic strategy where spectrum handoff is triggered periodically at the end of a reservation period. The simulation results show that both the dynamic and the hybrid are able to fulfill the achieved rates thanks to multi-channel adapted best fit algorithms and the rate compensation concept. The hybrid strategy performs better tradeoff between maximizing the achieved rates and reducing the number of handoffs. Interestingly, the long-term future information like the global optimization (GSH) does not necessarily obtain the maximum rate performance. This is because the long-term future information does not provide any clear insight on how to perform spectrum handoff, and the problem becomes more complex, since there are many possibilities for the spectrum handoff decisions and spectrum selections using these future information. Also, the limitation of the number of wireless interfaces is found to be a crucial factor which prevents classic weighted sharing approaches from reaching a good tradeoff between fairness and utilization. In contrast, our BFM-S and BFM-D algorithms consider carefully this limitation.

There are several close-up extensions to our work. First, we have considered a small number of users as well as the number of licensed channels in the system. Therefore, the scalability issue requires more analysis. Second, we are currently exploring deeply the performance of the hybrid spectrum sharing with heavy tailed distributions for the channel (un)availability. For example, we are using a Pareto distribution with a small tail index such that the variance is large. In other words, the available and unavailable periods of channels become highly unpredictable. Finally, it is possible to translate our proposed strategies into a distributed version for decentralized cognitive radio networks. Here, the challenge is the design of a robust protocol for control information exchange

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