Spectrum Sharing and Impact on Spectrum Handoff in Multi-Channel Cognitive Radio Networks

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Abstract—In cognitive radio networks, spectrum sharing among secondary users can benefit from having more transmission opportunities through spectrum handoff. However, the spectrum sharing strategy can also increase negatively the number of performed handoffs. In this work, we study formally the impact of spectrum sharing on spectrum handoff and at the same time the impact of the spectrum handoff on the overall achievable rates from spectrum sharing. We base our study on three proposed spectrum sharing strategies: static, instantaneous and global. We show that depending on the network configuration, static and/or instantaneous can be almost as powerful as the global strategy. In case handoffs are necessary, the global strategy reduces them significantly. Furthermore, we analyze the benefits of multi-channel communications on the quality of sharing in terms of fairness, achieved rate and number of handoffs.

I. INTRODUCTION

The new Cognitive Radio (CR) technology has been proposed in order to benefit from unused spectrum portions without impairing existing services over the licensed spectrum. CR improves the spectrum utilization by allowing secondary users (SUs) temporarily occupying the unused spectrum bands whenever they are not used by primary users (PUs). A challenge in Cognitive Radio Networks (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. In fact, when the connection of a SU is broken over a channel due to a PU arrival, SU may need to search for another available channel and reconfigure its operating frequency, thus performing a spectrum handoff operation. It is expected that spectrum handoffs allow the user to collect as much available resources as possible from different channels so that its requirement can be achieved. On the other hand, unnecessary spectrum handoffs cause usually degradation of the quality of service perceived by the application due to handoff delays but also due to the increase of channel contentions [1], [2]. Therefore, an effective spectrum sharing strategy should balance between the benefit of spectrum handoff that improves the sharing of the spectrum, and the unnecessary handoffs caused by an inadequate sharing.

Research on spectrum sharing in CRNs has mainly focused on how to efficiently allocate the available spectrum among SUs with the objective to maximize the utilization of the system. A dynamic allocation was addressed in [3] 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, leading to possible spectrum handoffs. The game theoretic approach was also used for CRNs to solve similar dynamic resource allocation problems, e.g. [4]. However, simply maximizing the total capacity may not provide fair allocations to all SUs. Also, the performance of this dynamic allocation is not shown compared to other strategies. A fairness utility function was applied in several works [5]–[7]. In [5], an optimization problem was proposed to provide a weighted fair allocation while maximizing the achieved rate for all SUs. Similar to [6], the fairness weights were computed based on the Homo Euclides model such that a fair allocation could be achieved. Furthermore, in [7], the proportional fair scheduling algorithm was addressed while considering the achieved rate and the interruption due to PUs appearance. Nevertheless, these works consider only a static sharing where the allocations are done only once, for instance, before starting transmissions. In other words, the possible benefits from spectrum handoff is not considered.

In this paper, we aim to study the interaction between spectrum sharing and spectrum handoff by considering and comparing originally three strategies of spectrum sharing: static, instantaneous which corresponds to dynamic allocations, and global which is proposed in an attempt to balance the tradeoff between benefits of spectrum handoff and the necessity of reducing their number. The latter strategy has not been addressed in the literature although it can serve as a reference of feasible performances. Simultaneously, we consider the three objectives related to maximizing the utilization, increasing the service satisfaction of SUs, and providing fairness among them. Furthermore, the use of multi-channel for sharing the spectrum is studied and the impact of the number of wireless interfaces per user is also explored exclusively. Generally, it is not sufficient to maintain the service quality for all SUs, if only one channel is allocated per user. Multi-channel communication should be a promising solution to improve the quality of service requirements as addressed in [3], [8], [9]. The results provide useful insights and guidelines for designing efficient spectrum sharing heuristics that take into account spectrum handoffs. Besides, the performance of all strategies are quantified through their corresponding problem formulations. In particular, we show the gain of increasing
the number of wireless interfaces in terms of handoff costs, fairness and utilization. Interestingly, we found that static or instantaneous strategies can achieve the same rate performance as the global optimization in some network configurations such as when the load is high and the availability periods of channels are mostly synchronized. Finally, the instantaneous strategy engenders generally more handoffs than the others and thus practical implementations should include a global vision by measuring and predicting the channels status.

II. SPECTRUM SHARING IN COGNITIVE RADIO NETWORKS

Consider an infrastructure-based CRN with a total of $N$ secondary users (SU) 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 power allocation techniques [8], or classic time and frequency division multiple access. The total capacity of channel $i$ is denoted by $bw(i)$. Each user $j$ has a different rate requirement $r_j$, which can be considered also as the user weight for sharing the available bandwidth. When PUs appear in the licensed channel, the SUs’ transmissions must handoff to other available channels. At a given time and according to some sharing criteria, each SU is allocated a fraction of bandwidth from each channel. Denotes by $w_j(i)$ the allocated fraction for SU $j$ over channel $i$, where $w_j(i) \in \mathbb{R}; 0 \leq w_j(i) \leq 1$. If $w_j(i) = 0$, then SU $j$ is not tuned to channel $i$ and thus is not transmitting over this channel. Finding the more appropriate weights in a static or a dynamic manner solves the sharing problem.

Solving the spectrum sharing problem while allowing possible spectrum handoffs is not straightforward especially that SUs are constrained with the number of wireless interfaces they possess. A simple example, without handoff, is illustrated in Fig. 1(a) where two SUs compete to access the three channels and each SU is equipped with $n = 2$ wireless interfaces (antennas). The rate requirements are 12 and 2 for SU 1 and 2 respectively. The available bandwidth of each channel is fixed to 4 for a total bandwidth of 12. Considering maximizing the total achieved rate of SUs as the objective, the solution is to give SU 1 a rate of 4 from CH1 and CH2 for a total of 8. Then give to SU 2 a rate of 2 from CH3. Even though, there is still some available bandwidth over CH3, SU 1 cannot utilize these amount of bandwidth to increase its satisfaction, since the number of its interfaces is limited to 2.

In scenario (b) we add another interface to SU 1, thus SU 1 has $n = 3$ and SU 2 has $n = 2$ wireless interfaces. One of the solutions allocates all available bandwidth of the 3 channels to SU 1 and none to SU 2 (Fig. 1(b)). The number of antennas of SU plays an important role in the optimization algorithm. In the first scenario, any optimization cannot maximize the utilization since SU 1 does not achieve its rate requirement even that there is still available bandwidth over CH3. Nevertheless, in the second scenario where there is no limitation of antennas for SU 1 who is able to satisfy its rate requirement, the allocation is not fair to SU 2. Spectrum handoff can improve the spectrum sharing as we will see later.

The challenge is then to maintain the service satisfaction for all SUs by applying an effective spectrum sharing strategy. The achieved rate $a_j$ and rate requirement $r_j$ are compared to evaluate the service satisfaction of each SU. Moreover, the bandwidth should be shared fairly among all SUs with respect to their different service satisfactions and capabilities in terms of number of wireless interfaces for instance.

III. INTERACTION BETWEEN SPECTRUM HANDOFF AND SPECTRUM SHARING

When a licensed channel is not available to SUs for transmission, the rate provided to the user is null. Despite of that, SU can keep using the channel and transmit only during availability periods without performing any channel handoff. The total average rate obtained may satisfy its rate requirement. On the other hand, SU can move to another available channel immediately or after some time of unavailability so that the total average rate achieved satisfies its demand. The tradeoff between the number of spectrum handoffs and the user satisfaction must be taken into account when designing spectrum sharing strategies. We consider three sharing strategies to study the impact of spectrum handoff on the efficiency of spectrum sharing, and to evaluate the impact of the sharing strategy on the number of spectrum handoffs. To do so, we formalize the spectrum sharing problem for each strategy and we solve it optimally, so that the results are representative of any spectrum handoff heuristic implementing the strategy. Accordingly, the first strategy is the Static Spectrum sharing without Handoff (SSH) which corresponds to the case where no handoff is performed during the transmission of SU. Concretely, this means that the spectrum allocation is done only once, for instance, before starting transmissions (Fig. 2). The second strategy is called Instantaneous Spectrum sharing with Handoff (ISH), in which, the allocation is recomputed periodically each time the list of available channels is changed (Fig. 2). This happens when an available channel becomes unavailable and vice versa. Therefore, the sharing is optimized “instantaneously”. Finally, the Global Spectrum sharing with Handoff (GSH) is proposed by including the global information of PU activities over the available channel (Fig. 2). This should offer the optimal sharing while reducing the number of handoffs. We denote by $p^t$, $t \in \mathbb{Z}^+$, the successive periods where the activity of PUs remains the same which means no change in the list.
of available channels. We later show that the GSH strategy provides a benchmark for the rate performance of practical and online spectrum sharing which are likely to be derived from SSH and ISH strategies.

**Optimization objectives:** In addition, each strategy considers two optimization objectives. First, to increase the service satisfaction and to provide fairness among all SUs, the Weighted MaxMin Spectrum Sharing (WMSS) is introduced. The service satisfaction $\alpha_s$ is defined as the ratio of achieved rate $a_j$ to the rate requirement $r_j$ of SUs as: $\alpha_s = a_j / r_j$, $\forall j \in \{1, 2, \ldots, N\}$. Second, the Weighted MaxMin with Maximized Utilization (WMMU) complements the previous one in order to maximize the utilization of the total capacity of CRN.

**A. Static Spectrum Sharing without Handoff**

In the Static Sharing without Handoff (SSH), we perform the allocation based on the average total available bandwidth provided by each channel. This is computed by multiplying $\beta(i)$, the availability ratio of channel $i$, by $bw(i)$, the bandwidth of channel $i$. If we denote the average of the availability period in which the channel can be allocated to SUs by $E[T_{av}^i]$, and the average of the unavailability period by $E[T_{un}^i]$. Then $\beta(i)$ can be computed as: $\beta(i) = \frac{E[T_{av}^i]}{E[T_{av}^i] + E[T_{un}^i]}$. Hence, the operating channels of each SU are fixed once for all. The number of spectrum handoffs is null. We formulate SSH as two optimization problems according to two objective functions.

**Weighted MaxMin Spectrum Sharing (WMSS):** Regarding the unfairness problem discussed in Fig. 1(b), simply maximizing the total achieved rate may not be fair to some SUs, since the system could allocate more bandwidth to some specific SUs. The Weighted MaxMin Spectrum Sharing is proposed with the objective to determine a fair optimal solution for SUs service satisfaction $\alpha_s$, such that the minimum service satisfaction $\alpha_{min}$ is maximized. The WMSS for Static Spectrum sharing strategy can be formulated as follows:

$$\begin{align*}
\text{max min } \alpha_s, \ a_j &= \sum_{i=1}^{M} \beta(i) \cdot bw(i) \cdot w_j(i) \quad (1a)
\text{s.t. } C1: \sum_{j=1}^{N} w_j(i) \leq 1, \forall i \in \{1, 2, \ldots, M\} \quad (1b)
\text{C2: } \sum_{i=1}^{M} [w_j(i)] \leq n_j, \forall j \in \{1, 2, \ldots, N\} \quad (1c)
\text{C3: } a_j \leq r_j, \forall j \in \{1, 2, \ldots, N\} \quad (1d)
\end{align*}$$

Equation (1a) computes the allocation of user $j$, $a_j$, by summing the fractions of bandwidth allocated from each channel $i$, $\beta(i) \cdot bw(i) \cdot w_j(i)$. Constraint $C1$ ensures that the total allocated bandwidth is not larger than the total bandwidth for every channel. The ceiling function $[w_j(i)] \in \{0, 1\}$ equals to 1 if channel $i$ is selected to $SU_j$ which means when $w_j(i) > 0$, and 0 otherwise which means when $w_j(i) = 0$. Consequently, the number of selected channels is restricted to the number of wireless interfaces $n_j$ (constraint $C2$). The last constraint $C3$ on $a_j$ ensures that the achieved rate of $SU_j$ can be equal to the requirement.

**Weighted MaxMin with Maximized Utilization (WMMU):**

WMSS may not maximize the utilization since the primary objective is to achieve an egalitarian service satisfaction. WMMU decomposes the optimization into two sequential steps. In the first step, we compute the minimum service satisfaction $\alpha_{min}$ obtained by solving the WMSS problem. In the second step, we feed $\alpha_{min}$ to the constraint of a second optimization problem where the objective function is to maximize the total achieved rates, thus providing additional bandwidth to SUs that can have it without reducing the service satisfaction of others. The second optimization of WMMU for Static Spectrum sharing strategy corresponds to

$$\begin{align*}
\text{max } \sum_{j=1}^{N} a_j, \ a_j &= \sum_{i=1}^{M} \beta(i) \cdot bw(i) \cdot w_j(i) \quad (2a)
\text{s.t. } C1, C2, C4: \alpha_{min} \leq a_j / r_j \leq 1, \forall j \in \{1, 2, \ldots, N\} \quad (2b)
\end{align*}$$

Here, constraint $C4$ guarantees the minimum service satisfaction for all SUs. In other words, no SU will obtain lower than the more constrained user.

**B. Instantaneous Spectrum Sharing with Handoff**

Spectrum handoff can enhance the spectrum sharing since it offers more combinations to achieve the required rate compared to the static strategy. Instead of computing the allocations using the average available bandwidth of channels, it is possible to compute the allocation instantaneously or more precisely when the list of available channels changes as illustrated in Fig. 2. The computation probably will change the allocations of some SUs which means concretely that they are required to perform a channel handoff. This strategy, called ISH, represents somewhat the class of heuristics that they are required to perform a channel handoff. The allocation is computed independently. The output is $w_j(i)$ and $a_j$ for each period. Then, we can compute the average rate achieved during some period of time ($\sum t^p$) and the necessary number of handoffs to achieve it. The WMSS for Instantaneous Spectrum sharing strategy corresponds to

$$\begin{align*}
\text{max min } \alpha_s, \ a_j &= \sum_{i=1}^{M} bw(i) \cdot w_j(i) \quad (3)
\text{s.t. } C1, C2, C3
\end{align*}$$
Furthermore, the second optimization of WMMU for Instantaneous Spectrum sharing strategy can be formulated as follows:

\[
\max \sum_{j=1}^{N} a_j, \quad a_j = \sum_{i=1}^{M} bw(i) \cdot w^t_j(i) \quad (4)
\]

\[
s.t. \quad C1, \quad C2, \quad C4
\]

Notice here that the ratio \( \beta(i) \) is not used any more in computing \( a_j \).

\[\text{C. Global Spectrum Sharing with Handoff}\]

It is expected that the instantaneous sharing would generate a lot of channel handoffs in contrast with the static strategy. Clearly, if complete knowledge on the channels availability is included in the sharing, then the handoff operations should be intuitively reduced. Besides, the average rate can be optimized also globally. That is the goal of the Global Spectrum Sharing with Handoff (GSH) strategy. It assumes that \( p^t \) are known. Even if they are not known, this strategy represents the class of heuristics that attempt to perform average rate sharing based on measurements and predictions. \( p^t \) are now included in the optimization problem GSH. Moreover, SUs may not perform spectrum handoff immediately when one of its current channels is not available, because they can compensate their lost rate when the current channel becomes available again, or when they move later to another available channel. The WMSS for Global Spectrum sharing with Handoff can be written as

\[
\max \min a_j, \quad a_j = \frac{\sum_{i=1}^{P} \sum_{j=1}^{M} bw(i) \cdot w^t_j(i) \cdot p^t}{\sum_{t=1}^{P} p^t} \quad (5a)
\]

\[
s.t. \quad C5 : \sum_{j=1}^{N} w^t_j(i) \leq 1, \\
\quad \forall i \in \{1,2,...,M\}, \forall t \in \{1,2,...,P\} \quad (5b)
\]

\[
C6 : \sum_{i=1}^{M} [w^t_j(i)] \leq n_j, \\
\quad \forall j \in \{1,2,...,N\}, \forall t \in \{1,2,...,P\} \quad (5c)
\]

\[
C7 : a_j \leq r_j, \forall j \in \{1,2,...,N\} \quad (5d)
\]

\( P \) is total number of considered periods where the list of available channels is the same (Fig. 2). Constraint \( C5 \) ensures that in each period \( p^t \) the allocated fraction of bandwidth to SUs over channel \( i \) is not beyond the channel capacity. The number of the selected channels of each period \( p^t \) is restricted to the number of wireless interfaces \( n_j \) indicated in constraint \( C6 \). Finally, in constraint \( C7 \), the average achieved rate of each SU is restricted to its rate requirement. Similarly, the WMMU for Global Spectrum sharing with Handoff can be formulated as follows

\[
\max \sum_{j=1}^{N} a_j, \quad a_j = \frac{\sum_{i=1}^{P} \sum_{j=1}^{M} bw(i) \cdot w^t_j(i) \cdot p^t}{\sum_{t=1}^{P} p^t} \quad (6)
\]

\[
s.t. \quad C4, \quad C5, \quad C6
\]

\[\text{IV. SIMULATION AND NUMERICAL ANALYSIS}\]

In this section, we analyze the performance of the different sharing strategies using the two optimization functions especially in terms of performed number of spectrum handoffs and achieved rates. We consider a CRN with \( M = 9 \) licensed channels and a total of \( N = 5 \) secondary users. Each channel has a fixed bandwidth of \( 10(bw(i) = 10) \). All optimization problems involved in the numerical analysis were solved by programming them using CPLEX 12.4 [10]. To take into account the primary user activity, 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 in the set \( \{0.5, 1, 1.5\} \) times units in order to create 9 channels with different properties. When at least one channel changes its state from the available to unavailable or vice versa, the value of \( p^t \) is recorded. The numerical simulation is repeated more than 10 times and averages along with 95% confident intervals computed with the t-distribution are shown in all plots, even though they are mostly too small in the figures. In addition, the simulation time are fixed as 60 time units in all scenarios.

\[\text{A. Achieved rates vs. number of handoffs}\]

In this section, we compare the performance of the spectrum sharing strategies while increasing the SU’s rate requirement. At the first step, 5 SUs have different rate requirements equal to 1, 2, 3, 4 and 5 respectively, hence the total rate demand is equal to 15. Then, we increase the rate requirement of each SU from the first step by \( \{1.5, 2, 2.5, 3, 3.5, 4\} \) times, thus the total rate demand is varied as follows 15, 22.5, 30, 37.5, 45, 52.5 and 60 successively. Fig. 3 shows the summation of achieved rates for all SUs while varying the total rate requirement. The objective of WMSS is to achieve an egalitarian service satisfaction thus the performance in terms of total achieved rate is worse than the WMMU. Concerning the performance of spectrum sharing strategies (SSH, ISH and GSH), it is proved that spectrum handoffs can enhance the spectrum sharing since it offers more possibilities to achieve the required rate as shown in Fig. 3(a), 3(b). Generally, SSH provides the worst rate performance compared to ISH and GSH since the spectrum handoff is not performed in SSH. Intuitively, GSH outperforms the other two strategies, the total achieved rate is increased up to 39.84% compared to SSH and up to 6.85% compared to ISH. Nevertheless, GSH still cannot satisfy the total rate requirement when it is large (> 37.5). The reason is the limitation of the number of antennas as discussed before in Section II.

Next, we compare the number of channel handoffs between ISH and GSH with the two optimization problems. As expected, GSH can reduce the number of channel handoffs significantly as illustrated in Fig. 4. Besides, when only fairness is sought (WMSS), the number of handoffs is smaller since users do not increase more their rates until reaching the full utilization. That means, when a channel is unavailable, they do not move necessarily to another one to get more rate. On the other hand, when considering the utilization (WMMU), the number of handoffs is larger since users do more handoff...
SUs cannot compensate their lost rates because the maximum obtainable bandwidth is fixed at the rate requirement, which shows clearly the weakness of using current spectrum status for sharing the spectrum. In contrast, SSH performs the allocation based on the average total available bandwidth, thus, when the rate requirement is low, unavailability occurrences and the synchronization between channels do not impact the achieved rates.

Fig. 6. Usability regions for different spectrum sharing strategies

Although, the GSH strategy always provides better performance in terms of achieved rates and service satisfaction, we have observed through these simulations that SSH and ISH strategies are also useful in some configurations. Fig. 6 shows the usability regions of the different spectrum sharing strategies. Here, the channel synchronization indicates the synchronization of unavailability periods of channels which is very high if all channels become unavailable simultaneously. As mentioned above, ISH can be employed in the case where the synchronization is rather low even with low requirements. As for SSH, it is appropriate for low rate requirements. However, when the synchronization is high, GSH and ISH cannot improve the achieved rates by spectrum handoff because in case of unavailability of current used channels, other available channels are rare. Thus, SSH is also powerful as GSH in this case. In practice, the environment of CRNs may change dynamically, and SUs have usually different requirements. Thus, the strategies of spectrum sharing would be combined adaptively depending on the dynamic spectrum resources and the heterogeneous requirements, knowing that it is easier to implement static sharing (SSH) in the network than ISH which is in turn more feasible than GSH.

C. Multi-Channel Benefits

According to the limitation on the number of wireless interfaces, SUs may not be able to achieve their rates and thus maximize the utilization of the spectrum. In this section, we consider a CRN with \( M = 20 \) licensed channels to emphasis better on the multi-channel properties. All SUs are equipped with the same number of wireless interfaces \( n_j \) and the total rate requirement is set to 120 to ensure a high load scenario. Here, the rate requirement of \( SU_1 \) to \( SU_5 \) are set to 8, 16, 24, 32 and 40 respectively. The results are presented only for GSH, since it is recognized as the best strategy from previous evaluations. Fig. 7(a) shows the total achieved rate while the number of interfaces is varied from 1, to 20. Using four wireless interfaces increases significantly the achieved rates. As for the number of handoffs (Fig. 7(b)), the more the number of wireless interfaces, the lower the number of handoffs when

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**Notes:**
- The diagrams and figures are not transcribed here due to the limitations of text-only representation.
the constraint of the number of wireless interfaces is released. In other words, when SUs are equipped with small number of interfaces. Indeed, using \( n_j = 1, 2, 3 \) is not sufficient for having more transmission opportunities to increase all users satisfactions, and hence lower number of handoffs are performed with lower achieved rates. On the other hand, when using four wireless interfaces, spectrum handoff is more useful to have more satisfaction beyond the achieved rate. Besides, the number of handoffs is reduced significantly when \( n_j = 4 \) 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 becomes equal to the total number of channels \( (4 \times 5 = 20) \).

![Graph](image)

Fig. 7. Impact of multi-channel communications

### D. Impact on Fairness

Regarding the objective of achieving a fair spectrum sharing, the Jain’s fairness index [11] is computed and compared with the variation of rate requirement (see Fig. 8(a)). In addition, we still consider a CRN with \( M = 20 \) licensed channels as previous section. Apparently, with WMSS, all requirements achieve maximum degree of fairness. As a matter of fact, the utility function of the sharing is to maximize the minimum service satisfaction \( \alpha \). For the WMMU, the maximum fairness cannot be achieved from a total rate requirement of 30 onwards, because beyond \( \alpha_{min} \) 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.

![Graph](image)

Fig. 8. (a) Varying rate requirement (b) Varying number of wireless interfaces Jain’s fairness Index for GSH strategy

Furthermore, multi-channel communications also improve fairness as shown in Fig. 8(b). The larger the number of wireless interfaces, the better the tradeoff between fairness and utilization.

## V. Conclusion

In this paper, we propose and study three spectrum sharing strategies while considering the impact of spectrum handoffs in cognitive radio networks. Specifically, these are the Static Spectrum sharing without Handoffs (SSH), Instantaneous Spectrum sharing with Handoffs (ISH) and Global Spectrum sharing with Handoffs (GSH). We examine how these strategies maximize the utilization of the spectrum and the fairness among users. To this end, the WMSS and WMMU optimization problems were formulated to supply the spectrum sharing solutions in multi-channel CRNs. We show that each strategy can be powerful under specific network configurations, and that the GSH strategy outperforms SSH and ISH in general, both in terms of utilization and number of handoffs. The GSH strategy, even that it is hard to implement practically, provides a quantification of the attainable performance that should be used by spectrum handoff and sharing designers. We learned that using multiple channels improves the tradeoff between fairness, utilization and number of handoffs even if the channels are dynamic. We learned also that increasing a lot the number of handoffs does not increase necessarily the quality of the spectrum sharing. Waiting at the current unavailable channel in an attempt to compensate later the lost rate seems to be a good approach. We are using this idea among other characteristics of the spectrum strategies to design a low complexity and efficient heuristic for spectrum sharing through spectrum handoff.

## References