Fairness Evaluation of a Secondary Network Coexistence Scheme

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Abstract—Due to the ever-increasing traffic demands and the fact that the spectrum resources are limited, it is very likely that several secondary networks (SNs) will coexist and opportunistically use the same primary user (PU) resources. In such coexistence scenarios, it is fundamental to guarantee fairness among the coexisting SNs. To that end, in this paper, we evaluate the performance of an SN coexistence scheme in terms of fairness and we show that it can achieve throughput and energy efficiency gains, while maintaining fairness among the coexisting SNs in comparison to other state-of-the-art approaches.

Index Terms—Cognitive Radio, Coexistence, Fairness, CSMA/CA, Spectrum Overlay, Green Communications.

I. INTRODUCTION

In the last years, the need for anywhere-anytime connectivity has led to the vast use of tablets, laptops and smart-phones along with their data-hungry applications. A way to meet these exponentially growing traffic demands and achieve capacity enhancement is to assign more spectrum to the network. However, the spectrum resources are limited and, in their majority, inefficiently used [1]. Therefore, there is a need for better spectrum utilization that can be achieved through “spectrum-awareness” (i.e., a specific type of context-awareness [2]). To that end, cognitive radio (CR) was proposed, which uses spectrum sensing to detect the unused licensed channels (LCs) and enables their opportunistic use by unlicensed users, also called secondary users (SUs) [3], [4].

Due to the limited spectrum resources, the coexistence of several secondary networks (SNs) has become a challenging topic. However, most papers in the literature deal with scenarios where a single SN is considered, thus totally overlooking any SN coexistence issues. To that end, in [5], we proposed a channel selection algorithm in a scenario where an SN coexists with other non-cooperating SNs and opportunistically uses the same PU resources according to a specific coexistence scheme. In such coexistence scenarios, it is very important to achieve fairness among the coexisting SNs, which implies equal transmission opportunities among their SUs.

Generally, achieving fairness among the SUs that share the same PU spectrum is a research topic that has received a lot of attention. In [6], a fair opportunistic spectrum access scheme is proposed that, based on a fast catch up strategy, manages to reduce the amount of time after which all SUs have equal access rights to the available LCs. In [7], a Homo-Egalis based learning model was proposed to achieve fairness among dissimilar SUs, while in [8] the authors proposed heuristic channel allocation algorithms based on multi-channel contention graphs and linear programming aiming at achieving a good trade-off between throughput and fairness, while ensuring interference-free transmissions. In [9], the authors derive the optimal access probabilities for two independent SUs focusing on achieving a good trade-off between spectrum efficiency and fairness. However, all these proposals assume that an LC that is occupied by an SU can not be accessed by another SU. In particular, the LC appears as being busy to the SU and thus it is avoided. Hence, most coexistence schemes in the literature totally overlook the case where several SNs coexist and share the same PU resources.

To overcome the aforementioned problem, in [10], the authors propose FMAC, a MAC protocol, that utilizes a three-state sensing model. Specifically, FMAC uses a spectrum sensing algorithm [11] to distinguish whether a busy channel is occupied by a PU or by an SU and, in the latter case, gives the option to the SU to share the channel with the SUs of other SNs that are currently using it. Nevertheless, in [10] a simple system model consisting only of one LC is considered, while more importantly, the scheme employs a constant back-off window. As a result, unlike the proposed coexistence scheme, it shows low adaptability to any changes in the number of contending SUs in an LC.

To that end, in this paper, we evaluate the performance of the coexistence scheme proposed in [5] in terms of fairness among the coexisting SNs. The considered coexistence scheme is compared with the reference approach (FMAC) by means of simulations and it is shown that it can achieve significant throughput and energy efficiency gains, while maintaining or even achieving better fairness among the coexisting SNs. Furthermore, we study the impact of different minimum back-off window values and different PU activity patterns on the performance of both considered coexistence schemes.

The rest of the paper is organized as follows: In Section II, an overview of the system model and the coexistence scheme is given. In Section III, the considered coexistence scheme is compared with the reference approach by means of simulation in terms of throughput, energy efficiency and fairness. Moreover, the performance of both coexistence schemes for several minimum back-off window values and PU activity patterns is studied and discussed. Finally, Section IV concludes the paper.
II. SYSTEM MODEL AND COEXISTENCE SCHEME

OVERVIEW

Fig. 1. System model example.

We consider a set of $M$, LCs, that are allocated to PUs and can be opportunistically accessed by SUs as long as they remain idle. A highly congested unlicensed channel (UC) is also considered, which may belong to the industrial, scientific and medical (ISM) band. In addition, we consider an SN consisting of $N$ SUs, which is able of operating both in the considered UC and LCs.

The SN under study has a coordinator, whose role may be assigned to each one of the $N$ SUs in a round robin way to achieve fairness in energy consumption [12]. Furthermore, each LC, when being idle, can be accessed by SNs, each one consisting of a different number of SUs. We denote as $N_{SU_{lic}}$, the maximum total number of SUs that can operate in an LC and as $N_{unic}$ the number of users that operate in the UC (this parameter does not include the $N$ users of the SN under study). At this point, it is worth mentioning that the $N_{unic}$ users that operate in the UC may constitute a mixture of SUs belonging to other SNs and users without CR capabilities that are only able of using the UC.

We further make the following assumptions:

1. The PU activity follows an exponential on-off traffic model, with the mean duration of on and off periods denoted by $T_{on}$ and $T_{off}$, respectively.

2. The nodes of the SN under study are adequately close to each other to be exposed to the same channel activity. However, note that their reported sensing results may differ due to false alarm and mis-detection probability.

3. The SN under study does not use a common control channel, and thus the LCs are shared for both control and data transmissions. Nevertheless, it is important that the SN under study exploits exclusively the LCs for data transmission and thus in the UC only control information exchange takes place (i.e., the initial setup of the network and the recovery when no idle LCs are tracked).

4. All the considered SUs are equipped with a single transceiver. Hence, even if they are capable of operating over multiple channels, including the LCs, they can either transmit or receive over a single channel at a time.

5. The transmissions of the SUs both in the UC and LCs follow the carrier sense multiple access with collision avoidance (CSMA/CA) method [13], while the PUs may use their own access method, while accessing the LCs (e.g., single-carrier frequency-division multiple access (SC-FDMA) in the uplink and orthogonal frequency-division multiple access (OFDMA) in the downlink for long-term evolution (LTE) access).

The SN is assumed to be initially located in the highly congested UC, where the coordinator triggers a sensing procedure divided into three parts: $t_{ph1}$, $t_{ph2}$, $t_{ph3}$ and ii) the order in which the SUs will sense the LCs. During sensing procedure will be triggered. The latter is determined by the parameter $T_{S}$. This parameter is constant and equal to the time from the beginning of operation in the first visited LC until the coordinator has a new RFS packet to send. For quickly changing PU activity, this value should be low to keep the information for every LC updated. On the successful RFS reception, only one of the SUs (i.e., the one defined to report its sensing results first) acts as a “leader” and sends an acknowledgment (ACK) to the coordinator, whereas on erroneous reception the leader does not send an ACK, prompting a retransmission. On erroneous reception by the rest SUs, negative ACKs (NACKs) are sent by them to collide with the ACK from the leader, thus destroying it and prompting a retransmission.

During $t_{ph2}$, all the SUs sense the LCs that were assigned to them in $t_{ph1}$. If the number of SUs of the SN is a multiple of the LCs, each LC is sensed by the same number of SUs. Otherwise, a subset of LCs is sensed by more SUs and cooperative spectrum sensing (CSS) using the OR fusion rule is applied to achieve better mis-detection and false alarm probability. Thus, when at least one of the cooperating SUs senses the LC as busy, the final decision declares the presence of a PU. In that case, the mis-detection probability ($P_{md}$) and the false alarm probability ($P_{fa}$) are respectively expressed as:

$$P_{md} = 1 - \prod_{i=1}^{k} (1 - P_{md,i})$$

$$P_{fa} = 1 - \prod_{i=1}^{k} (1 - P_{fa,i})$$

where $k$ is the number of SUs that cooperate during CSS and $P_{md,i}$ and $P_{fa,i}$ are the mis-detection probability and
false alarm probability of the $i^{th}$ SU, respectively. Generally, the OR fusion rule presents low mis-detection probability and high false alarm probability and thus it provides high protection to the PUs at the expense of low reusability of unoccupied LCs. During sensing, cyclostationary feature detection is used, which enables the distinction between PUs’ and SUs’ signals, at the expense of more complexity and longer sensing time [14]. The use of feature detection is very important, as otherwise (i.e., by using a simpler technique, such as energy detection) all the LCs occupied by other SUs would be considered busy and would be avoided, thus resulting in very low spectrum efficiency.

During $t_{ph3}$, the SN under study hops to the UC and the exchange of the sensing results takes place. Given the importance of exchanging the sensing results as soon as possible, we consider the reservation of the UC for the constant and known period of $t_{ph2}$ and $t_{ph3}$, as long as its duration is lower than the maximum tolerable delay$^1$.

Hence, the sensing result exchange starts with the coordinator broadcasting a beacon frame (of duration $t_B$) asking for the sensing results of the rest of the SUs, as depicted in Fig. 2. Subsequently, each SU has to wait $t_{SIFS}$ and then sends its sensing results (of duration $t_{SR}$) to the coordinator in the previously defined (in the RFS packet) order. Thereafter, the coordinator constructs and broadcasts a packet of transmission duration $t_{LIST}$ and the contention-free period ends.

According to the algorithm proposed in [5], the list will contain all the LCs that were sensed idle, sorted by the estimated number of contending SUs in ascending order (i.e., the LC with the lowest number of contending SUs takes the first place and thus higher priority).

Once the list is constructed, there are two possible cases:

- There are no LCs sensed idle: the SN stays in the UC and another sensing procedure is initiated.
- There is at least one LC sensed idle: the SN hops to the first LC in the list and operates there. Then, the normal CSMA/CA operation is interrupted in the following two cases:
  - The LC becomes busy: the SN has to leave the channel immediately in order not to interfere with the PU. We assume that the SN can detect the PU activity after $t_x$ and then reacts by hopping to the next LC in the list. In case there is no other LC in the list, the SN hops back to the UC and triggers a new sensing procedure.
  - It is time for the next sensing procedure to be initiated (i.e., $T_S$ has elapsed from the previous sensing): the coordinator contends to gain access to the LC to send the RFS packet.

III. PERFORMANCE EVALUATION

A. Scenario

In the extensive simulations we executed in MATLAB, we considered an SN consisting of $N=12$ SUs and a set of $M_c=6$ LCs, while $N_{unic}=50$. Without loss of generality, we assume that all the users are in saturated conditions (i.e., always having a packet to send). The channel conditions are assumed to be ideal (i.e., no hidden terminals, no exposed terminals and no packet corruption are considered) for both the considered SN coexistence scheme (SNCS) and the reference scheme (FMAC [10]). Please note that these parameters are omitted, since they would affect both approaches in the same way.

The LCs are divided into four categories according to the number of contending SUs already operating in each one. Specifically, in our scenario ($M_c=6$), we consider two LCs belonging to the first category (very low contended LCs), one to the second (low contended), one to the third (medium contended) and two to the fourth (high contended). Moreover, the interval of each category is determined by the parameter $N_{SU lic}$ (e.g., for $N_{SU lic}=40$, the first category ranges from 0 to 10 SUs, the second from 10 to 20, the third from 20 to 30 and the last from 30 to 40 SUs). The exact value of the actual number of SUs in an LC is randomly chosen between the interval of its category. The rest simulation parameters are summarized in Table I, where $l_p$ denotes the length of the packet $p$ and $P_j$ the power consumption in the state $j$.

In order to calculate the fairness among the coexisting SUs that contend for the same PU resources, we employ the well known Jain’s fairness index [16], that is given by:

$$J(x_1, x_2, \ldots x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2}$$

where $n$ is the number of contending SUs and $x_i$ denotes the number of transmission opportunities of the SU $i$. We consider that an SU has a transmission opportunity every time it transmits a packet on the channel independently of whether a successful transmission or a collision occurs.

B. Results

In Fig. 3 and 4, the average throughput and energy efficiency of the SN under study are respectively depicted for both SNCS and FMAC versus the maximum number of SUs of other networks in an LC, $N_{SU lic}$, for different minimum back-off window values, $CW_{min}$. As it can be observed, the throughput and the energy efficiency of the SN under study are decreased as the contention in the LCs increases, due to the increased number of collisions among the SUs. However, notice that the SNCS achieves better performance than FMAC for all the considered values of $CW_{min}$. This is due to the fact that, in FMAC, the SUs use a constant back-off

$^1$This channel reservation is compatible with existing standards, such as the transmission opportunity (TXOP) in 802.11 [15].
TABLE I
SIMULATION VALUES

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<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<td>$P_{off,i}$</td>
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<td>$t_{on}$, $t_{off}$</td>
<td>1 ms, 9 ms</td>
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<tr>
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<td>$t_{IFS}$</td>
<td>9 µs</td>
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<td>$ip_{i}$</td>
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<td>$IS_{i}, I_{ILIST}$</td>
<td>16 bytes</td>
</tr>
<tr>
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<td>Data $T_x$ Rate</td>
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<td>$P_{on}, P_{off}$</td>
<td>1900 mW</td>
</tr>
</tbody>
</table>

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Fig. 3. Average throughput of the SN under study versus the maximum number of SUs of other networks in a licensed channel, $N_{SU_{lic}}$, for different minimum back-off window values, $CW_{min}$.

Fig. 4. Average energy efficiency of the SN under study versus the maximum number of SUs of other networks in a licensed channel, $N_{SU_{lic}}$, for different minimum back-off window values, $CW_{min}$.

window every time a collision takes place, while the SNCS employs an exponential one and thus it manages the collisions more efficiently. Therefore, the maximum performance gain of SNCS is achieved for the lowest minimum back-off window value ($CW_{min} = 16$) and for high contention in the LCs ($N_{SU_{lic}} = 40$).

Moreover, as far as the fairness of the considered approaches is concerned, the average Jain’s index of all the SUs, that contend to gain access to an LC, is depicted for both approaches in Fig. 5, for different minimum back-off window values, $CW_{min}$. As we can notice, SNCS can achieve up to 25% better fairness than FMAC ($CW_{min} = 16$) for high contention in the LCs ($N_{SU_{lic}} = 40$). This stems from the fact that for short contention periods, i.e., in the case that the PU resumes its activity in the LC shortly after the SN under study has hopped to it, the SNCS achieves much better fairness among the SUs than in FMAC, as an SU that is involved in a collision defers its transmission for a longer time, and thus the transmissions opportunities are more equally distributed among the contending SUs.

To that end, in Fig. 6, 7 and 8, we study the performance of the considered coexistence schemes for different PU activity patterns. Specifically, we consider two different values of $T_{on}$ and $T_{off}$, that correspond to quickly ($T_{on}=T_{off}=0.5s$) and slowly changing PU activity ($T_{on}=T_{off}=2s$), respectively. Moreover, notice that the $T_S$ value is adapted according to the considered PU pattern. In particular, for quickly changing PU activity a low value of $T_S$ is employed to repeat the sensing procedure more frequently to keep the information for every LC updated, while for slowly changing PU activity, this value is chosen to be higher to let more time available for data transmissions to the SUs.

As it can be observed in Fig. 6 and 7, for slowly changing PU activity, the SN under study achieves higher throughput and energy efficiency, as there is more time devoted to transmissions and less to frequent unnecessary sensing procedures. In addition, the SNCS achieves better performance than FMAC for both the considered PU traffic patterns. Please note that we have selected $CW_{min} = 64$ for both approaches, to show the minimum gains that can be achieved in comparison to FMAC.

The average Jain’s index is depicted in Fig. 8 for different PU activity patterns. As we can notice, for slowly changing PU activity, both approaches achieve slightly better fairness among the contending SUs than in the quickly changing PU activity case, as there is more time devoted to transmissions. Moreover, for low contention in the LCs, FMAC achieves better performance in terms of fairness. However, according to the previously analyzed reasoning, for higher contention there is a cross point where the SNCS starts achieving better fairness. The SNCS maximum performance gain in this case is
again achieved for high contention in the LCs ($N_{SU_{lic}} = 40$).

Fig. 6. Average throughput of the SN under study versus the maximum number of SUs of other networks in a licensed channel, $N_{SU_{lic}}$, for different PU activity patterns.

Fig. 7. Average energy efficiency of the SN under study versus the maximum number of SUs of other networks in a licensed channel, $N_{SU_{lic}}$, for different PU activity patterns.

Fig. 8. Average Jain’s index versus the maximum number of SUs of other networks in a licensed channel, $N_{SU_{lic}}$, for different PU activity patterns.

IV. Conclusion

In this paper, we evaluated the performance in terms of throughput, energy efficiency and fairness of an SN coexistence scheme by comparing it to a reference approach, in a scenario where several non-cooperating SNs share the same PU resources opportunistically. By means of simulation, we studied how the performance of the coexistence scheme is affected by the employment of different minimum back-off window values. Furthermore, we studied the impact of different PU activity patterns on the considered coexistence schemes. We showed that the considered coexistence scheme can achieve throughput and energy efficiency gains, while maintaining fairness among the coexisting SNs in comparison to the reference approach. Specifically, the maximum gain is achieved for the lowest minimum back-off window value ($CW_{min} = 16$) and for high contention in the LCs ($N_{SU_{lic}} = 40$).

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REFERENCES