Impact of Secondary MAC Cooperation on Spectrum Sharing in Cognitive Radio Networks

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Abstract— **In this paper, the impact of secondary MAC cooperation on the sum-throughput of multichannel cognitive radio networks is studied. The main goal is twofold: Given the primary and secondary users' duty cycle, (i) investigate the amount of spectrum sharing (i.e., number of secondary users) that maximizes the sum-throughput in the presence of secondary MAC cooperation; (ii) assess the performance gains attainable with cooperation. First, analysis is provided for the idealistic case of perfect sensing, with a simple model for secondary cooperation. Then, for the more realistic case of imperfect sensing, novel cooperative secondary strategies are proposed that are shown to provide relevant performance gains in terms of sum-throughput. Finally, numerical simulation results are provided to evaluate the performance of the cooperative schemes relative to other non-cooperative schemes.**

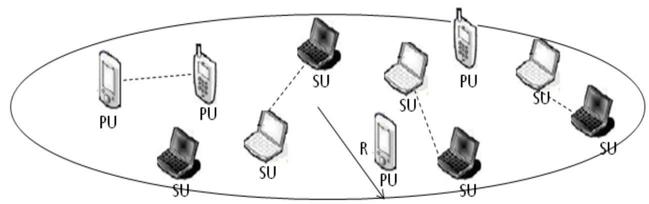


Fig. 1. A cognitive radio network: N_p primary and N_s secondary users are uniformly distributed on a disc of radius R. Each active primary node transmits on its own subchannel, while secondary nodes employ a listen-before-talk mechanism over all subchannels for opportunistic spectrum access [8].

I. Introduction

The need to accommodate fast-emerging wireless communication services has motivated academia and industry to look for a solution to the problem of available spectrum scarcity. In fact, recent studies on regulated spectrum access show that most of the allocated spectrum fragments are under-utilized both temporally and spatially [1]-[2]. Concepts such as spectrum sharing and opportunistic spectrum access, and more generally cognitive radio, were introduced as possible solutions (see, e.g., [3]-[4]). Cognitive radio has the potentiality to overcome the spectral shortage by enabling secondary (unlicensed) users to utilize spectrum holes left open by the primary inactivity. Secondary (or cognitive) radios are typically envisioned to employ a "sense-before-talk" strategy that prescribes channel access based on spectrum sensing for detection of spectrum holes. The limits of such an approach have been recently studied both in terms of sensing accuracy and overall throughput (see, e.g., [5]). It has been concluded that cooperation among the secondary nodes at physical and/or MAC layers is necessary to guarantee effective secondary spectrum access. For instance, reference [6] (see also references therein) shows that relevant gains in terms of secondary detector sensitivity can be accrued by deploying cooperative sensing at the physical layer, while [7] points to the advantages of MAC secondary cooperation.

In this paper, we are interested in extending the considerations mentioned above to the *spectrum sharing multichannel scenario* studied in [8] (see Fig. 1). In this model, the network designer is faced with the issue of optimizing the number of secondary users versus the number of available subchannels and primary users in order to optimize the system throughput given the primary and secondary traffic duty cycle. Reference [8] studies the trade-off at hand between regulation (more primary users) and autonomy (more secondary users) in the absence of cooperation among the secondary users. This paper, instead, studies the impact of secondary MAC cooperation on the throughput of the discussed spectrum sharing system. Following [8], we first consider an idealistic system with perfect sensing and a simple model for cooperation to gain analytical insight into the impact of secondary cooperation (Sec. II). This is followed by the study of a more realistic model with imperfect sensing and practical cooperation schemes (Sec. III), for which numerical results and comparison to the non-cooperative case [8] are provided in Sec. IV.

II. Perfect Sensing, Collision Model, Simple Cooperation Model

We consider the network model in [8] wherein a frequency band is equally divided into N_p subchannels, each assigned to one of N_p primary users[1], and time-slotted. The frequency band is also shared *opportunistically* among N_s secondary users for higher bandwidth efficiency. Primary and secondary users are located on a circle of radius R in a uniform distribution fashion as shown in Fig. 1. For analytical simplicity, we assume that primary and secondary users are active (backlogged) independently with equal duty

[1] The terms user and node-pair (transmitter-receiver pair) are used interchangeably in this context.

cycle (traffic generation probability) p $(0 \le p \le 1)$ in each time slot. Primary users transmit whenever they are active, whereas active secondary users access the subchannels only if deemed idle from primary transmissions. We extend the analysis in [8], where no cooperation was considered, by assessing the potential gains of secondary cooperation over the non-cooperative case. To simplify the analysis, we consider, at first, as in [8], *perfect sensing* (i.e., all secondary users can detect unoccupied channels with no errors), and a *collision model* where a transmission is successful only in the absence of interference. Furthermore, we assume a simple model for cooperation in which all the secondary users in a given area of "*cooperation radius*" R_{coop} can perfectly cooperate, thus avoiding collisions (see details below).

We now evaluate the average system sum-throughput, following the same basic notation of [8]. Defining as C the rate in bps/Hz of each packet transmission, it is easy to see that the primary users' sum-throughput C_p^{sum} can be expressed as $C_p^{sum} = CN_p p$, while the secondary users' sum-throughput depends on the current number of free subchannels i and can be written as

$$C_s^{sum} = \sum_{i=1}^{N_p} \binom{N_p}{i} p^{N_p - i} (1-p)^i \, C_s^{sum}(i). \qquad (1)$$

In (1), $C_s^{sum}(i)$ represents the secondary sum-throughput conditioned on the number of available subchannels i, which reads $C_s^{sum}(i) = \sum_{j=1}^{N_s} \binom{N_s}{j} p^j (1-p)^{Ns-j} \, C_s^{sum}(i,j)$, where the average secondary sum-throughput when j secondary users are active over i available (primary) subchannels can be written as follows

$$C_s^{sum}(i,j) = CE\left[\sum_{k=1}^{i} G_k\right] = C \cdot iE[G_k]. \qquad (2)$$

In (2), G_k is an indicator variable that equals one if the k^{th} subchannel is successfully used by one of the j active secondary users, and zero otherwise. In [8], (2) is evaluated to $C_s^{sum}(i,j) = Cj\left(1 - \frac{1}{i}\right)^{j-1}$ in the absence of secondary cooperation.

In order to evaluate (2) (and thus the sum-throughput) with secondary cooperation, here we consider the following simple model for cooperation. Each secondary user at first selects one of the i available subchannels randomly with probability $1/i$. The overall system region (of area πR^2, where R is the radius of the total area) is divided into "cooperative zones" of area πR_{coop}^2 in an arbitrary fashion. We assume that users within the same zone (that have selected the same subchannel) can perfectly cooperate before transmission so that only one such user will attempt transmission on the given subchannel. As shown in the Appendix, we have

$$C_s^{sum}(i,j) = Ci\left[j\frac{1}{i}\left(1 - \frac{1}{i}\right)^{j-1} + \sum_{l=2}^{j} \binom{j}{l} \left(\frac{1}{i}\right)^l \left(1 - \frac{1}{i}\right)^{j-l} \left(\frac{R_{coop}}{R}\right)^{2l}\right]. \qquad (3)$$

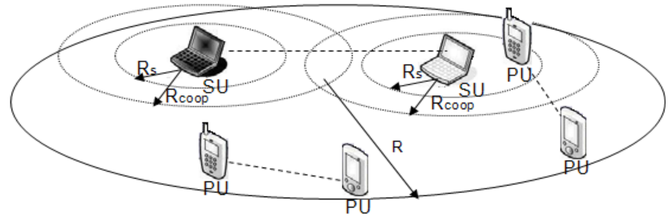


Fig. 3. The cognitive radio network of Fig. 1 with imperfect sensing, interference model, and local cooperation. Secondary node-pairs detect active primary transmitters only within their sensing regions of radius R_s and are able to communicate with other secondary neighbors within the cooperation region of radius R_{coop}.

so that the overall sum-throughput C^{sum} can be expressed as

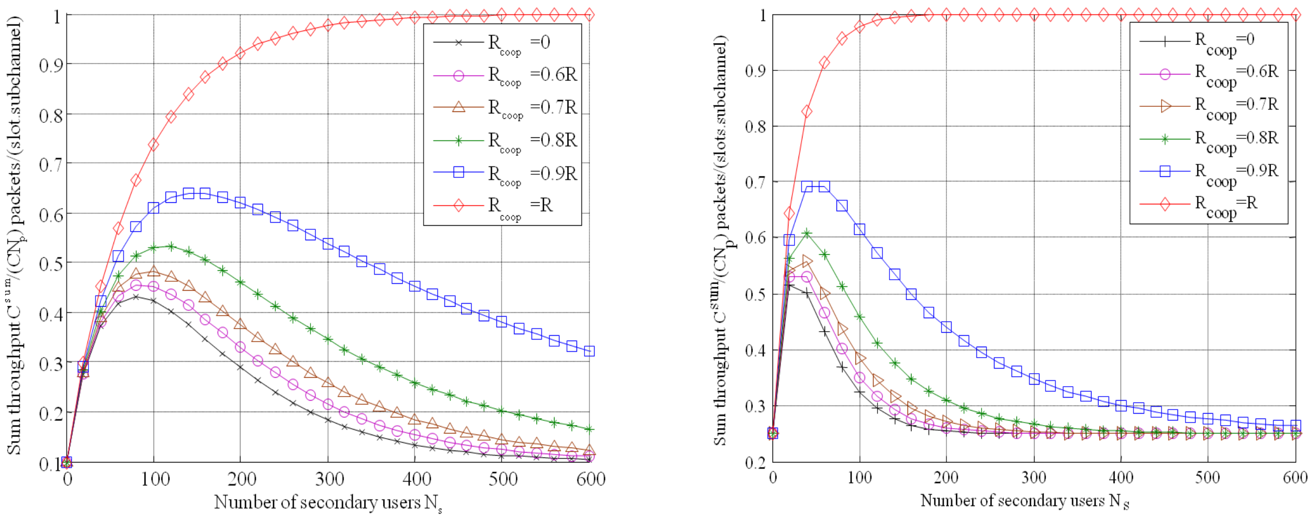
$$C^{sum} = CN_p p\left[1 + \frac{1}{N_p}\sum_{i=1}^{Np}\binom{N_p}{i} p^{N_p - i - 1}(1-p)^i \cdot i\left[N_s \tfrac{p}{i}\left(1 - \tfrac{p}{i}\right)^{N_s - 1}\left(1 - \left(\tfrac{R_{coop}}{R}\right)^2\right) + \left(1 - \tfrac{p}{i} + \tfrac{p}{i}\left(\tfrac{R_{coop}}{R}\right)^2\right)^{N_s} - \left(1 - \tfrac{p}{i}\right)^{N_s}\right]\right]. \qquad (4)$$

It is noted that for $R_{coop} = 0$ (no cooperation) equation (4) reduces to the sum-throughput derived in [8] (see (4) therein).

Fig. 2(a) shows the sum-throughput (4) normalized as C^{sum}/CN_p in packets/(time-slot×subchannel) versus the number of secondary users N_s for $N_p = 9$ and $p = 0.1$. For comparison, we plot the non-cooperative case $R_{coop} = 0$ for reference. It can be seen that the sum-throughput along with the optimal number of secondary users N_s^* increase as the cooperation radius R_{coop} increases. In the limit, for the case $R_{coop} = R$, a sufficiently large number of secondary users N_s allows a full normalized sum-throughput of 1 to be obtained. Fig. 2(b) plots the normalized sum-throughput C^{sum}/CN_p versus the number of secondary users N_s for a larger traffic generation probability $p = 0.25$. We notice that increasing the probability p decreases the optimal number of secondary users for the same cooperation radius R_{coop} due to smaller number of average available slots and larger secondary packet generation probability. Furthermore, similar gains as the previous case can be realized.

III. Imperfect Sensing, Interference Model, Local Cooperation

The discussion in the previous section has shown that large sum-throughput gains can in principle be attained via MAC secondary cooperation. Here, we consider more realistic assumptions on sensing and channel model following Sec. III of [8]: (*i*) *imperfect sensing*: a secondary user can detect primary transmitters only within a sensing radius R_s around the user itself (see Fig. 3); (*ii*) *interference model*: primary and secondary transmitters and receivers are randomly located in a circular area of radius R. Subchannel gains are determined by a path loss model as $|h_{mn}|^2 = 1/d_{mn}^{\gamma}$ where d_{mn} is the distance between the transmitting node m and receiving node



(a) Normalized sum-throughput C^{sum}/CN_p versus number of secondary users N_s for perfect sensing, collision model, simple cooperation $(p = 0.1, N_p = 9)$.

(b) Normalized sum-throughput C^{sum}/CN_p versus number of secondary users N_s for perfect sensing, collision model, simple cooperation $(p = 0.25, N_p = 9)$.

Fig. 2. Figures 2(a) and 2(b) plot the sum-throughput $C^{sum} = CN_p$ versus the increasing number of secondary users N_s for different values of cooperation radii R_{coop} for duty cycles $p = 0.1$ and $p = 0.25$ respectively.

n and γ is the path loss exponent. The signal-to-interference-plus-noise ratio (SINR) on an active link $m-n$ on subchannel k is given by

$$SINR_{mn,k} = \frac{|h_{mn}|^2 P}{1 + \sum_{i \in B_k, i \neq m} |h_{in}|^2 P}, \tag{5}$$

where the sum runs over the set B_k of primary and secondary transmitters active on the kth subchannel, and P represents the (equal) transmitted energy per symbol (Joule). Fixed-rate transmissions are attempted by all active transmitters with rate

$$R_{mn,k} = \log\left(1 + \frac{|h_{mn}|^2 P}{1 + I}\right), \tag{6}$$

where parameter I represents the interference tolerance [8]. In other words, from (5), a transmission from m to n is successful if and only if the aggregate interference satisfies $\sum_{i \in B_k, i \neq m} |h_{in}|^2 P \leq I$. Moreover, rather than considering ideal cooperation as in Sec. II, we propose MAC cooperation schemes based on the assumed ability of each secondary transmitter to broadcast brief "MAC cooperation messages" to all the active secondary users only locally, namely within a disc of radius R_{coop} around the transmitter itself, at the beginning of each slot. The objective of these cooperative schemes is to increase the sum-throughput by:

(a) minimizing "collisions" between active secondary users (as in Sec. II);

(b) reducing interference to active primary users (this was not relevant in Sec. II due to the assumption of perfect sensing).

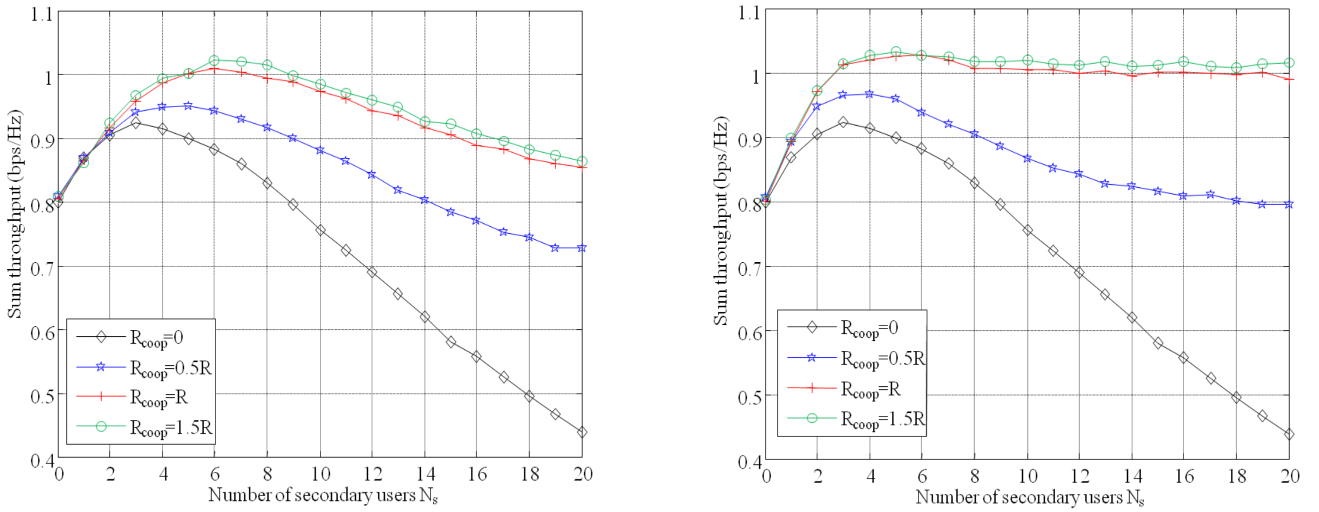
We propose two cooperative schemes, the first based on a one-shot message exchange (and aimed at (b)) and the second on a two-shot strategy (aimed at both (a) and (b)).

A. One-Shot Cooperation Scheme

In this cooperation scheme, we introduce a single subtime-slot at the beginning of each time-slot where each active secondary node broadcasts only one cooperation message to all secondary neighbors within its cooperation region. Each active secondary node j scans the bandwidth for spectrum holes and generates a "subchannel availability vector" $\mathbf{Z}_j$ of binary variables $Z_{ji} = \mathcal{I}$[the ith subchannel is detected as available by the jth user], where $\mathcal{I}[\cdot]$ is the indicator function. This vector $\mathbf{Z}_j$ is broadcast to all secondary nodes within the cooperation region of the jth user. After the end of the broadcast phase, each secondary node sums the received vectors $\mathbf{Z}_j$ entry-wise and selects the subchannel k with the largest entry (ties are resolved arbitrarily). If two or more subchannels have the same largest entry, a secondary node randomly selects one of them for transmission. This strategy basically reduces the probability of interfering with active primary transmitters and can be seen as an implementation of cooperative sensing.

B. Two-Shot Cooperation Scheme

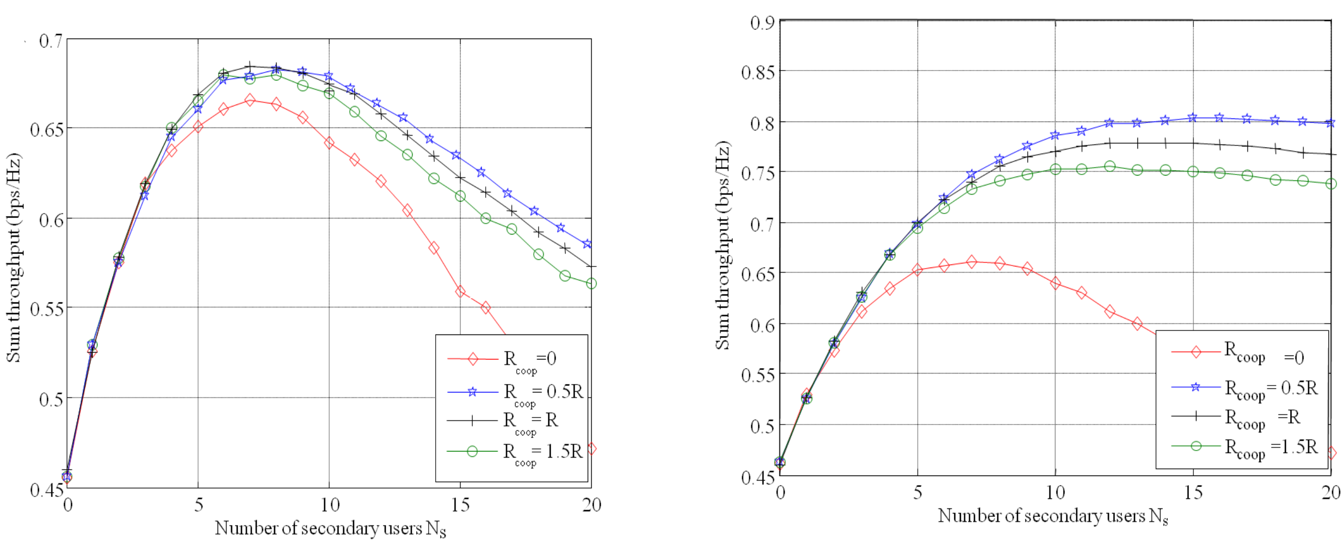
This cooperation scheme operates as the previous, but adds another subtime-slot after the first one, where active secondary nodes employ a second MAC message exchange to reduce the interference to other secondary nodes. Specifically, in the second phase, each active secondary node broadcasts its selected subchannel (see discussion above) to all secondary nodes



(a) One-shot cooperation scheme.

(b) Two-shot cooperation scheme.

Fig. 4. Sum-throughput C^{sum} versus number of secondary users N_s for imperfect sensing, interference model, local cooperation ($I = 0$,$R_s = 0.5$).



(a) One-shot cooperation scheme.

(b) Two-shot cooperation scheme.

Fig. 5. Sum-throughput C^{sum} versus number of secondary users N_s for imperfect sensing, interference model, local cooperation ($I = 2$,$R_s = 0.5$).

within its cooperation region. Then, each active secondary node performs random access, calculating the transmission probability as $1/l$, where $l > 0$ is the number of neighbors that have reported their decision as the selected subchannel (for $l = 0$, we set the probability to one). This strategy provides an improvement over the One-shot since not only it employs cooperative sensing but also it reduces collisions between active secondary nodes and therefore increases the secondary sum-throughput.

C. Simulation Results

In this section we explore the benefits of the secondary MAC cooperative schemes proposed above by numerically evaluating the sum-throughput for $N_p = 5$ primary users, fixed duty cycle $p = 0.5$ for primary and secondary users, and sensing radius $R_s = 0.5$. Figures 4 and 5 compare the sum-throughput with increasing number of secondary users N_s for different values of the cooperation radius R_{coop} for the one-shot cooperation and two-shot cooperation schemes for interference tolerance $I = 0$ and $I = 2$ respectively and confirms the general conclusions of Sec. II in that cooperation

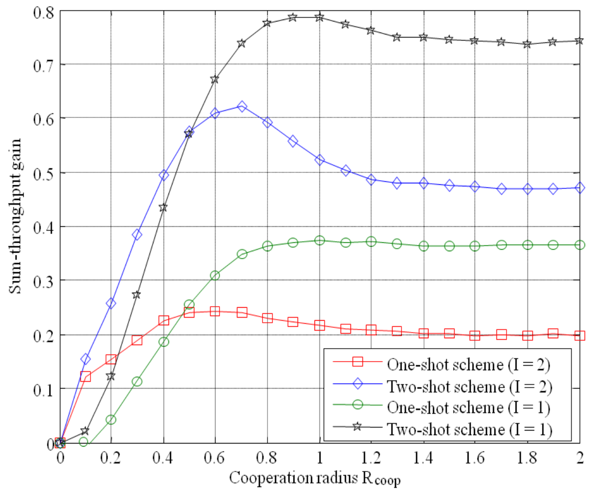


Fig. 6. The sum-throughput gain vs. cooperation radius for One-shot and Two-shot schemes ($I = 1$ and $I = 2$).

both increases the sum-throughput and the optimal number of secondary users N_s^*. It can be seen from Fig. 4(a) that the sum-throughput increases along with the optimal number of secondary users as we increase the cooperation radius R_{coop}. Fig. 4(b) shows the gains in the sum-throughput as the number of secondary users increases as a result of applying random access to the shared subchannel resource in the two-shot strategy. Notice that for $R_{coop} \geq 1$ we have a constant sum-throughput curve[2], i.e., no collisions between secondary users, and therefore the two-shot scheme can support a larger number of secondary node-pairs. Fig. 5(a) shows that, for the one-shot scheme with interference tolerance $I = 2$, a cooperation radius $R_{coop} = 0.5$ is more advantageous than larger values, since R_{coop} needs to strike a balance between accuracy of the primary detection (large R_{coop}) and exploiting the interference tolerance $I > 0$ by allowing more secondary transmissions (small R_{coop}). Fig. 5(b) shows again that the two-shot cooperation scheme outperforms the one-shot approach especially for larger values of N_s due to the ability to reduce secondary interference. Notice that the sum-throughput attained in Fig. 5 is lower than that in Fig 4 for fixed N_s and R_{coop} since employing higher interference tolerance dictates lower transmission rates. Fig. 6 compares the sum-throughput gain with increasing cooperation radius R_{coop} for $I = 1$ and $I = 2$ for the One-shot and the Two-shot cooperation relative to non-cooperative schemes given a fixed number of secondary users $N_s = 15$. It can be seen that the maximum achievable sum-throughput gain intermediates the two extremes of full competition ($R_{coop} = 0$) and full cooperation ($R_{coop} = 2$).

[2]Notice that here, unlike Sec. II, R_{coop} can be larger than one since we have to condition on the position of the secondary nodes.

IV. Conclusions

This paper has shown that, in a multichannel spectrum sharing system, the possibility of exchanging local MAC messages among secondary nodes: (*i*) leads to an optimal system design that prescribes a larger number of secondary users (that is, more autonomy and less regulation); (*ii*) yields relevant gains in terms of overall system throughput with respect to a non-cooperative scenario. The interplay between full competition and full cooperation among the secondary nodes is evident in the tradeoff between sum-throughput gain maximization and sum-interference minimization at the receivers. Based on the initial promising results in this paper, future work will need to address the full design of a MAC protocol that support such message exchange in the cognitive scenario at hand.

Appendix: Proof of (3)

Let S_k be the number of users that select a given subchannel k and T_k be the number of users that attempt transmission on such subchannel. The probability that an available subchannel k is successfully used by a secondary node can be expressed as

$$\begin{aligned} E\left[G_k\right] &= \sum_{l=1}^{j} \Pr\left[S_k = l\right] \Pr\left[T_k = 1 | S_k = l\right] \\ &= j\frac{1}{i}\left(1-\frac{1}{i}\right)^{j-1} + \sum_{l=2}^{j} \binom{j}{l} \left(\frac{1}{i}\right)^{l} \left(1-\frac{1}{i}\right)^{j-l} \Psi_l, \end{aligned}$$

where $\Psi_l = \Pr\left[T_k = 1 | S_k = l\right]$. We have $\Psi_1 = 1$ and to calculate $Pr[T_k = 1 | S_k = l]$, we observe that this is the probability that all the S_k users fall within the same cooperation subregion, which equals (assuming uniform user distribution in a disc of radius R):

$$\Pr\left[T_k = 1 | S_k = l\right] = \left(\frac{R_{coop}}{R}\right)^{2l}, \quad (7)$$

thus concluding the proof.

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