Throughput Enhancing Cooperative Spectrum Sensing Strategies for Cognitive Radios

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***Abstract*— We consider a wireless communication scenario where multiple unlicensed cognitive users seek to access unused frequency channels licensed to the primary users. A main challenge in this case is to design a spectrum sensing strategy that aids the cognitive users acquire the unused spectrum and limits the interference to primary users. Towards addressing this challenge, we propose a cooperative spectrum sensing strategy in which cognitive users collaborate to share their decisions regarding spectrum occupancy of the primary users. We demonstrate the effectiveness of the proposed cooperative sensing strategy which aims to equip all cognitive users with the occupancy information of as many channels as possible, and observe that the proposed cooperative spectrum sensing strategy improves the throughput of the cognitive users and decreases the interference to the primary users as compared to the non-cooperative scheme.**

I. INTRODUCTION

The explosive growth of wireless services continues to accelerate the exhaustion of usable radio spectrum. The radio spectrum is currently regulated and the licensed spectrum bands are not "shared". Surprisingly, at any given time and location, much of the licensed spectrum remains idle, leading to under-utilization of the spectrum [1]. Thus, to better utilize spectrum resources, one can envision that the licensed resources, whenever not in use, can be captured and used by additional users. To this end, cognitive radios which are amenable to employ a more open spectrum policy have attracted considerable attention recently [2] and the IEEE 802.22 working group on Wireless Regional Area Networks (WRAN) has worked on standardizing the opportunistic utilization of white spaces in the UHF/VHF TV band [3].

Cognitive radios allow a secondary (cognitive) user to access a spectrum hole unoccupied by a primary (licensed) user and improve the spectrum utilization while reducing the white spaces in the spectrum [2]. To do so, the cognitive user must detect the presence of the spectrum hole, or equivalently, detect the presence of the primary user's transmission [2]. Recent research efforts have investigated the scenario where a group of neighboring nodes cooperate with a desired cognitive user to improve the spectrum sensing performance of the desired user. It has been shown that such cooperative spectrum sensing provides reliable and fast detection of the presence of the primary users [4]–[7]. While these cooperative schemes provide the reliable spectrum sensing performance of a desired cognitive user, they might not be scalable for the scenario where multiple cognitive users co-exist and contend over a limited number of frequency channels unused by the primary users.

In this paper, we consider a cognitive network where a number of cognitive users seek to access the unused frequency channels licensed to the primary users. We consider the practical scenario where each cognitive user can sense one (narrowband) channel at a time. In this setup, a main challenge is to design a spectrum sensing strategy which enables access to unused frequency resources for as many cognitive users as possible while the interference to the primary users is kept to a minimum. Towards addressing this challenge, we propose a *cooperative spectrum sensing strategy* in which all cognitive users collaborate by sharing their decisions regarding spectrum occupancy of the primary users. To do so, we propose that each cognitive user maintains the list of "busy" channels that it identifies and shares this information via a broadcast control channel. Such an exchange between the cognitive users enables each cognitive user to obtain a more complete picture of the overall channel occupancy status of the primary users, leading to more opportunities for access to idle channels and fewer collisions with primary users. The proposed scheme is designed to work in a distributed fashion, requires only a common time-slotted control channel, and harvests simple network coding [8] gains in its quest to furnish all cognitive users with the overall channel occupancy information. The simulation results demonstrate that, as compared to the non-cooperative case, this simple cooperative sensing strategy improves the probability of successful transmission of the cognitive users.

The organization of the paper is as follows: In Section II, the system model is described. Section III describes the proposed cooperative spectrum sensing strategy. The simulation results are presented in Section IV with conclusions in Section V.

II. SYSTEM MODEL

We consider a cognitive network consisting of M primary users and K cognitive users which transmit their information by acquiring spectrum holes unused by the primary users. We assume that one licensed frequency channel is allocated to

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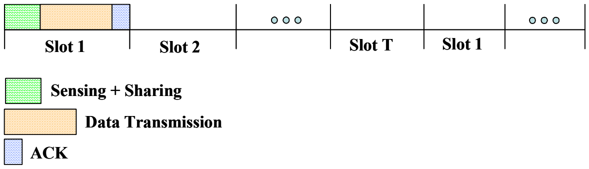


Fig. 1. Time-slotted Structure.

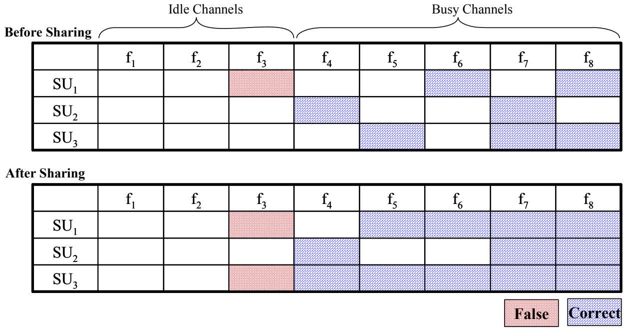
each primary user: there are M orthogonal frequency channels and cross channel interference is negligible. The interference to a primary user by a cognitive user occurs only when the cognitive user transmits over the channel that is being used by that primary user. We assume that the state of being busy or idle for each frequency channel remains unchanged for T time slots. After T, the state of each frequency channel changes independently. Each cognitive user contends over the available frequency channels. Each cognitive user knows the total number of frequency channels in the network and has a "frequency table" in which the user maintains the occupancy information of the frequency channels. Cognitive users communicate according to the time-slotted structure shown in Figure 1. In a slot, each cognitive user randomly picks and senses a frequency channel using an energy detector [9], and makes a decision as to whether the channel is busy or idle. If the channel sensed is deemed busy, the cognitive user marks the frequency channel in its frequency table and does not pick this channel for the remainder of the T-slot frame after which its frequency table is refreshed. If the decision is idle, the cognitive user transmits its data over this frequency channel and the transmission is successful if the same channel is not used by another (cognitive or primary) user, i.e., we consider a collision limited system.

III. A COOPERATIVE SPECTRUM SENSING STRATEGY

In this section, we propose a cooperative spectrum sensing strategy for all cognitive users to share their sensing information with one another, thereby furnishing the entire cognitive network with a more complete picture of the occupancy status of the channels by the primary users. We note that it is likely that the cognitive users belong to a secondary system which is ad hoc in nature, and hence aim to have a simple strategy with little coordination between the cognitive nodes.

The idea of the scheme is indeed very simple: each cognitive user "cooperates" by reporting the binary index of the frequency channel(s) marked as "busy" in its frequency table. The reporting is done via a common time-slotted control channel with C slots. Each cognitive user broadcasts its "report" over a slot chosen randomly. The report is successful if the same slot is not used by other cognitive users, i.e., once again, a collision limited communication scenario is assumed.

The preparation of the report of each cognitive radio is the key element of the cooperative sensing strategy. In particular, since the aim is to inform all cognitive users of all channel indices sensed as busy, we can exploit the multicast nature of this communication by employing simple mixing of data



Before Sharing

	f₁	f₂	f₃	f₄	f₅	f₆	f₇	f₈
SU₁			🟥			🟦		🟦
SU₂				🟦			🟦	
SU₃					🟦		🟦	🟦

After Sharing

	f₁	f₂	f₃	f₄	f₅	f₆	f₇	f₈
SU₁			🟥		🟦	🟦	🟦	🟦
SU₂				🟦			🟦	🟦
SU₃			🟥	🟦	🟦	🟦	🟦	🟦

🟥 False 🟦 Correct

Fig. 2. Frequency table before and after the cooperative spectrum sharing: SU_i, ith cognitive user.

at each transmitting node, and harvest simple network coding gains. We choose to employ the simplest such random mixing as follows: If there are two or more frequency channels identified as "busy" in the frequency table of a cognitive user, that cognitive user performs a binary XOR (exclusive OR) operation of the binary index numbers of the *two* of the randomly chosen channels in its frequency table. For example, if the total number of frequency channels is 16 and the current frequency table indicates that channels 5, 9, and 12 are busy, one possible report is $f_5 \oplus f_{12}$. By receiving the XOR-ed information, the remaining cognitive users can improve their frequency table information by decoding the received XOR-ed information, which is possible if the frequency channel f_5 or f_{12} is marked in their frequency tables. If there is only one frequency channel identified as "busy", the user reports the channel without the XOR operation. At the end of all the reporting, the cognitive users are likely to have obtained the indices of the channels occupied by all the primary users which leads to reduced potential collisions, as well as, by elimination, the indices of the channels that are likely to be idle which leads to increased probability of successful access.

In practice, a user might identify an idle channel as busy due to the non-zero false-alarm probability (P_f) of the energy detector. In this case, reporting the XOR-ed information might lead to missed opportunities for access. For lack of a better term, we will call these "false reports". A false report corresponds to the case where the report results in marking an idle channel as busy in a frequency table. Similarly, a "correct report" is when the report results in the identification of a new correctly-identified busy frequency channel. Figure 2 shows a snapshot of the frequency table of a cognitive user before and after a round of the cooperative spectrum sharing strategy. To see how often the false report and correct reports may occur, let us consider a simple network where two cognitive users and M primary users exist and find the probabilities of correct report (P_{CR}) and false report (P_{FR}) of the first cognitive user. Define w_1 to be the set of frequency channels of the first cognitive user that are incorrectly identified as busy when the channel is idle, and, c_1 to be the set of frequency channels of the first cognitive user that are identified correctly as busy when the channel is busy. Similarly, w_2 and

$$\begin{aligned} P_{FR} = {} & P[f_k, f_l \in w_1]\left(1 - P[f_k, f_l \notin w_2 | f_k, f_l \in w_1] - P[f_k, f_l \in w_2 | f_k, f_l \in w_1]\right) \\ & + 2P[f_k \in w_1, f_l \in c_1]\left(1 - P[f_l \notin c_2 | f_k \in w_1, f_l \in c_1] - P[f_k \in w_2, f_l \in c_2 | f_k \in w_1, f_l \in c_1]\right) \end{aligned} \tag{1}$$

$$\begin{aligned} P_{CR} = {} & P[f_k, f_l \in c_1]\left(1 - P[f_k, f_l \notin c_2 | f_k, f_l \in c_1] - P[f_k, f_l \in c_2 | f_k, f_l \in c_1]\right) \\ & + 2P[f_k \in w_1, f_l \in c_1]\left(1 - P[f_l \notin w_2 | f_k \in w_1, f_l \in c_1] - P[f_k \in w_2, f_l \in c_2 | f_k \in w_1, f_l \in c_1]\right) \end{aligned} \tag{2}$$

$$P_{FR} = \frac{\binom{W_1}{2}}{\binom{C_1 + W_1}{2}} \left(1 - \frac{\binom{I-2}{W_2}}{\binom{I}{W_2}} - \frac{\binom{I-2}{W_2-2}}{\binom{I}{W_2}}\right) + 2\frac{\binom{C_1}{1}\binom{W_1}{1}}{\binom{C_1 + W_1}{2}} \left(1 - \frac{\binom{B-1}{C_2}}{\binom{B}{C_2}} - \frac{\binom{I-1}{W_2-1}\binom{B-1}{C_2-1}}{\binom{I}{W_2}\binom{B}{C_2}}\right) \tag{3}$$

$$P_{CR} = \frac{\binom{C_1}{2}}{\binom{C_1 + W_1}{2}} \left(1 - \frac{\binom{B-2}{C_2}}{\binom{B}{C_2}} - \frac{\binom{B-2}{C_2-2}}{\binom{B}{C_2}}\right) + 2\frac{\binom{C_1}{1}\binom{W_1}{1}}{\binom{C_1 + W_1}{2}} \left(1 - \frac{\binom{I-1}{W_2}}{\binom{I}{W_2}} - \frac{\binom{I-1}{W_2-1}\binom{B-1}{C_2-1}}{\binom{I}{W_2}\binom{B}{C_2}}\right) \tag{4}$$

TABLE I
PERFORMANCE OF P_{CR} AND P_{FR}: B = 8, $P_f = (0.01, 0.05, 0.1, 0.15)$, AND $P_d = (0.8, 0.85, 0.9, 0.95)$.

P_f	0.01	0.05	0.1	0.15
P_{CR}	0.7192	0.7231	0.7165	0.7205
P_{FR}	0.0156	0.0178	0.080	0.0185

TABLE II
PERFORMANCE OF P_{CR} AND P_{FR}: $B = 4, 8, 12$, $P_f = 0.05$, AND $P_d = 0.85$.

B	4	8	12
P_{CR}	0.8564	0.7183	0.5598
P_{FR}	0.0436	0.0177	0.0061

c_2 are the corresponding sets for the second cognitive user, respectively. The cardinalities of w_i and c_i are W_i and C_i, for $i = 1, 2$. Let $f = f_k \oplus f_l$ be the binary XOR-ed data to be reported from the first cognitive user after performing binary XOR operation on the frequency channels k and l. Then, P_{FR} and P_{CR} of the first cognitive user are defined as (1) and (2), respectively. Out of M frequency channels, B frequency channels are busy and I frequency channels are idle ($M = B + I$). With the probabilities of detection (P_{d_i}) and false-alarm (P_{f_i}), we let $W_i = IP_{f_i}$ and $C_i = BP_{d_i}$. After substituting the corresponding probability expressions for each term in (1) and (2), we obtain P_{FR} and P_{CR} in (3) and (4), respectively. Table I shows P_{CR} and P_{FR} for $B = 8$ and $M = 16$. This simulation consists of an experiment run 2000 times by changing W_i and C_i. Table II shows P_{CR} and P_{FR} for varying B. We observe that a correct report transpires a lot more frequently than a false report. Observe that the probabilities exclude the case where neither correct report nor false report occurs, i.e., when the XOR-ed information of the first cognitive user is not decoded by the second cognitive user.

IV. SIMULATION RESULTS

In this section, we present simulation results demonstrating the performance of the proposed cooperative spectrum sensing strategy. The total number of potential primary users (M), i.e., the frequency channels, is 16. The number of cognitive users is 5. The state of the frequency channels remains unchanged for T time slots and changes independently afterwards. The cognitive users refresh their frequency table every T time slots. Any cognitive user causing interference to a primary user receives a *penalty* which bans its transmission for $P = 6$ time slots. For Figures 3-8, we assume that $P_{d_i} = P_d$ and $P_{f_i} = P_f$, $i = 1, 2, ..., 5$. The data rate of the cognitive users is $1Mbps$ and each data packet consists of 1000bits. The number of packets transmitted per slot over a frequency is 20. Hence, the duration for data transmission in each slot is $20ms$. The control channel transmission rate is $0.25Mbps$ and the total number of slots for the control channel is C. Thus, the overhead for each slot for the cooperative spectrum sharing is $16 * C\mu s$.[1] The ACK duration is 2 μs. Hence, the slot duration for the cooperative sensing strategy is 20,002 μs + $16 * C\mu s$. The corresponding slot duration for the non-cooperative strategy is 20,002 μs. We ignore the time spent in sensing of a channel as well as guard intervals since they are identical for the non-cooperative and the cooperative scheme. We also simulate a cooperative scheme in which each cognitive user simply forwards the index of one frequency channel marked busy. We run 2000 iterations and each iteration terminates when the cognitive users transmit all 200 the packets they have to transmit.

As a bench mark for performance, we also simulate a genie-aided scheme where each cognitive user instantly knows the sensing decision of all other users of a "busy channel" and

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[1] Given $M = 16$, 4 bits are needed to identify each frequency channel. If C = 10, the overhead time is $4 * 10 * 4\mu s = 160\mu s$.

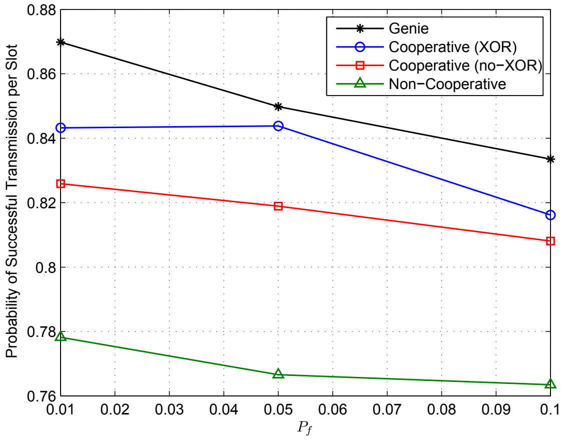

Fig. 3. Probability of successful transmission. $T = 14, B = 10, C = 10$.

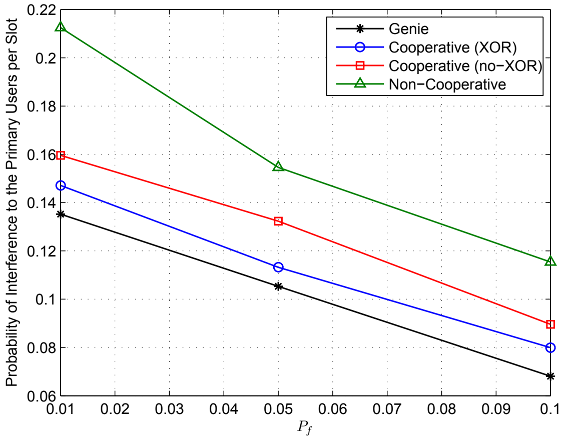

Fig. 4. Probability of interference to primary users. $T = 14, B = 10, C = 10$.

no false-alarms occur. Though not attainable in practice, the performance of this genie-aided scheme clearly provides an upper bound for any cooperative sensing scheme.

Figure 3 shows that the cooperative spectrum sharing schemes increase the probability of successful transmissions by the cognitive users, and the proposed cooperative scheme is close in performance to the genie-aided upper bound. The increase in successful transmissions leads to improved throughput for the cognitive users.

Figure 4 and 5 show the probability of interference to the primary users and the probability of missed opportunity for access per slot, respectively. As we expect, interference to the primary users is reduced as shown in Figure 4. As discussed in section III, sharing the channel occupancy information might result in the propagation of incorrect information leading to an increase in missed opportunities for access to idle frequency channels. We see from Figure 5 that this increase is modest.

For Figures 6-8, we use the values $P_d = 0.85$ and $P_f = 0.05$. Figure 6 shows the throughput per cognitive user as T varies. We observe that the cooperative schemes are always better than the non-cooperative scheme, and that our proposed scheme performs the best. The throughput gap between the cooperative schemes and the non-cooperative scheme becomes wider when the state of the frequency channels changes less frequently. Figure 7 shows the throughput per cognitive user as B varies. We define R as the ratio of the number of busy channels to the number of total channels, i.e., $R = B/M$. We observe that the proposed cooperative scheme outperforms the rest. The throughput gap between the cooperative schemes and the non-cooperative scheme becomes smaller when R is either small or large. For small R, most of the cognitive users are more likely to choose idle channels to sense. On the other hand, for large R, most of the cognitive users are likely to choose the busy channels to sense. Figure 8 shows the impact of the knowledge of T on the throughput of the cognitive users. When the system state changes every $T = 14$ slots, we observe that the largest throughput gain between the cooperative schemes and the non-cooperative scheme is

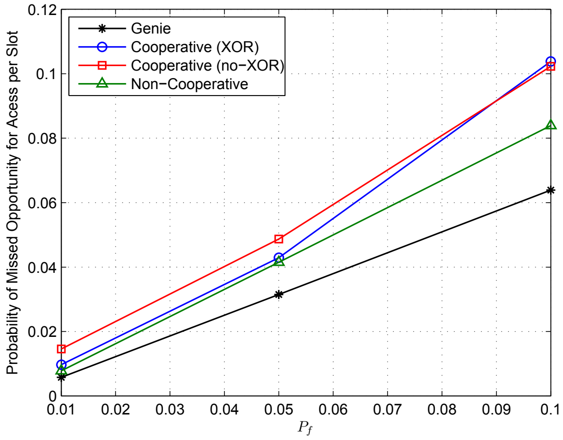

Fig. 5. Probability of missed opportunity for access: $T = 14$, $B = 10$, $C = 10$.

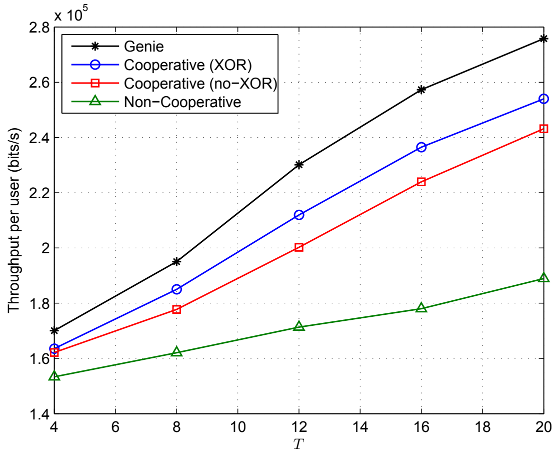

Fig. 6. Throughput per cognitive user: $B = 10$, $C = 4$.

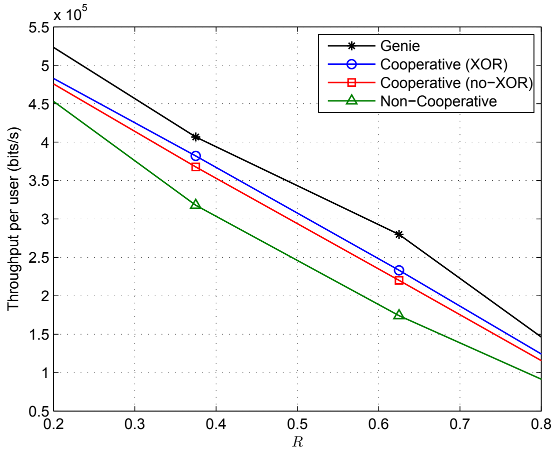

Fig. 7. Throughput per cognitive user: $T = 14$, $C = 10$.

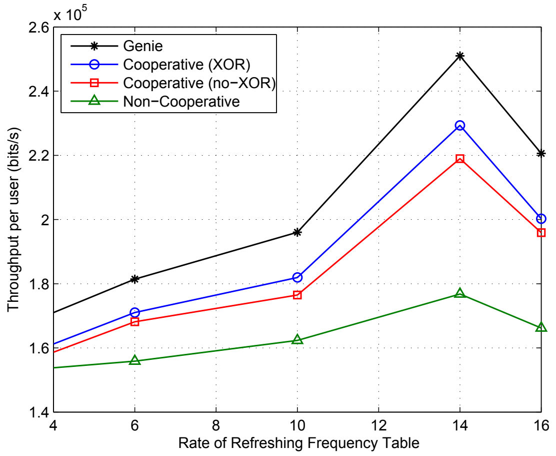

Fig. 8. Throughput per cognitive user: $T = 14$, $B = 10$, $C = 10$.

obtained when the cognitive users know the value of T and refresh their frequency table accordingly.

Lastly, we consider a more general scenario where the detection probability varies among cognitive users, depending on the channel between the cognitive user and the primary user whose channel the cognitive user is attempting to sense. P_d is now a function of $1/\lambda$, the variance of the fading channel, which is modeled as a zero-mean, independent, circularly symmetric complex Gaussian random variable. We assume that $1/\lambda_{AB} = 1/d_{AB}^{\alpha}$, where d_{AB} is the distance between the cognitive user A and the primary user B. α is the path-loss exponent. We let D_{max} be the maximum distance between any primary user and any cognitive user. The distance between the cognitive users and the primary users are randomly chosen within D_{max}. As shown in Figure 9, we observe that the proposed cooperative scheme outperforms the non-cooperative scheme as well as the no-XOR cooperative scheme. Also, as D_{max} increases, we observe that the performance degrades because P_{d_i} becomes smaller.

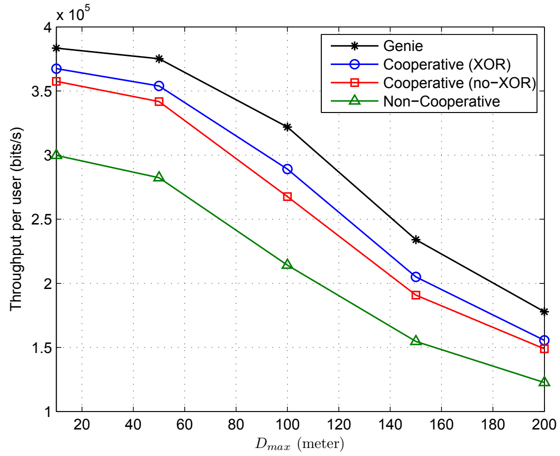

Fig. 9. Throughput per cognitive user: $T = 14$, $B = 10$, $C = 10$, $P_f = 0.01$, and $\alpha = 3$.

V. CONCLUSION

In this paper, we have considered a wireless communication scenario where multiple unlicensed cognitive users seek to access unused frequency channels licensed to primary users. We have proposed a simple and fully distributed cooperative spectrum sharing strategy in which cognitive users collaborate by sharing their channel occupancy information. We have observed that the throughput of the cognitive users is improved and the interference to the primary user is reduced as a result of the cooperative sensing strategy. These performance benefits require only a small price to pay in the form of a slight increase on the probability of missed opportunity for access and a mild overhead brought by a common control channel used for sharing the spectrum information.

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