Adaptive Sensing User Selection Mechanism in Cognitive Wireless Networks

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***Abstract*—Cognitive Wireless Ad-Hoc Networks use cooperation in order to accurately sense the spectrum. However, the space diversity provided by the cooperative sensing is only efficient when the cooperative users are selected appropriately. This paper proposes a distributed mechanism that allows each Secondary User to decide what channels are suitable to be sensed while reducing the sensing overhead.**

***Index Terms*—Cognitive wireless networks, user selection, cooperative sensing.**

I. INTRODUCTION

WITH the spread and deployment of a huge variety of wireless networks during the last decade and the consequent growth of the wireless broadband demand, the efficient use of the scarce radio resources has attracted the interest of the scientific community. In this context, the Federal Communications Commission (FCC) indicated in 2002 that the spectrum is currently being underutilized [1], and this underutilization is owing to variations of the spectrum allocation in terms of time, frequency, and geographical location. The possibility of exploiting the underused resources has encouraged the development of networks with cognitive capacity, the so-called Cognitive Wireless Networks (CWN), which are able to discover and reuse the available transmission opportunities.

Cognitive wireless ad-hoc networks are made up of a set of secondary users (SU) that sense the spectrum to detect unused frequency bands/channels. The spectrum sensed by the SUs is licensed to a set of primary users (PU), which have constraintless access. When an unused band is found, SUs coordinate themselves to establish a communication on that channel. SUs are allowed to use the frequency band as long as they do not incur interference on the PUs. When PUs transmissions are resumed, SUs must vacate the licensed band immediately. As the nature of the wireless medium entails undesired phenomena such as the hidden terminal or the exposed node problems, sensing becomes a critical aspect. Space diversity is an effective strategy to combat the unreliability of the sensed information, but it implies the cooperation of the SUs [2]. In cognitive wireless ad-hoc networks, where the lack of infrastructure and the scarcity of radio resources makes more essential to increase the efficiency of the sensing process, there exists a trade-off between the accuracy of the spectrum sensing information and the signaling overhead.

Although cooperative sensing challenges have been addressed extensively with different strategies [3], to the best of our knowledge, the proper selection of the cooperative SUs who sense the channels received little attention. In particular, in the literature works have focused on the selection and/or weighting of the received sensing information when all the SUs sense the same set of channels [4]. The main contribution of this paper is the design of a dynamic mechanism that allows each SU to sense only a subset of the channels. The intelligent channel selection and the cooperation among SUs guarantee the sensing of all the channels and the adaptability to environment variations, while reduce the amount of information exchange.

The paper is organized as follows: In Section II the motivation and the basis of the problem are stated. In Section III the proposed mechanism is explained. Finally, in Section IV the results are discussed. Conclusions are presented in Section V.

II. PROBLEM FORMULATION

Cognitive wireless ad-hoc networks are usually organized in clusters to cooperate.In each cluster, there is usually one of the SUs that undertakes the role of cluster head and manages the exchange of sensing information. This cluster head collects and combines the sensing observations from the rest of the SUs in the cluster and makes the decision on the availability of the channels. Then, the cluster head informs the rest of SUs about the decision. As cognitive wireless ad-hoc networks are dynamic in nature, the degree of cooperation among SUs determines the completeness of the available information. Nonetheless, the sensing information load grows as the number of SUs and sensed channels rises. Therefore, the proposed mechanism is intended to reduce the transmission of inaccurate or excessively redundant information.

Assume a cognitive wireless ad-hoc network comprised of a set of secondary users, $U = \{u_k : 1 \leq k \leq K\}$. The spectrum is also divided into a set of channels. Let us define $F = \{f_m : 1 \leq m \leq M\}$ as the set of channels to be sensed. The channels $f_m \in F$ are licensed to PUs, and they are sensed periodically by $u_k \in U$. The set of channels to be sensed, F, is selected by the cluster head and is distributed to the SUs in the cluster through a Common Control Channel, not licensed to PUs and where all SUs content to gain transmission opportunities. The Common Control Channel is denoted by f_0 -i.e. $f_0 \notin F$- and it is not interfered by PUs transmissions.
In order to reduce the sensing overhead, each SU selects and senses only N out of the M channels, with $N < M$. In other words, each SU only senses a subset of the channels selected by the cluster head. By doing so, all SUs experience a reduction of the time and energy consumption. The objective will be achieved if, notwithstanding the reduction of the cooperation degree, the accuracy of the cluster head decisions is maintained.

Regarding the algorithm used by the cluster head to select the set of channels for sensing, F, it is out of the scope of this study. The reader is referred to [5] for some examples.

Hereafter we propose a mechanism for each SU to perform the selection of the N channels.

III. MECHANISM DESCRIPTION

A. Estimation of the sensing accuracy

We define $\theta_m^{(k)}$ as the accuracy of the information obtained by u_k from channel f_m. In particular, $\theta_m^{(k)}$=1 if u_k is able to detect the presence of PUs transmitting on f_m and $\theta_m^{(k)}$=0 if it is not due to distance, fading, etc. As $\theta_m^{(k)}$ is unknown for u_k, each SU should estimate it. The estimation is denoted by $\theta_m^{(k)*}$.

If a user u_k senses a channel f_m during the nth sensing process, it generates the observation $s_k(f_m, n)$. $s_k(f_m, n)$ is the result of sensing f_m and may be 0 if no PU was detected and 1 otherwise. All the SUs that sense f_m during the nth sensing process generate an observation and informs the cluster head through the Common Control Channel f_0. The protocol used to transmit $s_k(f_m, n)$ from u_k to the cluster head is out of the scope of this work, but an example may be found in [6]. Upon the reception of all the observations, the cluster head combines/fuses them. There are several fusion rules that may be used, but the most common rules are the OR and the AND operations [7]. The result of fusing all the collected observations of f_m is denoted by $g(f_m, n)$, and it is also distributed to all the users in U through the Common Control Channel. Accordingly, by definition, $g(f_m, n)$ may be 0 or 1. The observations of the SUs are affected by the false alarm and misdetection probabilities, denoted by P_{fa} and P_{md} respectively. As a consequence of the combination process, the information distributed by the cluster head presents cluster false alarms and misdetection probabilities, different from P_{fa} and P_{md}, denoted by Q_{fa} and Q_{md}.

Notice that, if $\theta_m^{(k)}$=1, there will be rare situations where $s_k(f_m, n)$ and $g(f_m, n)$ differ. On the contrary, if $\theta_m^{(k)}$=0 there will be big differences between $s_k(f_m, n)$ and $g(f_m, n)$ very often. Therefore, if we define $\varphi_k(f_m, n)$ as the sum of the differences occurred between the observations of u_k and the decisions of the cluster head during the last W sensing processes, $\varphi_k(f_m, n) = \sum_{j=0}^{W-1} |s_k(f_m, n-j) - g(f_m, n-j)|$, we may estimate $\theta_m^{(k)*}$=1 for large $\varphi_k(f_m, n)$ values and $\theta_m^{(k)*}$=0 otherwise. Consequently, if a threshold φ_{th} is set, $\theta_m^{(k)*}$=1 when $\varphi_k(f_m, n) < \varphi_{th}$, and $\theta_m^{(k)*}$=0 otherwise.

B. Considerations about the estimation of the accuracy

The estimation of the accuracy, $\theta_m^{(k)*}$, is subject to P_{fa} and P_{md} as well as to the activity of the PUs. With regard to false alarm and misdetection, the proposed mechanism mitigates their effect on $\theta_m^{(k)*}$ by using $\varphi_k(f_m, n)$ and φ_{th}. Thus, the probability of an erroneous estimation decreases as W and φ_{th} grow. However, it is also true that the delay between a change in $\theta_m^{(k)}$ and the corresponding detection in $\theta_m^{(k)*}$ rises with W and φ_{th}. As for the activity of the PUs, notice that it is impossible to detect whether $\theta_m^{(k)}$ is 1 or 0 if the PU transmitting on f_m is silent, since $g(f_m, n)$=$s_k(f_m, n)$=0 even if $\theta_m^{(k)}$=0. Accordingly, if this situation lasts longer than $(W - \varphi_{th})$ sensing processes, $\theta_m^{(k)*}$ may be erroneously set to 1. Yet, this is not a serious problem, since such an erroneous accuracy estimation does not entail interference on PUs transmissions.

C. Channels selection

When a sensing process is triggered, each user u_k selects N out of the M channels contained in F. In order to minimize the amount of inaccurate sensing information, the N channels selected by u_k should have $\theta_m^{(k)}$=1. However, as $\theta_m^{(k)}$ is unknown, the estimation $\theta_m^{(k)*}$ is used instead of $\theta_m^{(k)}$ and the N selected channels should accomplish $\theta_m^{(k)*}$=1. Although the selection mechanism should guarantee that the selected channels have $\theta_m^{(k)*}$=1, the mechanism should also be able to adapt to the propagation variations and detect when an inaccurate channel turns into accurate. Therefore, the channels with $\theta_m^{(k)*}$=0 should also be sensed to check whether, for a user u_k, they are still inaccurate or not.

The mechanism proposed in this study is a probability-based method. Let us define $\lambda_{k,m}$ as a weighting factor for a channel f_m. The probability that a user u_k selects a channel f_m will be proportional to $\lambda_{k,m}$. As the mechanism is intended to reduce the amount of inaccurate information, the probability that a user u_k selects a channel f_m with $\theta_m^{(k)*}$=1 should be higher than the probability that u_k selects a channel $f_{m'}$ with $\theta_{m'}^{(k)*}$=0. Accordingly, $\lambda_{k,m} > \lambda_{k,m'}$.

We define $\lambda_{k,m}$=$\theta_m^{(k)*}(\gamma - 1) + 1$, where γ is a positive real number such that $\gamma > 1$. Hence, $\lambda_{k,m}$=1 when $\theta_m^{(k)*}$=0 -inaccurate observations- and $\lambda_{k,m}$=γ when $\theta_m^{(k)*}$=1 -accurate observations-. Now, the probability that a user u_k senses a channel f_m is defined as

$$P_k(f_m) = \frac{\lambda_{k,m}}{\sum\limits_{\substack{m' \\ f_{m'} \in F}} \lambda_{k,m'}} = \frac{\theta_m^{(k)*}(\gamma - 1) + 1}{\sum\limits_{\substack{m' \\ f_{m'} \in F}} (\theta_{m'}^{(k)*}(\gamma - 1) + 1)} \tag{1}$$

In practice, u_k selects the N channels as follows:

```
Num_Selected_Channels = 0
while ( Num_Selected_Channels $< N$ ) do
    Recalculate $P_k(f_m)$ $\forall m : f_m$ is not selected yet
    Generation of a uniform random variable $v \in [0, 1]$
    $m$ = 0
    while ( $v > 0$ ) do
        $m$ += 1
        if ( Channel $f_m$ is not selected yet ) then
            $v$ -= $P_k(f_m)$
        end if
    end while
    Channel $f_m$ selected
    Num_Selected_Channels += 1
end while
```

IV. RESULTS AND DISCUSSION

In the simulated scenario 5 licensed channels are considered, F=$\{f_m : m = 1, \cdots, 5\}$. The activities of the PUs on the channels are modeled as i.i.d. ON-OFF random processes. The probability that a channel which is in the ON (OFF) state remains in the same state is denoted by P_{OnOn} (P_{OffOff}).

With regard to the accuracy of the observations of a channel f_m sensed by a user u_k, the variable $\theta_m^{(k)}$ is also modeled as an ON-OFF process with a probability P_{00} (or P_{11}) of remaining in the same state when $\theta_m^{(k)}$=0 (or $\theta_m^{(k)}$=1). In the simulations, P_{OnOn}=P_{OffOff}=0.8 and P_{11}=P_{00}=0.95. The considered fusion rule is the OR operation. Each simulation consists in analyzing 500 consecutive sensing processes. The results are obtained by averaging 1000 simulations. N_1 is defined as the number of channels with $\theta_m^{(k)}$=1 selected by a user during a sensing process. Fig.'s 1 and 2 depict $P(N_1 = 0)$, the probability that none of the channels selected by u_k has $\theta_m^{(k)}$=1, and Q_{md} as a function of γ for different P_{md} and φ_{th} values. Notice that the smaller $P(N_1 = 0)$ is, the better the accuracy estimation $\theta_m^{(k)*}$ will be and, consequently, Q_{md} will also improve. The number of channels sensed by each user is N=2, and W=3. There are K=20 SUs in the cluster. It is assumed that all the SUs can communicate each other and that the cluster head only collects and distributes the sensing information, as well as makes the decision, but does not sense the spectrum. The channel between all the SUs is considered to be error-free, i.e. f_0.

Fig. 1 shows the impact of γ on $P(N_1 = 0)$. When $\gamma \to 1$ all the channels are sensed by a user u_k with the same probability, no matter if they are estimated accurate ($\theta_m^{(k)*}$=1) or inaccurate ($\theta_m^{(k)*}$=0), since $\lambda_{k,m}$=1. As γ grows, $P(N_1 = 0)$ decreases and tends to a stable value. According to Fig.'s 1 and 2, φ_{th} plays a key role. As stated in Section III-A, $\varphi_k(f_m, n)$ represents difference between the sensing observation of a user u_k and the cluster decision in the last W sensing processes. Regarding φ_{th}, it is the threshold used to modify the estimation of the accuracy. Large φ_{th} values (e.g. φ_{th}=3) reduce the erroneous accuracy estimations due to sensing errors but, at the same time, introduce a certain delay in the estimation update. It may be observed that in reliable sensing environments ($P_{md} \to 0$) large φ_{th} values are not required and the delay of the estimation update causes higher $P(N_1 = 0)$ and Q_{md}. On the contrary, when the reliability of the environment decreases (P_{md} grows, e.g. P_{md}=0.2), large φ_{th} values reduce the errors in the accuracy estimation and counteract the negative effect of the increase of the delay.

We define P_{loss} as the probability that the transmission of the sensing observation from the SU to the cluster head fails or collides. Fig. 3 plots $P(N_1 = 0)$ as a function of the number of SUs, K, for P_{loss}=0 and P_{loss}=0.4. It can be observed that, when the cluster is composed by few SUs, the knowledge of the environment is limited and the reliability of the accuracy estimation is low (and therefore, $P(N_1 = 0)$ is high). As K grows, $P(N_1 = 0)$ decreases until the information provided by the additional SUs is redundant and does not improve the environment knowledge. Accordingly, the number of SUs that transmit the sensing information to the cluster head can be limited without deteriorating the results but reducing the signaling overhead.

We introduce the parameter P_{idle}. Each SU will transmit the sensing observation to the cluster head with a probability $(1 - P_{idle})$. If the minimum required number of SUs that should share their sensing observation is denoted by K_{min}, P_{idle} will be computed as $P_{idle} = 1 - \frac{K_{min}}{K}$ for $K > K_{min}$ and 0 otherwise. Thus, it can be guaranteed that the number of sensing observations is enough and the redundant information is reduced. In Fig. 3, K_{min} would be 13 or 19 respectively.

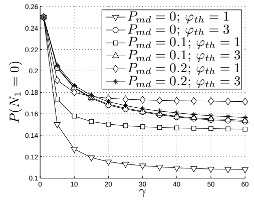

Fig. 1. Probability that none of the channels selected by a user has $\theta_m^{(k)} = 1$ (K=20, N=2, W=3).

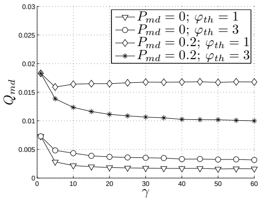

Fig. 2. Cluster misdetection probability (K=20, N=2, W=3).

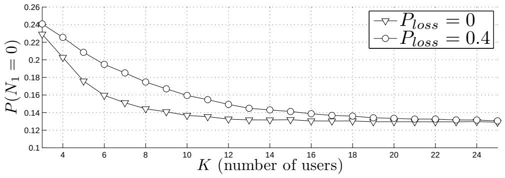

Fig. 3. Probability that none of the channels selected by a user has $\theta_m^{(k)} = 1$ (γ=30, P_{md}=0, N=2, W=3, φ_{th}=2).

V. CONCLUSIONS

The proposed mechanism is aimed at reducing the sensing process overhead by properly selecting the sensing users. The mechanism has shown that an appropriate sensing user selection may be carried out by distributing the decision and using local and global information. As a consequence users are able to classify the spectrum channels according to the accuracy of the measurement and diminish the amount of shared information.

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