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Impact of the knowledge of nodes' positions on spectrum sensing strategies in cognitive networks

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ABSTRACT

In this paper, we focus on cognitive wireless networking, where a primary wireless network (PWN) is co-located with a cognitive (or secondary) wireless network (CWN). The shared frequency spectrum is divided into disjoint "subchannels" and each subchannel is "freely" assigned (in a unique way) to a node of the PWN, denoted as primary user equipment (PUE). We assume that the nodes of the CWN, denoted as cognitive user equipments (CUEs), cooperate to sense the frequency spectrum and estimate the idle subchannels which can be used by the CWN (i.e., assigned to CUEs) without interfering the PWN. The sensing correlation among the CUEs is exploited to improve the reliability of the decision, taken by a secondary fusion center (FC), on the occupation status (by a node of the PWN) of each subchannel. In this context, we compute the mutual information between the occupation status and the observations at the FC, with and without knowledge of the positions of the nodes in the network, showing a potential significant benefit brought by this side information. Then, we derive the fusion rules at the FC: our numerical results, in terms of the network-wise probabilities of missed detection (MD) and false alarm (FA) at the secondary FC, indicate a significant performance improvement when knowledge of the CUEs' positions is available at the secondary FC, confirming the mutual information-based theoretical prediction.

1. Introduction

Dynamic spectrum access has been proposed to provide efficient radio spectrum utilization [1–3]. In such systems, a portion of the spectrum can be allocated to one or more users, which are called primary user equipments (PUEs). Such spectrum, however, may not be exclusively dedicated to PUEs, but could also be utilized, with lower priority, by secondary users, also denoted as cognitive user equipments (CUEs)—the notation comes from cellular systems where the proposed techniques can also be applied. In particular, CUEs can access the same spectrum (as long as the PUEs are not using it at that moment) or can share the spectrum with the PUEs (as long as the PUEs can be properly protected from undesired interference). By doing so, the radio spectrum can be reused in an opportunistic manner or shared all the time, thus significantly improving the spectrum utilization efficiency.

To support dynamic spectrum access, CUEs are required to sense the radio environment, i.e., they also are cognitive radio users [4,5]. One of the main tasks of a CUE is represented by spectrum sensing, defined as the task of

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finding portions of spectrum licensed to some PUEs but left unused for a certain amount of time [6]. Sensing from a single node does not always guarantee satisfactory performance because of the following: sensing noise; the intrinsic random nature of the nodes' positions; and unpredictable channel fluctuations. For example, a CUE could not detect the signal from a primary transmitter behind a high building and could decide to access a licensed subchannel, thus partially interfering with the primary receiver. On the other hand, collaboration of multiple users may highly improve spectrum sensing performance by introducing a form of spatial diversity [7,8]. In cooperative spectrum sensing, CUEs send the collected data to a combining user or fusion center (FC). Alternatively, CUE may first independently decide on the statuses of the subchannels and report binary decisions to the FC, which uses such data to take a decision on the occupation of each subchannel.

Although a well-established technique, great attention has recently been paid to cognitive radio since it has been identified as a key enabling technology for next-generation 5G systems [9]. Among all possible usages of cognitive radio in 5G scenario, a very interesting application lies in the field of the so-called green communications [10], i.e., the design of wireless infrastructures with limited cost and energy consumption. As an example, in [11] the authors propose green cognitive relaying, where data transmissions opportunistically occur when spectrum holes are identified, whereas energy harvesting is performed when PUEs occupy the licensed spectrum.

In this paper, we focus on cognitive wireless networking, where a primary (i.e., licensed) wireless network (PWN) is co-located with a cognitive (or secondary) wireless network (CWN). In particular, the nodes of the CWN reach their associated access point (AP) directly (i.e., single hop communications are assumed). The nodes of the CWN cooperate to sense the frequency spectrum and estimate the subchannels unused by the nodes of the PWN. The CUEs transmit packets containing the observations on the channels' statuses (idle or busy) to their FC, "embedded" in the secondary AP, which makes a final decision about the status of each subchannel and broadcasts this information to all CUEs. In this context, we first derive an expression for the mutual information between the occupation status and the observations at the FC. Then, optimal fusion rules, with and without the knowledge of the positions of the nodes, are derived and the missed detection (MD) and false alarm (FA) probabilities are computed to obtain system receiver operating characteristic (ROC) curves [12]. Both approaches indicate a significant performance improvement when knowledge of the nodes' positions is available at the secondary FC. Our work is inspired by recent advances in wireless communications, where proper transmission and signal processing-aided schemes are designed to exploit the knowledge of nodes' positions [13,14].

This scenario has been preliminarily analyzed in [15], where the case without knowledge of the positions of the nodes in the network is considered. Note that related work is carried out in [16], where a scenario with CUEs with known positions, close to each other and far from a PUE, is considered. In this case, the sensing channels are correlated and, therefore, sub-optimal fusion rules are devised to take into account this correlation. Unlike [16], here we consider a more realistic sensing scenario where CUEs are not necessarily close to each other and, therefore, channel impairments may be independent. However, the correlation between the decisions of the CUEs can be exploited if the secondary AP knows their positions, thus improving the network performance, in terms of MD and FA probabilities on the status of each subchannel.

The rest of this paper is structured as follows. In Section 2, we present the system model. In Section 3, we analyze the MD and FA probabilities from a single CUE perspective. In Section 4, we derive an information-theoretic framework to compute the ultimate performance limits, in terms of mutual information between the observation vector at the FC and the binary data representing the occupation status of a subchannel, of the considered cognitive networking scenario, distinguishing between the cases with and without knowledge of the positions of the nodes. Then, in Section 5 we derive optimal fusion rules at the FC, with and without knowledge of nodes' positions, evaluating the MD and FA probabilities of the decision by a CUE on the occupation status of a subchannel. Finally, concluding remarks are given in Section 6.

2. System model

The scenario of interest is shown in Fig. 1. The FC, "embedded" in the secondary AP, is placed at the center of the region of interest (ROI), which is a circular cell with a given radius R, while CUEs and PUEs are independent and identically distributed (i.i.d.) according to a uniform distribution in the ROI.[1] The numbers of PUEs and CUEs are indicated as P and N, respectively. The PWN can operate on N_{ch} orthogonal subchannels corresponding to non-overlapping frequency bands, i.e., each PUE can transmit data on one of such N_{ch} channels. Each PUE is assigned one of the N_{ch} orthogonal subchannels to transmit its own data (when available) with fixed power P_{T}. Due to the assumption of orthogonal subchannels, in the rest of the paper we will focus, without loss of generality, on a generic subchannel. The binary status of the reference subchannel S is defined as follows:

$$S = \begin{cases} S_0 & \text{with probability } P(S_0) \\ S_1 & \text{with probability } P(S_1) = 1 - P(S_0). \end{cases}$$

Data transmissions follow a classical model for cellular environments, where the path-loss is completely characterized by two parameters: (i) the distance attenuation factor α (adimensional, in the range $2 \div 4$) and (ii) the standard deviation σ (in dB) of the log-normal shadowing [17].

Each CUE scans the subchannel in order to detect the presence of a primary signal transmission. In other words, each CUE performs a binary hypothesis test on the presence of a primary signal in the subchannel, which is idle under hypothesis S_0 and busy under hypothesis S_1. The sensing time of the CUEs depends on the particular

[1] No assumption is done on the position of the primary AP, which, for instance, may be co-located with the secondary AP.

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