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Improved spectrum sensing and achieved throughput of multiband cognitive radio systems under probabilistic spectrum access

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ABSTRACT

We investigate wideband spectrum sensing for multiband cognitive radio (CR) to opportunistically detect spectrum holes without causing harmful interference to licensed (primary) subchannels. In classical wideband energy detection, primary subchannels are *absolutely* classified into *vacant* or *occupied* according to the measured energy. CR signal transmission is then performed over all vacant subchannels. In this paper, we first introduce a *probabilistic spectrum access* method, which assigns a probability for CR signal transmission over each primary subchannel. More precisely, in our proposed method, each primary subchannel is *likely* to be classified into *vacant* or *occupied* via the definition of a *spectrum access probability* for CR transmission, in contrast to *absolute* sub-channel classification used in classical methods. Second, we derive the secondary information rates achieved by the proposed spectrum sensing method and compare it to those provided by classical wideband spectrum sensing. Third, we perform optimal power allocation to maximize the CR achievable rates constrained on the total power and interference introduced to the primary network. Numerical results indicate that the proposed spectrum access outperforms the classically-used spectrum sensing in terms of secondary achievable data rates.

1. Introduction

1.1. Background

Cognitive radio (CR) technology has been proposed as a solution of the inefficient spectrum usage in recent wireless communications systems [1,2]. According to the CR terminology, primary users (PU) s are defined as the users who have higher priority or legacy rights on the usage of a specific part of the spectrum. On the other hand, secondary users (SU) s with lower priorities, exploit the available primary spectrum opportunistically, in a way that they impose a limited and a tolerable interference to the PUs [2]. CR systems distinguish three spectrum access paradigms based on the type of available network information and regulatory constraints: *underlay*, *overlay*, and *interweave* [3]. For the underlay spectrum access paradigm, the CR transmitters send their signals such that the interference caused to the PU receivers is kept below a given threshold. In [4,5], the interference introduced to the PUs has been modeled and analyzed. The overlay approach can be considered similar to cooperative transmission between SUs and PUs based on the assumption that the secondary transmitter knows the message sent by the primary transmitter. Overlay spectrum access paradigm is relatively difficult to be implemented due to the need of the prior information about PU's message [3]. In the interweave spectrum access paradigm, the CR users opportunistically exploit so called *spectrum holes* to communicate without disrupting the PU communications. These spectrum holes can be considered as multidimensional within frequency, time, code, and space [1,2]. The implementation of the interweave scheme is a challenging task because it requires a perfect detection about the presence of PUs.

1.2. Motivation

One of the important capabilities of the CR system is reliable spectrum sensing and decision about the presence/absence of the PUs [1]. Hence, most of research efforts in CR is focused on spectrum sensing techniques and efficient spectrum access policies. Examples of narrowband spectrum sensing techniques are energy detection, matched filtering and cyclostationary detection [6]. Energy detection is the most common approach to perform spectrum sensing with relatively low computational and implementation complexities and the fact that it does not need *a priori* information about the PU activity (see for example [7–12]). Wideband spectrum sensing is able to search for multiple frequency bands at a time where on each subband, one of the existing narrowband sensing techniques can be applied. In [8], a bank of multiple narrowband energy detectors are optimized to increase the throughput of the CR system. In [9,13], the authors investigate the

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optimality of cooperative spectrum sensing in a multiband CR scheme operating in the presence of malicious users. In [14], an adaptive multiband energy detection procedure is proposed for identifying multiple vacant subchannels in a wideband CR system. A spectrum sensing method based on singular value decomposition (SVD) is proposed in [15] with aim of maximizing the detection probability and reducing the sensing time.

Another desired feature of a CR system is the ability of allocating the radio resources in a way that a maximum performance is achieved by the secondary network while at the same time, the interference introduced to the primary network is minimized (see for example [16–20,11]). In [16], a power allocation algorithm for a wideband OFDM-based CR system is proposed with the aim of maximizing the transmission capacity of the CR user. However, this work has assumed that primary frequency bands are sensed and perfectly known by the CR. The effect of the imperfect channel estimation and other spectrum sensing errors on the performance of OFDM-based CR is analyzed in [17–19]. Although [21,22] have optimized the CR transmission time and transmission power based on a probabilistic model for the PU transmission activity, the CR transmission is not probabilistic and will occur whenever the PU is detected to be absent.

In classical wideband spectrum sensing based on interweave paradigm, subbands are *absolutely* classified into *vacant* or *occupied* according to the measured energy. Then, the CR relies on the spectrum sensing results and starts transmission solely over subbands specified as vacant. The implementation of the interweave scheme is also challenging because it requires a perfect detection about the presence of PUs. In [23,24], as an alternative to the aforementioned classically-used spectrum access, we have introduced a method referred to as *probabilistic spectrum access* (PSA). In contrast to classical methods, PSA assigns to each primary subchannel, a probability for CR signal transmission which is determined according to the measured energy on that subchannel. More precisely, in PSA, each primary subchannel is likely to be used by the CR user with a probability that depends on the measured energy. The *probabilistic spectrum access* and *probabilistic resource allocation* terminologies have been widely used in the literature (see [25–32] for instance), but the underlying concepts in these works are different from that in our proposed methodology. More precisely, the authors in [29], develop the concept of probabilistic reasoning and risk-constrained spectrum access in spectrum sharing. The related analysis model uses probabilistic factors associated with the locations of users in a Monte-Carlo simulation process to evaluate signal propagation. A multi-layer multi-cast routing protocol for multi-hop mobile ad hoc CR networks has been proposed in [28], where the proposed protocol employs a probabilistic approach in performing the channel assignment and path selection process. The authors in [27], describe the design and characterization of a probabilistic reasoning methodology for spectrum situational assessment. The approach uses a form of Bayesian network to represent the propagation environment and enables parameter estimation in uncertain environments. The probabilistic resource allocation for opportunistic spectrum access has been investigated in [32], which is based on the probabilities of channel availability obtained from spectrum sensing, i.e., the probability about presence/absence of PU conditioned on the measured energy. In this work, the weighting coefficients related to the rate and average power are probabilities of channel availability than the hard coefficients used in the conventional approaches. Notice that the concept of probabilistic spectrum access investigated in the aforementioned literature is mainly related to modeling the CR performance parameters.

1.3. Contribution

In this paper, we investigate the optimal spectrum access function and derive the expression of the secondary achievable information rates and the average interference introduced to the PU associated to the proposed probabilistic spectrum access method and compare it to those provided by classical wideband spectrum sensing. In addition, we perform optimal power allocation to maximize the achievable CR rates constrained on the total power and interference limit of the primary network. The main contributions of this paper can be summarized as follows.

- As an alternative to the aforementioned classical spectrum access approach, here we introduce the concept of spectrum access function, denoted $\phi(y)$, that defines a new transmission rule for accessing the PU spectrum based on the measured energy. In this way, we show that just comparing the measured energy to a threshold is not necessarily the optimal decision rule for all CR scenarios which leads to lower secondary data rate compared to the proposed spectrum access methodology.
- We formulate a more general framework for energy detection in CR where sensing parameters such as miss detection and false alarm probabilities are derived and characterized in term of the proposed spectrum access function.
- Considering the proposed probabilistic spectrum access methodology, we formulate a power allocation problem so as to maximize the secondary achievable data rate while limiting the interference introduced to the PU under total power budget constraint. We show through numerical simulation that the optimal solution for $\phi(y)$ can be different from the classical rule where the derived optimal solution leads to superior performance than those achieved with the classical methodology.

2. System model and main assumptions

As can be seen from Fig. 1, in this paper, we consider a communication system composed of one CR user pair (composed of one transmitter and one receiver) and one PU. We assume that both CR and PU are using multiband signaling with N subbands where the CR performs energy detection over each primary subband. Let us denote the channel gain between PU and CR user during the spectrum sensing phase, at the k-th time-slot by $h_{n,k}$, the channel gain between CR transmitter and CR receiver in downlink transmission by h_n^{ss} and the channel gain between CR user and PU during the data transmission phase by h_n^{sp}, where subscript $(\cdot)_n$ indicates the n-th subband. Let us denote by $\sqrt{P_n}x_n^{[k]}$ and by $y_n^{[k]}$ the PU transmitted signal and the CR received signal over the n-th subband at the k-th time slot, respectively. O_n and V_n denote binary hypotheses characterizing the presence and absence of PU in the n-th subband, respectively, and P_n is a constant amplification factor. We have

$$y_n^{[k]} = \begin{cases} \sqrt{P_n}x_n^{[k]}h_{n,k} + z_n^{[k]}, & \text{under } O_n \\ z_n^{[k]}, & \text{under } V_n \end{cases} \tag{1}$$

where $z_n^{[k]}$ is the additive white Gaussian noise (AWGN) in the n-th CR subband at the k-th time-slot, i.e., we have $z_n^{[k]} \sim \mathscr{CN}(0,\sigma_n^2)$. The CR user performs energy detection over each primary subband where M samples $|y_n^{[k]}|^2$, $(k = 1,\dots,M)$ are averaged during one detection interval as

$$Y_n = \frac{1}{M}\sum_{k=1}^{M} |y_n^{[k]}|^2. \tag{2}$$

According to the central limit theorem, for large M, the measured energy Y_n is approximately distributed as a Gaussian random variable, i.e., $Y_n \sim \mathscr{N}(E\{Y_n\},\text{Var}\{Y_n\})$. We have [8]

$$E\{Y_n\} = \begin{cases} \sigma_h^2 + \sigma_n^2, & \text{under } O_n \\ \sigma_n^2, & \text{under } V_n \end{cases} \tag{3}$$

and