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Cooperative spectrum sensing for cognitive radio networks under limited time constraints

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ABSTRACT

User cooperation for spectrum sensing in cognitive radios has been proposed in order to improve the overall performance by mitigating multi-path fading and shadowing experienced by the users. However, user cooperation results in high energy consumption, extra time for results exchange, as well as delay and security risks. In this paper, we investigate the effects of cooperative spectrum sensing (CSS) on energy consumption and achievable performance. Our analysis is based on a limited time resources assumption. This implies that the time resources dedicated for CSS process are limited and shared between spectrum sensing and results reporting, which depend on the number of sensing users. Our results show that cooperation among large number of users not only causes high energy consumption, but it also degrades the performance. Motivated by these considerations, the number of sensing users is optimized for different setups: throughput maximization, energy consumption minimization, and energy efficiency maximization. The optimal number of the sensing users is computed in a closed-form for both throughput maximization and energy minimization setups, while a simple iterative algorithm is proposed for obtaining the optimal number of sensing users for maximizing energy efficiency. Moreover, a novel energy efficient approach is presented that is able to significantly improve energy efficiency without degrading achievable throughput.

1. Introduction

Recent results have shown that most of the licensed spectrum is not efficiently used, and that unlicensed users suffer from a spectrum shortage [1]. As a solution, cognitive radio (CR) has been proposed [2]. There are two well-known approaches of CR, namely, underlay and overlay[1] [4]. In underlay CR, unlicensed users can simultaneously use the spectrum with the licensed users [5], while in overlay CR, the unlicensed users can access the licensed spectrum when it is not occupied by the licensed users [6]. In this paper we focus on the overlay approach. To identify the used/unused status of the spectrum, the unlicensed users have to detect the activity of the licensed users over the frequency spectrum. This process is called spectrum sensing (SS).

Since SS is the first stage of cognitive communications, it plays a significant role in the success of the whole process. Therefore, SS has received a lot of attention in order to perform it efficiently. A very promising solution to enhance the reliability of SS is the so-called cooperative spectrum sensing (CSS) [7–10], where the sensing users, after their individual sensing, collaborate to make a final decision about the used/unused status of the frequency spectrum under analysis. Cooperation is enabled by reporting the results of the local sensing to a central entity, called fusion center (FC), where the results are combined and a final decision is taken [11]. The performance of CSS is evaluated through two indicators: the detection probability and the false alarm probability. The former is defined as the probability of identifying the used spectrum as used, while the latter is the probability of identifying the unused spectrum as used. Notice that lower detection probability results in a higher interference at the licensed users, whereas high false alarm probability leads to inefficient usage of the available spectrum.

Although CSS considerably decreases the error probability of identifying the correct status of the spectrum, by mitigating the effects of multi-path fading and shadowing [12,13], it has some important limitations, such as the increased energy consumption, a larger delay to make a decision about the status of the spectrum,

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[1] In some references overlay CR approach has been called interweave CR, and overlay CR is referred to the concurrent transmission with the using of dirty coding to mitigate the resulting interference [3].

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as well as security risks [14,15]. In particular, the energy inefficiency is due to the need to report local decisions to the FC, and, as such, it increases with the number of cognitive users (CUs) and the amount of information to be reported by each of them. Therefore, the analysis of the energy efficiency of CSS must be investigated before making any conclusions on the actual benefits of CSS.

In fact, the energy efficiency of CSS has been investigated in many papers. However, the results available in the literature are not often directly comparable since the analysis is performed under different assumptions. In [8,16–18], it is proposed to reduce the amount of information to be reported as a means of saving energy. In [8], the local results are quantized by using only one bit, which is known as hard-based scheme. In [16], an optimal quantizer for the sensing users is proposed. In [17], a confidence-voting scheme is introduced, where each user sends its sensing result only if it has a given confidence level. The confidence level is computed from the history of the local result compared to the final result. In [18], only informative test statistics are reported to the FC. However, all these protocols foresee that all the users still sense the spectrum, which consumes a considerable amount of energy. In [19], the rule for making the decision is optimized in order to maximize energy efficiency. In [20], an alternative approach is proposed, which is called cluster-based spectrum sensing. It foresees that each group of users selects a cluster-head to process their results and to report just one decision on behalf of all of them. However, also in this case all users still sense the spectrum. In addition, extra energy is consumed due to the information exchange between the cluster-head and cluster-members. From these considerations, it follows that reducing the number of sensing users represents a favored approach, as it reduces both sensing energy and reporting energy. Such approach can be found in [21–23].

As mentioned above, the detection performance of CSS increases with the number of sensing users, but the required overhead (energy, delay, sensing and reporting times, etc.) also increases accordingly. Therefore, many works have investigated the optimization of the number of sensing users for several objectives. The problem was firstly formulated by [24], where the number of users is optimized to maximize a target function combining the detection performance and the usage efficiency of the resources. In [25], the target function is defined as the network utility, which is a function of detection accuracy and number of sensing users. In [11], the number of users is optimized to minimize error rate in CSS. A trade-off between sensing performance and throughput is investigated in [26]. In [27], two different setups are presented, energy efficient setup and throughput maximization setup. In the first setup, the number of sensing users is minimized to reduce energy consumption while achieving predefined constraints on detection accuracy, while in throughput maximization setup, throughput is maximized by minimizing the number of users while attaining a predefined threshold in detection accuracy. In [28], an iterative algorithm which jointly optimizes the threshold and sensing time together to decrease the effect of the error and to increase the achievable throughput. However, these works either do not provide an analytical solution of the optimal number of users [11,24,27], or the optimization is performed without taking into account overhead load or proper limited time resources constraint. [24,25,28].

In this paper, we investigate the problem of optimizing the number of sensing users for CSS under three different setups: throughput maximization, energy minimization, and energy efficiency maximization, while satisfying a predefined constraint on the detection probability. The optimization problems are based on a pragmatic limited time resources constraint. More specifically, we assume that the total frame has a finite and fixed duration. A fixed part of it is dedicated for data transmission, while the rest is distributed between local sensing and results' reporting as a function of the number of sensing users. With this finite frame duration assumption, if the number of users increases, the reporting time has to be longer, and, thus, a shorter time is left for local sensing. Compared with the above-mentioned state-of-the-art papers, we assume that the time duration of data transmission is kept fixed and sensing/reporting times are variable. State-of-the-art papers sometimes assume a fixed sensing time and a variable data/reporting times [24,25,27]. Our assumption does not affect data transmission, and, thus, makes CSS a less invasive process.

Although the work in [27] is related to ours, there are three main differences between both works: (i) Different time distribution mechanisms are assumed, where in [27] the sensing time is fixed so that the overhead load affects the transmission time, while we fix the transmission time and the overhead load affects the sensing time, (ii) No closed form expression are presented in [27] for the two considered setups, while we present simple closed forms for the optimal number of sensing users that maximizes throughput and minimizes energy consumption, (iii) Unlike our work, neither energy minimization nor energy efficiency maximization are tackled in [27]. Nevertheless, since both works are based on different assumptions, our approach can be considered as parallel contribution to those presented in [27]. Another related work is [26], where the sensing time is optimized for throughput maximization. However, the optimal number of CUs has not been investigated in [26], and the optimization is confined on throughput maximization setup. Moreover, the time distribution assumption is different form ours, where the transmission time is left variable and the reporting time has not been considered.

The contributions of our work can be summarized as follows:

- Deriving, in closed-form, the optimal numbers of sensing users that maximize the achievable throughput and minimize energy consumption, while limiting the resulting interference by satisfying a predefined constraint on detection probability.
- Proposing a simple iterative algorithm that is able to find the optimal number of sensing users that maximizes the energy efficiency while limiting the resulting interference by satisfying a predefined constraint on detection probability.
- Proposing a novel scheme that is able to improve energy efficiency by finding the optimal number of sensing users that minimizes energy consumption while keeping the same throughput as when all available users cooperate, and satisfying a predefined threshold on the detection probability.

The rest of this paper is organized as follows, Section 2 describes the system model. In Section 3, the optimization of the number of sensing users is presented for the three different objectives, throughput maximization, energy consumption minimization and energy efficiency maximization, followed by proposing a suboptimal energy efficient approach. In Section 4, performance evaluation is discussed using analytic and simulation results. Finally, Section 5 concludes the paper.

2. System model

A CR network with N_T CUs is considered. The CUs try to use a specific spectrum without affecting the licensed user. Hence, they have to sense the spectrum and detect the unused portions of it in order to be able to start their own transmission. The simplest SS technique, and the most efficient when no prior information is available, is the energy detection [9]. In the energy detection method, SS is performed by collecting a number of energy samples S by each CU. The signal observed by each CU is as follows: