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Research Article

Bi-Threshold Cooperative Spectrum Sensing with the Ability of Simultaneous Improving Throughput and Reducing Energy Consumption in Cognitive Radio Network

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Abstract

By performing cooperative spectrum sensing in a cognitive radio network, although the network throughput increases with the increase in the number of secondary users, at the same time, it also causes an increase in energy consumption. This makes it necessary to provide a system that can create a tradeoff between throughput and energy consumption. In contrast to the conventional method of spectrum sensing based on one detection threshold, spectrum sensing with double thresholds avoids reporting unreliable data to the fusion center, thus potentially leading to greater energy saving. In this paper, a double threshold spectrum sensing cognitive radio network with a non-ideal reporting channel is optimized. The values of the threshold and the sensing time are jointly optimized to maximize the throughput of the network, provided that the network energy consumption and the amount of interference with the primary users are limited. The optimization problem is formulated and a numerical method is presented to solve it. The simulation results show a flexible system that can simultaneously provide higher throughput and lower energy consumption than the conventional sensing method. These results, while confirming the higher tolerance against the error of the reporting channel, show a significant energy saving of up to 70% by guaranteeing the throughput efficiency greater than 1.

Keywords: Cognitive Radio, Cooperative Spectrum Sensing, Energy Consumption, Energy Detection, Throughput.

Highlights

- Optimization of cooperative spectrum sensing in a cognitive radio network with limited energy and non-ideal reporting channel.
- Converting the multi-parameter optimization problem to a single-parameter problem using an analytical method.
- Transforming the nonlinear constraint of the problem into a simple linear search using a numerical method.
- Improving network performance in terms of throughput and energy consumption.

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1. Introduction

Cognitive radio is a wireless communication technology that regularly monitors its surrounding radio environment and intelligently identifies busy and idle frequency channels. It opportunistically uses idle channels for data exchange while avoiding busy channels to prevent interference with licensed users, known as primary users. As a secondary user, it improves spectral efficiency while preventing interference with primary users [1]. This technology enables the telecommunications and IT industries to meet the increasing demand for high-quality and high-speed communication services.

The essential functions of any cognitive radio include spectrum sensing, dynamic spectrum management, and adaptive communications [2]. Spectrum sensing, aimed at detecting unused frequency bands at a specific time or location, is considered the most crucial function [3]. Energy detection, due to its lack of need for prior knowledge of the primary signal, simplicity, and low computational cost, is one of the common methods of spectrum sensing. If each cognitive radio performs primary user detection independently, its performance can degrade due to issues like fading and shadowing. Cooperative spectrum sensing has been proposed to address such problems. This method uses information from all or some radios in the final detection process [4].

In cooperative sensing, a base station called the fusion center collects and processes local information from radios. This cooperation occurs in two main ways: data fusion and decision fusion. In data fusion, a weighted version of the energy collected by each secondary user is sent to the fusion center without processing, and the final decision is extracted using some algorithms. In decision fusion, secondary users independently conduct local sensing and each makes a binary decision (1 or 0) regarding the activity of the primary user. These local decisions are reported to the fusion center, where they are combined based on a predefined rule, and the final decision is made. One widely used rule is the OR rule, which states that if at least one secondary user votes for primary user activity, the fusion center also declares primary user activity and prevents secondary users from occupying the channel and exchanging data. This rule provides higher safety for primary users against the harmful effects of cognitive radio network interference.

Unfortunately, as the number of secondary users participating in the spectrum sensing process increases, so does the energy consumption. This issue is particularly unacceptable for battery-powered systems like mobile devices and wireless sensor networks [5]. Therefore, finding ways to save as much energy as possible is crucial. In non-cooperative spectrum sensing, each secondary user operates in one of two phases at any time: sensing or transmission. In the sensing phase, the frequency environment is monitored, and upon detecting an idle band, it switches to the transmission phase and starts data exchange. However, in cooperative sensing, an additional phase called the reporting phase exists between the above phases. In this phase, after sensing, secondary users report their local sensing results to the fusion center and wait for its instruction to know whether to start communication. The total energy consumption of a cooperative cognitive radio network equals the sum of energy consumed in these three phases.

Conventional spectrum sensing with a single detection threshold does not control energy consumption. This paper considers a system with two threshold values where only reliable local decisions are sent to the fusion center [6]. This method reduces overall energy consumption by reducing energy use in the reporting phase. Most previous work assumed an ideal or error-free reporting channel. However, such an assumption is clearly not valid in real applications. The bit error rate of the reporting channel, even with accurate local sensing results and optimal sensing time settings, can significantly reduce cooperative sensing performance [7]. Therefore, our proposed model is based on the assumption of a non-ideal reporting channel.

The history of energy-efficient methods for wireless sensor networks is as old as the technology itself, but for cognitive radio networks, it only dates back a few years. In [8], a method for locating primary and secondary users was proposed to accurately determine radio transmission ranges and thus effectively adjust their transmission power, reducing the network's overall energy consumption. In [9], network energy consumption was reduced by adjusting the sensing frequency and inserting sleep times between consecutive sensing periods.

Allocating network resources effectively among secondary users to ensure quality of service and save resources has been the subject of some related work [10-12]. Improving spectral efficiency is the main goal of cognitive radio networks. Therefore, increasing throughput is of great importance in such networks. In [13], a balance between throughput and detection accuracy was examined under secondary user mobility conditions. In [14], a method was proposed to allocate appropriate times for various cognitive radio activities to improve throughput. Some studies have also focused on maximizing throughput in networks capable of wireless energy harvesting [15-17].

In recent years, two-threshold energy detection for spectrum sensing in cognitive radio networks has attracted attention. Most of the work has focused on improving detection performance [18-24]. Some have also considered network throughput and energy consumption [25-27]. In [18], to address spectrum scarcity and significant environmental changes in vehicular communication networks, a cognitive radio technology with self-adjusting detection thresholds was used to keep false alarms and detection probabilities at desired values. In [19], cooperative spectrum sensing was presented considering sensing history. In this method, if the test statistic is unreliable, more samples from the past received signal are included in the test statistic calculation, improving detection accuracy. In [20], detection thresholds were optimized to minimize the final decision error in majority-rule-based cooperative sensing. In [21], to enhance sensing accuracy for Gaussian channels with Rayleigh fading, each radio network's decision was weighted according to its channel condition, and the final decision was made at the fusion center by combining these weighted decisions. In [22], a soft decision rule combining energies received by secondary users was proposed and its performance was evaluated in terms of throughput and sensing accuracy. In [23] and [24], a combination of hard and soft fusion was used where if the test statistic lies between two thresholds, the secondary user sends the test statistic value to the fusion center instead of a binary sensing result. In the aforementioned studies, the main goal was to increase cooperative spectrum sensing accuracy or improve the receiver operating characteristic (ROC) curve, without evaluating network throughput and energy consumption as done in the present paper.

In [25], energy-saving was achieved by combining two-threshold detection with clustering. Depending on the radios' locations, the network is divided into clusters where only the cluster head communicates with the fusion center. Also, detection results that lie between the two thresholds are ignored and not sent to the fusion center. This paper focused solely on minimizing energy under sensing performance constraints without considering throughput optimization. In [26], the convexity of the problem of increasing network throughput with limited energy consumption was emphasized. This study showed that for a specific range of false alarm and detection probabilities and limiting the number of secondary users, the objective function and constraints are convex. Unlike [26], we propose a numerical solution to the optimization problem, converting energy consumption constraints and interference with primary users into a simple linear search between two sensing time limits. Furthermore, no restrictions are placed on false alarm and detection probabilities or the number of secondary users. In [27], a model was proposed where if the test statistic lies between two thresholds, the spectrum sensing phase is repeated until the sensing result clearly indicates either the activity or inactivity of the primary user. Simulation results showed improved throughput. However, the additional energy required for repeated sensing phases increases the network's overall energy consumption, but the study did not consider energy consumption constraints.

2. Innovation and contributions

In this paper, the main focus is to present a cooperative spectrum sensing method that simultaneously encompasses all aspects of network throughput, energy consumption, and sensing efficiency.

Among the innovations of this paper, the following can be stated:

1- Optimization of cooperative spectrum sensing in a cognitive radio network with limited energy and non-ideal reporting channel
2- Converting the multi-parameter optimization problem to a single-parameter problem using an analytical method
3- Transforming the nonlinear constraint of the problem into a simple linear search using a numerical method
4- Introducing energy saving and energy ratio to evaluate network performance
5- Improving network performance in terms of throughput and energy consumption

3. Materials and Methods

The proposed method was simulated using MATLAB software.

4. Results and Discussion

Figure 1 illustrates the optimal sensing time as a function of SNR for both conventional and proposed cognitive radio networks. The energy saving parameter (g) is set at 60%. It is observed that in both ideal and non-ideal reporting channel scenarios, the proposed method achieves its maximum throughput at shorter sensing times. Throughput efficiency is defined as the ratio of the maximum throughput of the proposed method to the conventional method. Figures 2 and 3 depict how throughput efficiency varies with energy consumption. Figure 2 demonstrates the robustness of the proposed method against channel reporting errors. When error increases, throughput degradation occurs in both methods, but the proposed method shows improved throughput efficiency, indicating significantly less adverse impact from channel errors compared to the conventional method. The inverse relationship between energy saving and accessible throughput efficiency is clearly observable. Higher energy savings typically correlate with reduced throughput efficiency. Nevertheless, substantial energy savings up to 70% can still achieve throughput efficiency greater than 1. Figure 3 displays energy efficiency against energy savings across different SNR levels, showing a decreasing function of energy savings on throughput efficiency. For instance, at -12dB, throughput efficiency remains nearly above 80% for all energy savings values, indicating minimal impact on efficiency.

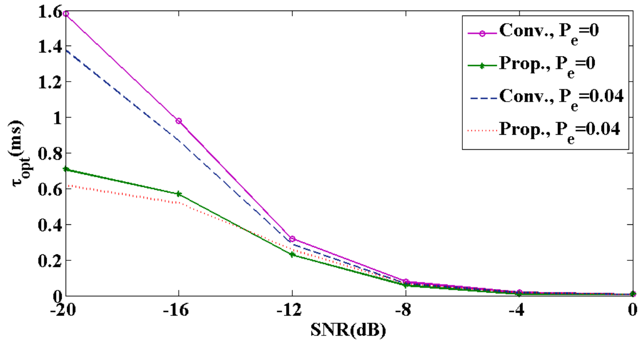

Figure 1. Optimal sensing time versus SNR

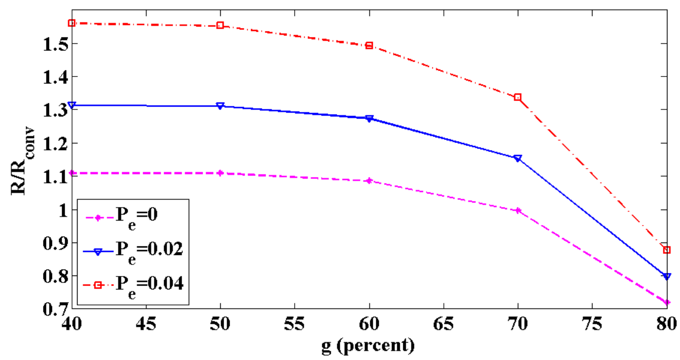

Figure 2. Throughput efficiency versus energy saving for different channel error probabilities

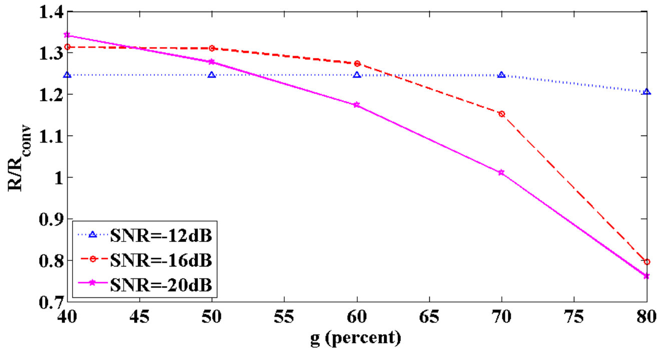

Figure 3. Throughput efficiency versus energy saving for different SNRs

We are interested in evaluating the performance of the proposed method from a different perspective. We allow the system to optimize energy consumption as much as possible regardless of network throughput. The ratio of achievable throughput to minimum energy consumption is depicted in Figure 4. While this scenario leads to minimal throughput, the aforementioned ratio in the proposed method can be significantly higher than the conventional method, as observed. Figure 5 addresses changes in throughput as a function of the number of secondary users. When the network includes a large number of secondary users, its performance improves. In the conventional method, all secondary users collaborate in sensing tasks, whereas in the proposed method, only a subset of trusted users participate in spectrum sensing. This method, simultaneously enhances network throughput and increases energy savings. In Figure 6, we observe that increasing the energy ratio parameter leads to higher network throughput efficiency. Considering that unreliable local decisions are not reported to the fusion center, increasing reporting energy relative to sensing energy reduces overall energy consumption in the proposed method. In fact, in this scenario, the sensing time is able to satisfy the energy constraint over a broader range, thereby improving throughput.

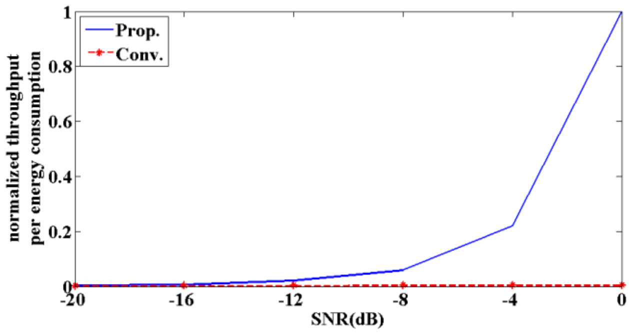

Figure 4. The ratio of achievable energy to minimum energy consumption

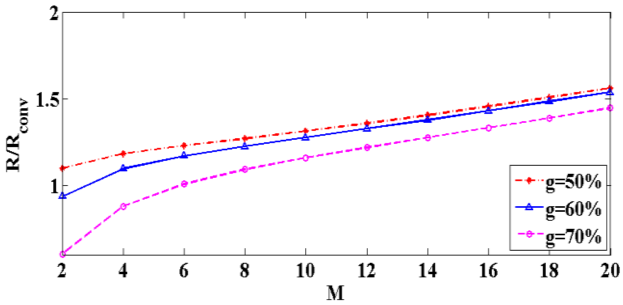

Figure 5. Throughput efficiency as a function of the number of secondary users (SNR=-16dB)

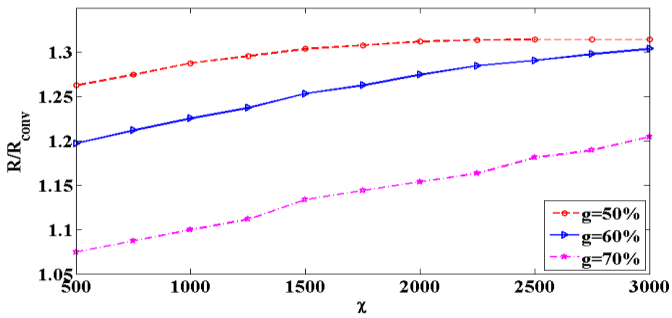

Figure 6. Throughput efficiency as a function of energy ratio (SNR=-16dB)

5. Conclusion

This article presents a cognitive radio system designed for collaborative spectrum sensing to enhance throughput, restrict energy usage, and safeguard primary users from interference. It introduces optimal dual-threshold energy detection and sensing times, comparing them with traditional approaches. Simulation results highlight the system's flexibility in balancing throughput and energy consumption. The system's performance under non-ideal reporting channels demonstrates resilience to errors, requiring shorter optimal sensing times. Furthermore, increasing secondary users and energy ratio parameters enhances overall system performance. The proposed method achieves superior throughput compared to conventional methods while maintaining specified energy consumption levels.

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