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# Does cognition come at a net energy cost in ad hoc wireless LANs?

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ABSTRACT

Cognitive radios have been proposed in recent years to make more efficient use of the wireless spectrum and alleviate congestion on widely used frequency bands. A key aspect of these radios is the "cognition" gained through a spectrum scanning process. The benefit of this cognition is apparent and well studied in terms of achieving better communication performance on selected spectrum and detecting the presence of primary users. The benefits in terms of reduced energy consumption in secondary users, however, due to easier channel access and less contention have not been quantified in prior work. On the other hand, spectrum scanning to gain cognition is a power-intensive process and the costs incurred in terms of energy lost need to be accounted for. Thus, it is not clear whether a cognitive radio-based node would be more energy-efficient than any conventional radio node, and if so, under what circumstances. This focus on energy consumption is particularly important when considering portable communication devices that are energy constrained. This work takes a first step in this direction for the ad hoc Wireless LAN scenario that works in the highly congested ISM bands. The interplay between different important parameters involved is analyzed and their impact on energy consumption is studied.



## 1. Introduction

With the rapid increase in the number of wireless enabled devices, contention for wireless spectrum has never been higher. Cognitive radios have been seen as the way to minimize the congestion by allowing multiplexing between primary users of a piece of spectrum with other opportunistic secondary users of the same spectrum. This allows each radio to look out for less congested spectrum to move to and possibly improve its communication performance. The cognitive radio (CR) technique mainly deals with how spectrum can be sensed, and how this sensed information can be used. In traditional cognitive radio networks (CRNs) as envisioned in [1], the goal of sensing was to avoid primary users (PUs) of the spectrum by secondary users (SUs) who must then move to a different channel to avoid interfering with PUs. However, the CR technique of finding and moving to desirable channels can also be used by general wireless radios to alleviate congestion in dense deployments such as wireless LANs (WLANs) on ISM bands as pointed out in [2].

The increased attention to develop CR techniques to find and use wireless spectrum, has however, resulted in researchers overlooking the importance of energy consumption in the devices that employ such techniques. Scanning for wireless spectrum, and possibly switching between frequency channels, is power-intensive due to the radio constantly staying in an active mode and processing received packets. This could result in rapid depletion of the lifetime of energy-constrained devices like PDAs, laptops, smart phones, wireless sensors, among others. The fact that the success of the CR technique depends on such a power-intensive operation can undercut the very paradigm in such portable devices. Thus, research needs to be done to study the extent of energy consumed by employing CR techniques and its impact on device lifetimes.

On the positive side, however, the CR technique could also reduce the energy consumed for communication in nodes by finding spectrum that is less congested. This would enable communication with less contention for the medium, another major factor of energy consumption in wireless devices. Higher contention for the medium typically results in more packet collisions, more time spent backing off when using CSMA protocols, and more overheard packets from other nodes. Thus, the CR technique's positive impact on energy consumption needs to be studied and quantified as well to understand how energy-constrained devices would fare in terms of operating lifetime.

The goal of this work is to weigh the positive and negative impacts of the CR technique on energy consumption of nodes and determine if its usage can prove energy efficient in portable

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devices. Through this work we make the following technical contributions: (i) model and analyze energy consumption of a radio that employs CR techniques as opposed to a conventional radio that does not (ii) propose and compare different algorithms that scan for more desirable spectrum, with energy consumption as a metric, and (iii) provide an operating range where a CR-based radio can save energy taking into account higher layer aspects like number of frequency channels, node distribution, time spent scanning a channel, and number of contending nodes.

We will consider the heavily congested ad hoc WLAN scenario as a case study for this work. Our goal is to gain insight on how various parameters interact with each other and their joint impact on energy consumption in the ad hoc WLAN scenario. For this study, we consider a case where multiple nodes compete against each other for communication and look at the merits/demerits in terms of energy consumption of employing CR techniques. Much of prior work with CRNs has considered the detection of PUs as the primary goal for SUs and have just studied the case of one SU (e.g. [3–6]). In this work we focus on the communication of multiple nodes (that could also be SUs communicating independent of PUs) and associated energy consumption.

The results of this work indicate that node distribution across channels, and time spent in scanning a channel (and gaining information about it) are the most important factors in determining whether a node employing CR techniques (scanning spectrum and switching to better channels) is more energy efficient than a conventional node radio (that does not keep attempting to seek better spectrum). For typical values of these factors under the ad hoc WLAN scenario, our results show that a CR-based radio can be energy-efficient (savings of 20–40% easily possible). These savings are possible because the reduction in energy consumed to communicate on a channel with reduced node contention typically outweighs the energy costs of scanning to find such a channel. However, there do exist some scenarios where the energy consumed for scanning spectrum does not provide any meaningful benefits in terms of reduced energy for communication. In such cases, the node is better of not employing CR techniques. This paper helps identify such cases where a node, especially a battery-operated mobile device, must not employ CR-techniques to conserve critical energy.

The rest of the paper is organized as follows. Section 2 briefly surveys the literature on research in the cognitive radio area and discusses the significance of our contribution. In Section 3, we define the problem in terms of an energy model and state our goals formally. Section 4 presents our analysis of energy consumption with a conventional radio and with a CR-based radio that uses either the optimal scanning technique or the greedy scanning technique. Section 5 evaluates the impact of various parameters on CR-based radio's energy consumption as compared to a conventional radio. Additional evaluations for more dynamic scenarios are considered in Section 6. Finally, conclusions are presented in Section 7.

## 2. Related work

In this section we survey the literature on cognitive radios, focusing specifically on the sensing/scanning aspects and channel access of the medium, the key aspects under consideration in this work.

The sensing aspect of CRs mainly deals with finding the right spectrum to use for communication, as introduced in the seminal paper [1]. This involves finding spectrum that provides the best communication possibilities for the node in terms of metrics such as throughput, fairness, interference, and utilization. The channel assignment/allocation problem in CRs has been studied through different optimization formulations in [7–14]. Further, the detection and avoidance of PUs of the spectrum is of utmost importance. It involves detecting a PU receiver and/or transmitters on the spectrum and has been of considerable interest to researchers [3–6]. Some important considerations include the determination of the duration to sense the channel [15,16] and the duration to communicate packets [17]. Since scanning is energy intensive, energy consumed in scanning is classified as the number one problem that might delay the advance of CRs [18]. In [19] authors proposed new MAC protocol to optimize scanning time while the authors of [20] worked on finding an ideal ordering of channels to sense. The work in [21] focuses specifically on using CR techniques for WLANs to solve the performance degradation issue due to congestion. Like other work, energy consumption with regard to CR techniques is not considered.

The channel access aspect of CRs can be classified based on the type of network architecture: infrastructure/centralized or ad hoc/de-centralized. MAC protocols for CRNs in *infrastructure networks* make use of the centralized base station to synchronize and conduct node access operations. The carrier sense multiple access (CSMA) MAC protocol proposed in [22] for infrastructure CRNs is a random-access protocol which relies on differentiated access to the medium for packets from or to PUs, with other CR nodes having a lower priority. The IEEE 802.22 standard for CRs uses the notion of superframes and slots at the base station to control access to the medium [23]. In general, in an infrastructure network, the base station is in control of the network and dictates what frequency all nodes in its network should use. Nodes are, however, free to search for and associate with other base stations to satisfy communication requirements. In *ad hoc* CRNs, spectrum sensing and medium sharing are distributed in nature, along with responsibilities of forming packet forwarding routes and time synchronization, if required. Proposed protocols in literature can be classified further based on whether nodes have one or multiple radios [14]. We assume two radios in this work as is common, with one radio for scanning spectrum and another for communication. Further reading on MAC protocols for CRs can be found in the survey in [24].

Research that is closely related to this work revolves around the issue of energy and the use of CRs. The work in [25] explores energy consumption aspects of CRNs but not on CR-techniques for a broader class of radios independent of PUs The work in [26] presents techniques for reducing energy consumption of a cognitive radio. Their work is mainly targeted towards physical layer adaptations involving the power amplifier, modulation, coding, and radiated power. The work in [27] studies sleep scheduling and detection in cognitive sensor networks with energy considerations while the work in [28] proposes energy-efficient cooperative spectrum sensing techniques. Our work is complementary to these works and looks at the problem from a higher layer perspective in ad hoc networks. We study the impact of parameters like scanning time per channel, number of contending nodes on the medium, node distribution across channels, and evaluate four approaches to scan for better spectrum. In early preliminary work by the authors in [29], we had defined the problem and proposed some of the approaches mentioned in the paper, but conducted only a limited performance evaluation. For example, this work fundamentally studies the energy consumption for scanning channels and explicitly compares it to the energy spent in communicating a packet. Further, this work performs additional experiments to understand the implications of the number of channels available for nodes to switch to. Finally, this work also improves over the work in [29] by studying the impact of dynamic channel conditions through simulations.

The biggest difference of this work over prior work in literature is its focus on a general scenario where multiple nodes compete to find and utilize spectrum for communication. All the above mentioned work look at PU related aspects of CRNs and fail to consider