Does Cognition Come at a Net Energy Cost in Ad Hoc Wireless LANs?

Anm Badruddoza*, Vinod Namboodiri*, Neeraj Jaggi†
*Department of Electrical Engineering and Computer Science, Wichita State University
{axbadruddoza, vinod.namboodiri}@wichita.edu
†Department of Electrical Engineering, Columbia University
nj2268@columbia.edu

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.

Index Terms
Cognitive Radios, Energy Consumption, Spectrum Scanning, Wireless LANs, Ad Hoc Networks

I. 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 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 (eg. [3], [4], [5], [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 II briefly surveys the literature on research in the cognitive radio area and discusses the significance of our contribution. In Section III, we define the problem in terms of an energy model and state our goals formally. Section IV 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 V 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 VI. Finally, conclusions are presented in Section VII.

II. 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], [8], [9], [10], [11], [12], [13], [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], [4], [5], [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 the fact that CR techniques could be useful for general wireless nodes (that could be a group of SUs as well) that compete with other nodes for a
Radio 1

\[ T \quad T \quad T \]

Radio 2

\[ T_{\text{scanp}} \quad T_{\text{scanp}} \quad T_{\text{scanp}} \]

Fig. 1. Model of communication and periodic scanning with two radios at a CR node.

desirable spectrum for communication. The focus of this work is on the energy consumed by a node employing the CR-approach of periodically scanning spectrum to seek out a channel most suited for its communications. Such a CR-based node is compared with another non-CR node that does not use spectrum scanning to make its decisions, but instead, stays fixed on its initially chosen channel. The focus of this work is on ad-hoc WLANs and the associated IEEE 802.11 standard MAC protocol due to high congestion in the ISM bands on which such nodes communicate [2] where the benefits of CR-techniques would be most apparent and useful.

III. PROBLEM DEFINITION

In this section, we formally define the problem under consideration. We consider the energy consumption of a non-cognitive node that always communicates on a single channel and compare it to that of another node that periodically scans the spectrum (and expends additional energy) for a better channel for communication. Subsequently, we will describe the application scenario considered and assumptions made.

A. Problem Statement

We define a ‘better’ channel as one that will consume less energy to communicate on than the current channel for similar performance in terms of achieved throughput. One channel could consume less energy for communication than another channel due to factors like node contention for the channel, interference, and channel noise, with all other parameters being the same across channels.

A CR node’s energy consumption can be modeled as the sum of energy to communicate a packet on a newly found channel, and the energy to scan for this new channel. It is assumed that the scanning and selection of a channel to use occurs through a different radio simultaneously, a common assumption [14], [24]. This occurs for a duration of \( T_{\text{scanp}} \) before the next unit of time \( T \) begins, as shown in Figure 1. Later in this paper, the overall time to scan \( T_{\text{scanp}} \) considered is shown to depend on the nature of the scanning scheme chosen and not a constant as shown in Figure 1 for simplicity.

Let \( k \) be the number of nodes on a selected channel by the cognitive radio as opposed to \( n \) nodes on the current channel. Also, let \( T \) be the duration between beginning each scan, and \( \hat{E}_{\text{scan}} \) be the expected energy consumed per scan. If \( \hat{E}_{\text{pkt}}^{k, \gamma} \) and \( \hat{E}_{\text{pkt}}^{k, \gamma} \) are the expected energy and time required to send a single packet with \( k \) nodes contending for specific channel conditions, \( \gamma \), then the expected per-packet energy consumption of the cognitive radio, \( \hat{E}_{\text{CR}} \) can be modeled as

\[
\hat{E}_{\text{CR}} = \hat{E}_{\text{pkt}}^{k, \gamma} + \frac{\hat{E}_{\text{scan}}}{T/T_{\text{pkt}}}.
\]

where the second term amortizes the cost of scanning over the number of packets sent in period \( T \) computed as \( T/T_{\text{pkt}} \).
Since the conventional non-CR radio has no scanning overhead and stays on the current channel, its expected per-packet energy consumption on a channel can be expressed as
\[ \hat{E} = \hat{E}_{\text{pkt}}^{n,\gamma_0}, \]  
where \( n \) nodes contend on the current channel with channel conditions \( \gamma_0 \).

The CR-based node under consideration saves energy for packet communication if
\[ \hat{E}_{\text{CR}} < \hat{E}. \]  
(3)

Let \( f(\gamma) \) be the expected number of re-transmissions needed per packet for a specific channel condition \( \gamma \). For each packet sent by a node in ideal channel conditions—with signal-to-noise ratios (SNR) high enough to result in bit error rates low enough that retransmissions are not required—it would need to send \( f(\gamma) \) additional packets under non-ideal conditions with lower SNR and higher bit error rates.

Thus, above equations could be written as
\[ \hat{E}_{\text{CR}} = \{1 + f(\gamma)\} \hat{E}_{\text{pkt}}^k + \frac{\hat{E}_{\text{scan}}}{T/T^k} \{1 + f(\gamma)\}, \]  
(4)
and
\[ \hat{E} = \{1 + f(\gamma_0)\} \hat{E}_{\text{pkt}}^n, \]  
(5)
dropping the super-script for channel condition under ideal channel conditions.

Note that for \( k \geq n \), that is no channel was found with lesser nodes than \( n \), the conventional radio will consume less energy under similar channel conditions \( \gamma = \gamma_0 \). The difference between \( n \) and \( k \), or the difference in contention, plays a significant role in the cardinality and magnitude of energy savings. In this paper we consider only the impact of node contention in our analysis and do not study the impact of channel conditions.\(^1\) Thus, in Equations 4 and 5 we make a simplifying assumption of \( \gamma = \gamma_0 \). That is, channel conditions across different channels are similar. It would be easy to extend our model to different values of \( \gamma \) for different channels once we understand the relative impact of channel contention and channel scanning in terms of energy consumption in this paper. The results of this work are still very useful and provide great insights on the relative roles of node contention and channel scanning while keeping channel conditions constant. This assumption keeps the models more simple and analytically tractable. We discuss the impact of relaxing this assumption on our results later in Section VII.

Thus, now we define a “better” channel as one that has less number of nodes contending for the channel than the current channel\(^2\). A new channel is sought to alleviate contention. In Equation 4 the condition \( k < n \) would now hold. A new channel with \( k \geq n \) would never be chosen as it cannot be better by our definition.

\(^{1}\)Studying channel conditions require a more dynamic setting with temporally varying node arrival and departures and channel error rates \( \gamma \). Such a dynamic environment study is more suited to a simulation-based study that is complementary to this analytical study. This simulation based study of the impact of channel conditions provides complementary results and can be found in [30].

\(^{2}\)At various places in the paper, we term the newly found channel as the chosen channel or selected channel.
network, we do not consider aspects of PU detection such as energy detection, matched filter detection etc. Studying the WLAN scenario on the ISM band offers an interesting case study of a highly congested environment and helps better understand the tradeoffs between the energy consumed for spectrum scanning and the benefits in terms of reduced contention on channels that are lightly loaded.

Minimizing overhead of communication is critical to saving energy. Overhead occurs due to factors like contention for the medium with other nodes, and channel conditions that may necessitate packet re-transmissions. Greater contention and noise on the medium also has the effect of making radios that employ carrier-sense techniques wait their turn for transmission. Such delays can result in radios staying in the idle state for a longer period of time compared to the lower power sleep state, thus increasing energy consumption. Thus, quantifying energy consumption under the factors: node contention and channel conditions is very important.

IV. ENERGY CONSUMPTION ANALYSIS

In this section we analyze for the components of \( \hat{E}_{CR} \) and \( \hat{E} \) as given in Equations 4 and 5. This analysis requires us to determine the energy required to communicate by a node on a channel with a total of \( k \) nodes contending. Thus, our first step is to compute \( \hat{E}_{\text{pkt}}^k \). We begin by describing the basic energy model and analyzing the building blocks required to compute \( \hat{E}_{\text{pkt}}^k \). Subsequently, we propose four spectrum-scanning algorithms and analyze the energy required to scan, \( \hat{E}_{\text{scan}} \), for each of them.

A. Energy Model

![Figure 2. Packet communication in the basic access mode of IEEE 802.11 standard](image)

We base our analysis on Figure 2 which shows the behavior and timing of a node that is transmitting, receiving, or just listening to the medium using the basic access mode without RTS/CTS. For simplicity, we will ignore the small time for SIFS.

1) Transmission Energy: A successful transmission has the energy cost

\[
E_{tx} = P_{tx} T_{data} + P_{rx} T_{ack} + P_{idle} T_{difs},
\]

while a packet collision incurs the following cost

\[
E_{coll} = P_{tx} T_{data} + P_{idle} (T_{ack} + T_{difs})
\]

All variables of the notation \( P_{(\cdot)} \) are power values, while all variables of notation \( T_{(\cdot)} \) are time values, with the sub-scripts self-explanatory in most cases and related to either radio or protocol states.

2) Receiving Energy: Three cases can be considered when a packet is received: (i) packet is intended for the node, (ii) packet is not intended for the node and needs to be discarded, and (iii) packet has been jammed due to a collision. A successful reception, case (i), has the energy cost

\[
E_{rx} = P_{rx} T_{data} + P_{tx} T_{ack} + P_{idle} T_{difs}.
\]

When a received packet has to be discarded, case (ii), the following cost is incurred

\[
E_d = P_{rx} T_{hdr} + P_{idle} T_{difs} + P_{sleep} T_{nav}
\]
where $T_{nav} = T_{data} - T_{hdr} + T_{ack}$ is the time duration of network allocation vector (NAV) (as defined in [23]) where a radio has to wait for other nodes, and thus could possibly go to the sleep state.

When a received packet is discarded due to a collision, case (iii), the energy cost can be expressed as

$$E_{rxc} = P_{rx}T_{hdr} + P_{idle}(T_c - T_{hdr} + T_{dfs})$$

(10)

3) Energy Consumed for Backoff: We base our analysis on [32] and [33] where the notion of a tick is introduced instead of a slot for analyzing the IEEE 802.11 Distributed Coordination Function (DCF). The energy spent during a tick period equals the energy spent between two successive decrements of a node’s backoff counter. The tick period is perceived by a node in backoff, and has $n - 1$ other potential transmitting nodes. Backoff counters are decremented by one per time slot if no other node attempts a transmission. Backoff countdowns are suspended if the channel is sensed busy, and resumes again only when the medium is sensed idle.

Two possibilities arise when a given node is trying to transmit in a given tick time with $n - 1$ other potential transmitters. The probability that only the given node transmits, $\rho_{nc}$ can be expressed from the use of the binomial distribution expression with parameters $n - 1$ and $\tau$ as

$$\rho_{nc} = (n - 1)\tau(1 - \tau)^{n-2},$$

(11)

where $\tau$ denotes the probability that a node transmits at a given tick time and is a function of the initial size of the sliding window $W_0$, number of times the backoff window can be incremented $m$, and number of contending nodes $k$ [33].

The probability that more than one node attempts to transmit can be given as

$$\rho_c = 1 - (1 - \tau)^n - n\tau(1 - \tau)^{n-1}$$

(12)

The average energy consumed per tick can then be expressed over all the three possibilities: the slot is idle, the node transmits successfully without collision, or there is a collision [32].

$$\hat{E}_{tick} = (1 - \rho_{nc} - \rho_c)P_{idle}T_{slot} + \rho_{nc}\{p_{r}E_{rx} + (1 - p_{r})E_d + \hat{E}_{tick}\} + \rho_c(E_{rxc} + \hat{E}_{tick})$$

(13)

where $p_{r}$ is the probability that a packet on the medium is destined to the given node.\(^3\)

B. Energy Consumed to Communicate on a Channel

The IEEE 802.11 DCF has been well analyzed by previous work in [32], [33]. Using the results of their analysis and our energy model above, the energy consumption of communicating a packet with a total of $k$ nodes contending can be given as

$$\hat{E}_{pkt}^k = E_{tx} + \frac{p_{k}}{1 - p_{k}}E_{coll} + \hat{R}(p_{k})\hat{E}_{tick},$$

(14)

where $p_{k}$ is the probability with which a collision occurs given the number of contending nodes $k$. The subscript $k$ in $p_{k}$ will henceforth be omitted for simplicity. $\hat{R}(p)$ is the expected number of ticks that need to be counted down, not counting collisions, before the packet can be sent and was analyzed as $\hat{R}(p) = \left[W_0\frac{(1-p) - p(2p)^m}{1-2p} - 1\right]$ where $W_0$ is the initial contention window size, $m$ is the number of times the backoff window can be incremented before it reaches the maximum allowed size. Note that, $\hat{R}(p)$ depends only on the number of contending nodes, $k$, that determines the all-important value of $p$. We can get the value of $\hat{E}_{pkt}^k$ in Equation 4 (without using the notation that includes $\gamma$) using the analysis above summing up all the time components.

\(^3\)For our evaluations later in this paper, we take $p_{r} = \frac{1}{n-1}$ for the scenario where any of the other nodes could be the possible destination.
C. Energy Consumed to Scan Channels

The energy consumed by the scanning process ($\hat{E}_{\text{scan}}$ in Equation 4) depends on the scanning algorithm used. Below we propose four different scanning algorithms and analyze the energy consumed to scan when using each of them. Later in our evaluations we compare the energy consumption of a cognitive radio to a conventional radio for each of these algorithms and study their merits and demerits and range of parameters where they save energy. It is expected that these four algorithms would represent most possible algorithms in the design space.

Assume there are a total of $M$ channels to scan including the current channel. Let $T_{\text{scan}}$ and $T_{\text{sw}}$ be the time spent in scanning a channel and time required to switch between channels respectively. Let $\hat{E}_{\text{chscan}}$ be the expected energy consumed while scanning a single channel, and $P_{\text{sw}}$ be the average power consumed for switching channels.

1 Optimal Scanning

In this technique, all channels are scanned before the optimal channel among them is chosen. In the context of this paper, an optimal channel is one that has the least number of nodes contending on it. Thus, the energy consumed by the scanning process $\hat{E}_{\text{scan}}$ can be written as

$$\hat{E}_{\text{scan}} = M\hat{E}_{\text{chscan}} + (M-1)P_{\text{sw}}T_{\text{sw}} + p_{\text{sw}}P_{\text{sw}}T_{\text{sw}}$$  \hspace{1cm} (15)

where $p_{\text{sw}}$ is the probability that a better channel is found than the current one and the node will switch channels as a result. The expression in Equation 15 accounts for the energy consumed to scan $M$ channels, including the energy to switch between them, and a final switch to the chosen channel, if needed.

$\hat{E}_{\text{chscan}}$ depends on what fraction of the scanning period $T_{\text{scan}}$ is spent in receiving packets (collision-free or collided), and what fraction is spent in the idle mode. Using the analysis in [32], and appropriate modifications, we can express this as

$$\hat{E}_{\text{chscan}} = \frac{T_{\text{scan}}}{T_{\text{tick}}}[\rho_{\text{nc}}P_{\text{idle}}T_{\text{slot}} + \rho_{\text{nc}}E_d + \rho_{\text{c}}E_{\text{rxc}}]$$  \hspace{1cm} (16)

where $\rho_{\text{nc}}$ and $\rho_{\text{c}}$ are the probability of receiving a collision-free or a collided packet respectively as expressed in Equations 11 and 12, and $E_d$ and $E_{\text{rxc}}$ are the energy consumed in receiving a collision-free packet and a collided packet respectively as expressed in Section IV-A. The term $P_{\text{idle}}T_{\text{slot}}$ is the energy consumed to stay in idle mode. The multiplicative factor $\frac{T_{\text{scan}}}{T_{\text{tick}}}$ accounts for the number of ticks in a scanning period $T_{\text{scan}}$, with $T_{\text{tick}}$ found as

$$T_{\text{tick}} = (1 - \rho_{\text{nc}} - \rho_{\text{c}})T_{\text{slot}} + \rho_{\text{nc}}(T_{\text{hdr}} + T_{\text{difs}} + T_{\text{nav}}) + \rho_{\text{c}}(T_{\text{hdr}} + T_{\text{c}} - T_{\text{hdr}} + T_{\text{difs}})$$  \hspace{1cm} (17)

2 Greedy Scanning

In greedy scanning, a node scans channels one by one in a pre-determined order, and if any channel has lesser contention by a pre-defined threshold $\Delta$, this channel is chosen over the currently used channel.

Let $q$ be the probability that the next channel is found better than original or current channel by a threshold $\Delta$. Let random variable $X$ represent the number of channels that would need to be scanned. $X$ can have the possible values from 1 to $M-1$, where $M$ is the total number of channels, including the current channel. $X$ will have a probability distribution based on a geometric distribution for the first $M-2$ channels as

$$Pr(X = k) = q(1 - q)^{k-1} \quad \forall k = 1 \text{ to } M-2.$$  \hspace{1cm} (18)

$^4$We assume that this power to switch between channels is fixed and not variable based on channel characteristics. Future work could study how channel characteristics could impact this value. Note that differences in transmission and receiving power across channels have already been accounted for separately in our model through variables $P_{\text{tx}}$ and $P_{\text{rx}}$. 
This gives the probability that the last channel will be scanned as

$$Pr(X = M - 1) = 1 - \sum_{k=1}^{M-2} q(1 - q)^{k-1}$$  \hspace{1cm} (19)$$

taking into account that regardless of whether this last channel is better or not, there are no more channels
to scan. Based on Equation 18, we can further calculate the probability that the radio will switch from
the current channel as

$$p_{sw} = \sum_{k=1}^{M-1} q(1 - q)^{k-1},$$  \hspace{1cm} (20)$$

where we sum up the probability that any of all remaining channels other than the current one are found
better.

From Equations 18 and 19 we can calculate the expected value of the number of channels scanned
using the greedy algorithm as

$$E_X = \frac{(1 - (1 - q)^{M-2})^2}{q} + (M - 1)(1 - q)^{M-2}$$  \hspace{1cm} (21)$$

Thus, energy to scan can be expressed as

$$\hat{E}_{scan} = E_X[P_{sw}T_{sw} + \hat{E}_{chscan}] + p_{sw}P_{sw}T_{sw},$$  \hspace{1cm} (22)$$

where $\hat{E}_{chscan}$ calculated as in equation 16.

The probability that a channel is better than the current one, or simply the probability to switch
channels, $q$, can be found as follows.

Let $F_Z(\cdot)$ be the cumulative distribution function of number of nodes on each channel, where $Z$ is the
random variable representing the number of nodes on the channel that was scanned. Then,

$$q = Pr(Z < n - \Delta n) = F_Z(n - \Delta n) - Pr(Z = n - \Delta n)$$  \hspace{1cm} (23)$$

where $n$ is the number of nodes on the current channel and $q$ is the probability that the next channel is
found better than original or current channel by a threshold $\Delta$.

Previous work by [34] presented data on the distribution of nodes on channels in a WLAN scenario.
We modeled that data with a geometric distribution with parameter $g$.

Thus, $q$ can be expressed as

$$q = F_Z(n - \Delta n) - (1 - g)g^\lambda,$$  \hspace{1cm} (24)$$

where $N$ is the total number of nodes on all $M$ channels under consideration, and $g = N/(N + M)$
with the expected mean number of nodes per channel at steady state $\lambda = N/M$.

3 Sticky Scanning

In this scanning process a node stays with a channel until the anticipated energy consumption goes higher
than a definite threshold. If other conditions are kept identical, energy consumption will depend on the
number of contending nodes. So in other words a node will hunt for another channel only if the number
of contending nodes goes above a certain number, say $n_c$. But it must scan its own channel in periodic
fashion (every period $T$) to know the number of contending nodes, $n$ on the current channel.

Suppose $r$ is the probability for a node to stick to its current channel. Let $Y$ be the average number of
channels that need to be scanned. According to the sticky scanning scheme, $Y$ can have the value from
1 (current channel) to $M$. We have

$$Pr(Y = 1) = r$$  \hspace{1cm} (25)$$
Let $q$ be the probability that on scanning, the next channel is found having contending nodes less than $n_c$, somewhat similar to the greedy scanning scheme described earlier. The probability to scan channels 2 to $M - 1$ can be expressed based on equations 20 and 25 due to the similarity to our greedy algorithm

$$Pr(Y = k) = (1 - r)q(1 - q)^{k-2} \quad \forall k = 2 \text{ to } M - 1. \quad (26)$$

So the probability to scan $M$th channel:

$$Pr(Y = M) = [1 - r - (1 - r) \sum_{k=2}^{M-1} q(1 - q)^{k-2}] \quad (27)$$

From equations 25, 26, and 27 the expected average number of channels to be scanned can be calculated as

$$E_Y = r + (1 - r)[1 + \frac{1 - (1 - q)^{M-2}}{q} + (3 - M)(1 - q)^{M-2}]. \quad (28)$$

Let $F_Z(\cdot)$ be the cumulative distribution function of number of nodes on the current channel, where $Z$ is the random variable representing the number of nodes on the current channel. Then,

$$r = Pr(Z \leq n_c) = F_Z(n_c). \quad (29)$$

In sticky scanning, a node has to scan only its own channel if $n \leq n_c$. Otherwise it will start scanning other channels until it gets $n \leq n_c$. When it finds such a channel, it will consume energy to switch to this channel as well. The number of channels expected to be scanned until such a channel is found is $E_Y$. The total energy to scan can be expressed as

$$\hat{E}_{\text{scan}} = E_Y \hat{E}_{\text{chscan}} + (E_Y - 1)P_{sw}T_{sw} + (1 - r)P_{sw}T_{sw} \quad (30)$$

where $\hat{E}_{\text{chscan}}$ is calculated using Equation 16.

### 4 Selective Scanning

In this scanning scheme a node scans all $M$ channels when it is turned on and then selects a subset $\alpha M$ of these channels that have the least contention. It saves those channels and keeps scanning only those channels each period $T$. The assumption is that those low contention channels will always provide a good channel for communication without incurring the cost of scanning all channels before finding such a good channel. As the selected subset of channels might get worse over a period of time, a node scans all $M$ channels again after $C \cdot T$ periods, where $C$ is a configurable count that controls how often we do a complete scan.

Similar to Equation 15 (and using Equation 16 for $E_{\text{chscan}}$) we can write down the energy to scan under this scheme as

$$\hat{E}_{\text{scan}} = \frac{1}{C}[(C - 1)\{(\alpha M - 1)(\hat{E}_{\text{chscan}} + P_{sw}T_{sw}) + p_{sw}P_{sw}T_{sw}\} + M\hat{E}_{\text{chscan}} + (M - 1)P_{sw}T_{sw} + p_{sw}P_{sw}T_{sw}] \quad (31)$$

where we amortize the energy consumed for $C - 1$ periods where we only scan $\alpha$ fraction of all channels and the one time when we scan all $M$ channels. Note that, the optimal scanning scheme presented earlier in this section is a special case of selective scanning with $\alpha = 1$ or $C = 1$ or both.
V. Evaluation

Here we evaluate the energy consumption of a cognitive radio that can scan and select from other channels and compare it to that of a conventional radio stationed on one channel, the current channel. We consider all four scanning algorithms presented in Section IV-C. All the results presented below are based on numerical evaluations of the expressions developed in the previous section using values for constants shown in Table I. These values were obtained through a combination of actual experimental measurements and specifications for the Ralink 802.11n Wireless Card running on Linux using the RT2860 driver. The experimental setup used was similar to that reported in [35] and used the commonly known technique of measuring the current flow through a 1 Ohm resistor. It is expected that the trends seen in our evaluations will hold for other hardware conforming to the IEEE 802.11 standard as well, though there might be some differences in scale if they are based on Single Input Single Output (SISO) technology. We also varied some of the important parameters from this table (such as transmit power, power to scan and receive packets, and time to switch channels) to study the impact on our results. The change in values only altered the scale of some of the results, but all trends remained the same, thus allowing us to use these representative values for all our experiments. For our experiments, the size of a data packet was set at 800 bytes.

<table>
<thead>
<tr>
<th>Description of Constant</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power to Transmit a Packet</td>
<td>$P_{tx}$</td>
<td>750 mW</td>
</tr>
<tr>
<td>Power to Receive a Packet</td>
<td>$P_{rx}$</td>
<td>750 mW</td>
</tr>
<tr>
<td>Power in Idle Mode</td>
<td>$P_{idle}$</td>
<td>500 mw</td>
</tr>
<tr>
<td>Power in Sleep Mode</td>
<td>$P_{sleep}$</td>
<td>10 mW</td>
</tr>
<tr>
<td>Power to Switch Channels</td>
<td>$P_{sw}$</td>
<td>750 mW</td>
</tr>
<tr>
<td>Power to Scan/Monitor a Channel</td>
<td>$P_{scan}$</td>
<td>700 mW</td>
</tr>
<tr>
<td>Time for Data Packet</td>
<td>$T_{data}$</td>
<td>0.15 ms</td>
</tr>
<tr>
<td>Time for ACK Packet</td>
<td>$T_{ack}$</td>
<td>0.005 ms</td>
</tr>
<tr>
<td>Time for DIFS</td>
<td>$T_{difs}$</td>
<td>0.06 ms</td>
</tr>
<tr>
<td>Time for Packet Header</td>
<td>$T_{hdr}$</td>
<td>0.002 ms</td>
</tr>
<tr>
<td>Time to Switch Channels</td>
<td>$T_{sw}$</td>
<td>0.06 ms</td>
</tr>
<tr>
<td>Slot Duration</td>
<td>$T_{slot}$</td>
<td>0.06 ms</td>
</tr>
</tbody>
</table>

TABLE I
VALUES FOR CONSTANTS USED IN EVALUATIONS

A. Preliminary Evaluation - Energy for Communication versus Scanning

Equation 1 characterizes the energy consumed by a cognitive radio; it encompasses packet transmission and channel scanning energy. A CR’s ability to save energy depends on this balance between energy saved by finding a channel with reduced contention versus the energy spent in scanning to find such a channel. So we did some preliminary evaluations studying this fundamental relation between communication energy and scanning energy.

Our first experiment was to study the energy consumed to send a packet for varying number of nodes on the channel. The x-axis was the time spent to scan a channel, $T_{scan}$. As communication does not depend on scan time of a channel $T_{scan}$ at all, we get horizontal lines as show in Figure 3(a). Greater the contention, greater the energy consumed as one would expect.

Our second experiment was to study the energy spent in scanning for varying $T_{scan}$ and number of nodes $n$. The scanning energy over a period $T$ was divided by the number of packets that could be sent in that period $T$ to get scanning energy consumed per packet. This would allow direct comparison to the energy to communicate a packet. This experiment would show the cost of scanning for a better channel.
As Figure 3(b) shows, increasing $T_{scan}$ results in increasing energy consumption. What is interesting is that if the number of active nodes on a channel, $n$, is larger, it also consumes much greater energy to scan the channel. The reason for this is the additional energy to process packets received from those nodes during scanning; many more packets are overheard from other nodes during the scanning period for each packet sent out.

Combining the above results of energy to communicate a packet and energy to scan into a common ratio, we get a plot as shown in Figure 4. This result shows that for lower values of $T_{scan}$ the energy to communicate a packet is far greater than energy spent in scanning. Thus, it is advisable to spend energy on scanning to reduce contention. As $T_{scan}$ increases, scanning energy starts offsetting any gains of reduced channel contention. The number of nodes $n$ on channels does not make a big difference to the ratio $\frac{E_{pkt}}{E_{scan}}$ as any energy reduction in the numerator due to reduced contention (Figure 3(a)) is offset by a reduction in the denominator of the ratio of energy to scan channels due to fewer received packets during scanning (Figure 3(b)).

These results suggest that reducing channel contention is more important by finding a ‘good’ channel than the energy spent in finding such a channel, if the scan time per channel is not too large. The
subsequent evaluations will focus on the relative benefits in terms of energy savings for all four proposed channel scanning schemes.

<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter</th>
<th>Relevancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of active nodes on a channel</td>
<td>(n)</td>
<td>entire system</td>
</tr>
<tr>
<td>Number of channels</td>
<td>(M)</td>
<td>entire system</td>
</tr>
<tr>
<td>Overall number of nodes in the system</td>
<td>(N)</td>
<td>entire system</td>
</tr>
<tr>
<td>Ratio of active nodes on any chosen channel to the current channel</td>
<td>node ratio</td>
<td>optimal scheme</td>
</tr>
<tr>
<td>Average number of nodes on a channel distributed geometrically</td>
<td>(\lambda)</td>
<td>greedy scheme</td>
</tr>
<tr>
<td>Factor of reduction sought over current channel</td>
<td>(\Delta)</td>
<td>greedy scheme</td>
</tr>
<tr>
<td>Critical threshold of number of nodes on a channel below which scanning is not done</td>
<td>(n_c)</td>
<td>sticky scheme</td>
</tr>
<tr>
<td>Number of periods (T) after which a complete scan is done</td>
<td>(C)</td>
<td>selective scheme</td>
</tr>
<tr>
<td>Fraction of channels scanned when not doing a complete scan of (M) channels</td>
<td>(\alpha)</td>
<td>selective scheme</td>
</tr>
<tr>
<td>Node arrival rate from a channel per time slot</td>
<td>(\eta)</td>
<td>simulations</td>
</tr>
<tr>
<td>Node departure rate from a channel per time slot</td>
<td>(\mu)</td>
<td>simulations</td>
</tr>
</tbody>
</table>

**TABLE II**  
List summarizing parameters of interest in evaluations and where they are relevant.

**B. Optimal Scanning**

We begin with the optimal scanning scheme. To quantify the impact of reduction in node contention from the current channel to the chosen channel, we define a term node ratio as the ratio of nodes active on the chosen channel to that of the current channel. Thus, if there is a ten-fold reduction in the number of nodes on the chosen channel, the node ratio would be 0.1. Smaller the node ratio, greater the reduction in contention by switching to this channel.

We quantify the magnitude of energy savings when using the optimal scanning scheme in Figure 5. We fix \(M\) to a value of 20, and study the impact of a varying \(T_{\text{scan}}\) with node ratio fixed at 0.25. \(T_{\text{scan}}\), the time to scan one channel, was varied from 100 to 1000 ms in steps of 100.\(^5\) We look at multiple values of \(n\), the number of nodes on the original channel.

In Figure 5, it can be observed that there is a linear decrease in energy savings with increasing \(T_{\text{scan}}\). This can be expected due to the increase in energy spent for scanning. Noticeably, the value of \(n\) does not make a significant difference to the amount of energy saved.

When \(T_{\text{scan}}\) is fixed and node ratio varied as shown in the bottom portion of Figure 6, there is a similar trend of a linear decrease of energy savings. For a very low node ratio, the energy savings for \(N = 10\) is flat due to rounding off the number of nodes to 2 as mentioned before. Thus, some of the key results as observable from the evaluation of the optimal scanning technique (and true for the most part for the other schemes later as well) are that (i) increasing values of \(T_{\text{scan}}\) reduce the benefits of using a cognitive radio due to greater scanning overhead, but in a linear fashion, (ii) the energy savings is greater for smaller values of node ratio due to the difference in number of nodes between the current channel and the newly chosen channel. However, the node ratio needs to be small for any energy savings. For close to balanced node distributions on channels, a conventional radio consumes less energy, and (iii) a larger value of \(M\) results in energy for scanning eventually becoming the critical factor in determining whether a cognitive radio can save energy or not.

\(^5\)In practice, a node would set the value of \(T_{\text{scan}}\) based on how much time it would require to estimate number of nodes on a channel which would depend on factors such as number of users, probability of collisions, and SINR. Preliminary experiments, using packet sniffing tools such as Wireshark and scripts to extract unique MAC addresses of nodes, showed that these could be done under 100ms. It is obvious that higher the value of \(T_{\text{scan}}\), greater the accuracy of information obtained.
C. Greedy Scanning

For these experiments, as mentioned in Section IV-C, the distribution of nodes on channels is assumed to be geometric with a parameter $g$ and an average of $\lambda$.

Figure 7 presents the results of possible energy savings when using greedy scanning for a fixed value of $M = 20$. For only a 20% improvement in contention sought ($\Delta = 0.2$) energy savings are less than 10% as can be observed in Figure 7a. To check if increasing $\Delta$ keeps providing greater energy savings, we varied $\Delta$ for different fixed values of $N = 400$, $M = 20$, and $T_{scan} = 200$ ms as shown in Figure 7b.\(^6\) We find that increasing $\Delta$ does indeed provide greater savings. Keeping $\Delta$ large, however, can have the disadvantage in practical scenarios that no channel satisfying the condition may be found, thus possibly compromising on any lesser node reduction that may have been available.

\(^6\)In Figure 7b the line for $n = 0.5\lambda$ flattens out for large $\Delta$ because the $\Delta$ times $n$ has hit the minimum threshold of two nodes needed on a channel for communication.
D. Sticky Scanning

The aim of our evaluation of this scheme is to mainly understand what is an optimal value of \( n_c \). A small value of \( n_c \) would lead the radio to encounter less contention on the channel. On the other hand, finding such a channel with small \( n_c \) might require excessive scanning. Figure 8a shows energy savings as a function of \( T_{\text{scan}} \). In Figure 8b, with the values of \( N = 400 \), \( M = 20 \), and \( T_{\text{scan}} = 200 \)ms, we can see that \( n_c = 2 \), the smallest possible value, is easily the optimal value emphasizing that for these small values of \( \lambda \) (equal to 20), \( M \), and \( T_{\text{scan}} \) chosen, the energy saved due to reduced contention outweighs the energy cost of scanning. In Figure 8b the line for \( n = 0.5 \lambda \) is flat for \( n_c \geq 10 \) because the node stops scanning for better channels as it already has a channel with 10 nodes that is less than \( n_c \).

E. Selective Scanning

Figure 9 shows the impact of varying \( C \) and \( \alpha \) on energy savings for a cognitive radio. Increasing \( \alpha \) decreases the energy savings linearly until \( \alpha = 1 \) at which point the scheme resembles the optimal scanning scheme. Increasing \( C \), similarly, increases energy savings, albeit exponentially initially and more steadily later. At \( C = 1 \), the scheme resembles the energy savings of optimal scanning scheme. Thus, these two parameters can help improve over the optimal scanning scheme. Theoretically larger \( C \) is better. However, \( C \) should be chosen carefully, as channel conditions can be time varying, and smaller \( C \) allows a node to get updated information more frequently. In future, we plan to model temporal variations in channel conditions and node distributions, and to address the appropriate choice of \( C \).

F. Impact of varying number of channels \( M \)

Finally, the impact of varying the number of channels in the system \( M \) is studied here. So far, we had been using a fixed value of \( M = 20 \). Figure 10 shows how the energy consumed by all four schemes varies with number of channels \( M \). It can be observed that more energy is consumed for larger \( M \) for both the optimal and selective schemes. This is especially true for the optimal scheme as it has to scan all channels, and greater the value of \( M \), the more channels it has to scan. Note that with a fixed node ratio, the contention on each channel is kept constant. For the selective scheme, it has to scan all channels only periodically (every \( C \) period), and thus consumes lesser energy. The greedy and sticky schemes are not impacted at all by a varying \( M \) as they do not necessarily have to scan all \( M \) channels; they stop as soon as they find a desirable channel. Thus, the greedy and sticky schemes could be considered more scalable and better suited when the overall number of channels to be considered is large.
Fig. 9. Selective Scanning: Energy savings for varying values of $C$ and Channel Ratio $\alpha$.

Fig. 10. Energy consumed when using each of the four proposed scanning schemes with varying number of channels $M$. For all schemes, $T_{\text{scan}}$ was kept fixed at 200 ms.
VI. Simulations for Dynamic Channel Scenarios

In prior sections we studied the energy benefits of CR-technique only for the single-shot scenario where a node just makes one decision to switch channels or not and how much energy it can save over its current channel. It was assumed that after the switch the two channels (old and new) maintain their relative node contention. In practice, the number of nodes on channels will vary over time with arrivals and departures of nodes. In this section we provide a brief evaluation through simulations of such dynamic node arrival and departure channel scenarios over time. We consider only the optimal and greedy schemes here; the intention of this section being simply to understand the impact of dynamic channel scenarios without considering and comparing all the schemes presented in the paper.\(^7\)

A. Simulation Setup

We simulated 20 dynamic channels (to stay consistent with most of the numerical results obtained in the previous section where \(M = 20\) was the most common value used) using MATLAB with nodes arriving and departing per time slot based on the poisson distribution.\(^8\) Both the arrival (\(\eta\)) and departure (\(\mu\)) rates were set to either 0.01 or 0.4 per time slot to study slowly varying and highly dynamic channels respectively. On all 20 channels we began with a fixed number of nodes each, and let the channels vary based on the arrival and departure rates. One of the channels was chosen randomly to be the current channel where the node began its communications, and this was also the channel which was used to compute energy consumed by the conventional radio over the period of the simulation. The node employing the CR-technique shifted across channels and chose the best channel it found based on the specific scanning scheme under consideration during the simulation. We computed the average energy consumed for both the node employing CR-technique and the conventional radio for 1000 repeated experiments. The data points shown are the mean over these experiments; for \(\alpha = \mu = 0.01\) the standard deviation of the energy savings seen was very small due to little variability; for \(\alpha = \mu = 0.4\) the standard deviation was of the order of 10\% due to the large variability in number of nodes on each channel. Due to the asymmetricity in values of standard deviation for these two lines, we do not show these in our plots.

B. Evaluation Results

Energy savings when using optimal scanning in dynamic channel scenarios beginning with 20 nodes on each channel is shown in Figure 11. For \(\eta, \mu = 0.4\) the trend can be observed to be similar to the results from our numerical evaluations before, but a direct comparison is difficult as we do not have parameters like node ratio here. The CR finds channels that are better over the current channel when it switches, but the degree of improvement varies over time. Thus, for small values of \(T_{\text{scan}}\) energy savings are of the order of 15-20\%. Higher values of \(T_{\text{scan}}\) eat up most of energy benefits of reduced benefits and end up costing energy after a point. For the slowly varying channel (\(\eta, \mu = 0.01\)), the CR ends up consuming more energy due to the periodic scanning it has to do; there is little or no benefit in terms of reduced contention with the number of nodes on each channel remaining more or less static.

For the greedy scanning scheme we performed two experiments: one with fixed \(\Delta\) and one with variable \(\Delta\), where \(\Delta\) was the threshold improvement sought. With decisions to be made every time slot on what is the next channel to use for a CR, \(\Delta\) is the threshold improvement over the current channel, where the current channel keeps changing as channel switching happens. For the conventional radio, the

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\(7\)Interested readers are referred to the paper that appeared at CROWNCOM 2013 \(^{[30]}\) for results of all four schemes; an extended version of this paper is available as a technical report in \(^{[36]}\).

\(8\)Though we have not found any prior work characterizing node arrivals and departures in ad hoc scenarios, prior work in \(^{[37]}\) has characterized node arrivals on specific channels in infrastructure-WLAN scenarios that can be characterized through a poisson process. It is also common to use a poisson process to simulate arrival/departures in computer systems.
Fig. 11. Optimal Scanning: Percentage energy savings for varying $T_{scan}$. Number of nodes per channel at the beginning of the simulation is 100.

Fig. 12. Greedy Scanning: Percentage energy savings for varying $T_{scan}$. Number of nodes per channel at the beginning of the simulation is 100.

Fig. 13. Greedy Scanning: Percentage energy savings for varying $\Delta$. Number of nodes per channel at the beginning of the simulation is 100.

channel where it began operation was still considered to be the current channel. For these experiments we started each channel with 100 nodes so as to avoid the boundary conditions of only 1 or 2 nodes on a channel when $\Delta$ is very large (e.g. 0.9). In Figure 12 we can see that the CR saves a similar amount of energy as the optimal scanning scheme for a fixed $\Delta$ value of 0.2. The interesting results are then for the case of varying $\Delta$.

In Figure 7b we had observed energy savings exponentially increasing with increasing delta for the non-dynamic scenario with greedy scanning. In the dynamic scenario considered here in Figure 13 for $\eta, \mu = 0.4$, the energy savings are the greatest with a small $\Delta = 0.1$, and then slowly decrease with increasing $\Delta$. This can be attributed to the fact that being able to find channels with greater improvement over a current channel gets more and more difficult with increasing $\Delta$, resulting in many time slots where the current channel is retained after all $M$ channels scanned. This does not hurt energy savings a lot overall though as the big improvement in channels found help offset some of the loss of energy due to excessive scanning. The conclusion from this experiment then is that seeking only a small improvement over a current channel every time slot is a good strategy for a CR. That is, the greedy scheme should not get too greedy. For $\eta, \mu = 0.01$, we see the same trend of the CR wasting more energy than a conventional radio. As $\Delta$ increases, the CR scans more channels and ends up wasting more energy; for small $\Delta$ it still has to at least scan its channel every period which is an extra cost.

VII. CONCLUSIONS

This paper presented an analysis of the energy consumed by CR-based radios when competing amongst themselves to find and utilize spectrum for communication. The ad hoc WLAN scenario in the ISM band was used as a case study of a highly congested environment. Numerical evaluations and simulations compared the energy consumed by a secondary user with CR capabilities of scanning and selecting spectrum to a traditional WLAN node staying on a channel all the time.

Four channel scanning schemes were proposed for CR-based nodes that were shown to result in considerable energy savings for a CR-based node compared to a conventional radio under certain conditions. These conditions are based on the node distribution across frequency channels (represented by the node ratio parameter for optimal and selective scanning schemes, and $\lambda$ for the greedy and sticky scanning schemes), the amount of time $T_{scan}$ required to scan a channel and determine relevant factors like node contention on it, and the number of channels $M$ being considered. Our evaluations showed the impact of
these relevant parameters on the energy consumption of a CR node as compared to a conventional radio node.

Relative comparisons among the schemes show that the selective scanning scheme can perform better than its special case, the optimal scanning scheme, if $\alpha$ and $C$ are properly chosen. The greedy and sticky schemes are better in terms of scalability than the optimal scheme as they need not necessarily scan all channels, but like the selective scheme, rely on picking correct values of $\Delta$ and $n_c$, respectively. The optimal scheme is a very simple scheme that guarantees channels with the least node contention; the other three schemes can be tuned to find such channels as well, possibly without scanning all channels. Simulations of more dynamic channel scenarios showed that the energy benefits of cognitive radios still remain, but there are some changes to how some parameters impact the results under these scenarios.

We can further relax the assumption of constant channel conditions and modify our scanning algorithms to improve how we select a channel for communication by considering both node contention and channel conditions. Including channel conditions in the selection of channels is not expected to change our result that energy spent in scanning is outweighed by the energy saved by the quality of the channel found. Channel conditions, for example error rates, would be a new dimension along with the studied dimensions in this paper. This new dimension is better explored through simulations$^9$ as it allows the creation of a highly dynamic environment and can be extended to consider other schemes and parameters. However, the analytical results in this paper still serve as a useful guideline for more static scenarios with more or less constant channel conditions across the spectrum under consideration.

**ACKNOWLEDGEMENT**

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**REFERENCES**


$^9$As is done and presented in the paper that is set to appear at CROWNCOM 2013 [38], an extended version of which is available as a technical report in [36].


