On the Energy Efficiency of Cognitive Radios -
A Simulation Study of the Ad Hoc Wireless
LAN Network

Abstract—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 has mainly dealt with how spectrum can be sensed, the co-existence of primary and secondary users, and the channel access aspect.

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 achieving better communication performance on selected spectrum. The benefits in terms of reduced energy consumption, however, due to easier channel access and less contention have been quantified in prior work. This work reviews all analytical results, simulate real network with channel condition, compares analytical and simulated results, studies important parameters and their impact on energy consumption.

Index Terms—Cognitive Radios, Energy Consumption, Spectrum Scanning, Wireless LANs

I. INTRODUCTION

We explained our proposed scanning schemes and formulated mathematical models in [1]. In analytical approach, fixed values of many parameters have been used to perform numerical analysis. But in reality those parameters are dynamic in nature. In cognitive radio, nodes admit, drop and move among specified number of radio channels. So, number of nodes in any radio channel at any given time will be unpredictable. Numerical evaluation over simplified the validation process. In this work we take it to the next level by adapting all the parameters with their uncertain values.

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The goal of this work is to weigh the positive and negative impacts of the CR technique on energy consumption 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 cognitive radio as opposed to a conventional radio (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 cognitive radio can save energy taking into account a model that includes both the physical layer as well as higher layer aspects like number of frequency channels, node distribution, time spent scanning a channel, and number of contending nodes.

Mandayam [2] points out that one of the main driving factors for using cognitive radios has been the increasing density of Wireless LAN (WLAN) deployments and resulting congestion. Thus, our focus in this work would specifically be on WLAN devices. 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. Limiting this study to just the WLAN scenario allows us to understand the results against the backdrop of an extensive amount of research already done in the WLAN area. Further, this acts as the first step in preparing for similar research involving other wireless technologies like cellular data networks and wireless sensor networks.

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 cognitive radio. Section V describes simulation setup and the value of various parameters range. Section VI evaluates the impact of various parameters on cognitive radio energy consumption as compared to a conventional radio. We discuss the implications of our results and possible future work in Section VII.

II. RELATED WORK

The sensing aspect of CR mainly deals with finding the right spectrum to use for communication, as introduced in the seminal paper [3]. This involves finding spectrum that provides the best communication possibil-
ities 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 [4], [5], [6], [7], [8], [9], [10], [11]. Further, the detection and avoidance of primary users (PU) 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 [12], [13], [14], [15]. Some important considerations include the determination of the duration to sense the channel [16], [17] and the duration to communicate packets [18]. In [19] authors proposed new MAC protocol to optimize scanning time. They used only one radio for both channel scanning and data transmission.

The channel access aspect of CR can be classified based on the type of network architecture: infrastructure/centralized or ad-hoc/de-centralized. MAC protocols for CR 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 [20] for infrastructure CR networks is a random-access protocol which relies on differentiated access to the medium for packets from or to primary users (PUs), with other CR nodes having a lower priority. The IEEE 802.22 standard for CR uses the notion of superframes and slots at the base station to control access to the medium [21]. 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 CR networks, 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 [11]. Comprehensive scanning is not realistic for real time data transmission. Authors worked on sensing order in [22]. Further reading on MAC protocols for CR can be found in the survey in [23].

The work in [24] 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 work by [2] specifically points out that one of the biggest motivations for CR techniques is WLAN spectrum congestion and continuing density increase of wireless devices. The work in [25] 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. Our work is complementary to their work and looks at the problem from a higher layer perspective. 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 our preliminary work [26], we had defined the problem and looked at only a subset of these approaches with a limited performance evaluation.

### 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 cognitive radio (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 [11], [23]. This occurs for a duration of $T_{\text{scans}}$ before the next unit of time $T$ begins, as shown in Figure 1.\(^1\)

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 $E_{\text{scan}}$ be the expected energy consumed per scan. If $E_{\text{pkt}}$ and $T_{\text{pkt}}$ are the expected energy and time required to send a single packet with

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1. Later in this paper, it will be shown the the overall time to scan depends on the nature of the scanning scheme chosen and not a constant as shown in Figure 1 for simplicity.
$k$ nodes contending for specific channel conditions, $\gamma$, then the expected per-packet energy consumption of the cognitive radio, $E_{CR}$ can be modeled as

$$E_{CR} = \hat{E}_{pk} + \frac{\hat{E}_{scan}}{T/T_{pk}},$$

where the second term amortizes the cost of scanning over the number of packets sent in period $T$ computed as $T/T_{pk}$.

Since the conventional radio has no scanning overhead and stays on the current channel, its expected per-packet energy consumption can be expressed as

$$\hat{E} = \hat{E}_{pk},$$

where $n$ nodes contend on the current channel with channel conditions $\gamma_0$.

The cognitive radio under consideration saves energy for packet communication if

$$E_{CR} < \hat{E}. \quad (3)$$

Channel conditions could be modeled by letting $\gamma$ be the bit error rate on a channel. Let $f(\gamma)$ be the expected number of re-transmissions needed per packet for a specific $\gamma$. For each packet sent by a node in ideal channel conditions, it would need to send $f(\gamma)$ additional packets.

Thus, above equations could be written as

$$\hat{E}_{CR} = (1 + f(\gamma))\hat{E}_{pk} + \frac{\hat{E}_{scan}}{T/T_{pk}(1 + f(\gamma))}, \quad (4)$$

and

$$\hat{E} = (1 + f(\gamma_0))\hat{E}_{pk}, \quad (5)$$

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.

B. Application Scenario and Assumptions

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.

It is assumed that every node always has packets to send. This assumption makes sense when comparing an ordinary radio to a cognitive radio, as better spectrum is sought when there is high contention on one channel and a different channel with fewer nodes is sought. We assume an ad-hoc WLAN environment in this work where nodes are free to choose the channels they wish to communicate on, with no centralized deployment authority. This assumption allows the flexibility to later extend this work to non-WLAN scenarios as well which may have no fixed infrastructure.

IV. Energy Consumption Analysis

In this section we analyze for the components of $E_{CR}$ 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 $\hat{E}_{pk}$. We begin by describing the basic energy model and analyzing the building blocks required to compute $\hat{E}_{pk}$. Subsequently, we propose four spectrum-scanning algorithms and analyze the energy required to scan, $\hat{E}_{scan}$, for each of them.

A. Energy Model

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

$$E_{tx} = P_{tx}T_{data} + P_{tx}T_{ack} + P_{idle}T_{difs} \quad (6)$$

while a packet collision incurs the following cost

$$E_{coll} = P_{tx}T_{data} + P_{idle}(T_{ack} + T_{difs}) \quad (7)$$

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

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

(8)

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

\[ E_d = P_{rx}T_{hdr} + P_{idle}T_{difs} + P_{sleep}T_{nav} \]  

(9)

where \( T_{nav} = T_{data} - T_{hdr} + T_{ack} \) is the time duration of network allocation vector (NAV) (as defined in [21]) 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

\[ E_{rxc} = P_{rx}T_{hdr} + P_{idle}(T_{c} - T_{hdr} + T_{difs}) \]  

(10)

where \( T_c \) is the duration of the collision after which the station does not decode the packet any further.

3) Energy Consumed for Backoff: We base our analysis on [27] and [28] 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 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 [28]. 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 as [27]

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

(13)

where \( p_{r} \) is the probability that a packet on the medium is destined to the given node.\(^{2}\)

\(^{2}\)For our evaluations later in this paper, we take \( p_{r} = \frac{1}{x} \) for the scenario where any of the other nodes could be the possible destination.

B. Energy Consumed to Communicate on a Channel

The IEEE 802.11 DCF has been well analyzed by previous work in [27], [28]. 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.

C. Energy Consumed to Scan Channels

The energy consumed by the scanning process (\( \hat{E}_{scan} \) 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 \( x \) channels to scan including the current channel. Let \( T_{scan} \) and \( T_{sw} \) be the time spent in scanning a channel and time required to switch between channels respectively. Let \( E_{ch\_scan} \) be the expected energy consumed while scanning a single channel, and \( P_{sw} \) be the average power consumed for switching channels.

Thus, the energy consumed by the scanning process \( \hat{E}_{scan} \) can be written as

\[ \hat{E}_{scan} = x\hat{E}_{ch\_scan} + (x-1)P_{sw}T_{sw} + ps_{sw}P_{sw}T_{sw} \]  

(15)

where \( p_{sw} = 1 \) if a better channel is found than the current one else \( p_{sw} = 0 \). 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.

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 takes least energy to transmit a data packet by considering number of nodes contention and channel condition.

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.

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 and channel condition. So in other words a node will hunt for another channel only if the anticipated energy goes above a certain number, say $E_c$. But it must scan its own channel in periodic fashion (every period $T$) to know the critical energy, $E$ on the current channel.

4 Selective Scanning
In this scanning scheme a node scans all $M$ channels when it is turned on and then selects a subset of $M$ channels that have the least anticipated energy. It saves those channels and keeps scanning only those channels at each period $T$. The assumption is that those channels will always provide a good channel for communication without incurring the cost of scanning all channels. As the selected subset of channels might get worse over the period of time, a node scans all $M$ channels again after $C \cdot T$ period, where $C$ is a configurable count that controls how often a node does a complete scan.

V. Simulation Setup

We used MATLAB for this simulation. Theoretically cognitive radio can use as many radio channels as it can. But we are considering WLAN only at this time and WLAN does not have more than twenty channels. So our simulation is restricted to use only twenty channels. But to show the impact of number of channels on energy savings, more than twenty channels have been used once.

Random number generator is used to simulate number of nodes in any radio channel at any given time. We studied two discrete random variables: Binomial and Poisson distribution. Poisson random variable is a count of Poisson distribution. Binomial random variable is the number of successes in a series of trials. So we chose Poisson random generator to generate random numbers. Admission rate increases little bit when peak hour approaches and departure rate increases when off peak hour approaches. If we ignore small time interval in between off peak and peak hour, admission and departure rates are almost equal. Multiple admission/departure rates: 0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 are chosen to grasp different traffic density at different time of the day. In our plot we used 95% confidence interval. We did not consider primary users at this time as we focused on WiFi bands which don’t have PUs.

VI. Simulation Evaluation

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. More information about our experimental setup for measuring these values can be found in [29].

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

TABLE I VALUES FOR PARAMETERS USED IN EVALUATIONS

A. Optimal Scanning

In Figure 3(a), node reduction increases with higher admission/departure rate. But at low rate cognitive radio can’t save energy.

In Figure 3(b), node reduction rate increases with admission/departure rate but not at the same pace like in ideal channel condition case.
In Figure 3(c), at low admission/departure rate, energy savings is positive. Cognitive radio can save energy if it uses optimal scheme in ideal network case. It can save even more in non-ideal network scenario.

In Figure 3(d), energy savings increases when number of channels increase from 10 to 20 and then it decreases. When no of channels increases too much it has to spend more energy to scan all the channels in optimal scheme. Though it gets more chance to find relatively better channels, ultimately it can not beat the energy spending for scanning. So energy savings reduces.

B. Greedy Scanning

In Figure 4(a), node reduction increases at higher admission/departure rate. So does Energy savings.

In Figure 4(b), in non ideal network, we see negative energy savings and almost zero node reduction at low rate. But node reduction increases with higher admission/departure rate.

Energy savings for both ideal and non-ideal cases are presented in Figure 4(c). Whether network is ideal or not, energy savings is not happening at low rate.

In Figure 4(d), energy savings increases at some point of delta. After that point we get reduced energy savings. And at one point we get negative values in energy savings for both ideal and non-ideal network scenarios.

C. Sticky Scanning

In Figure 5(a), node reduction and energy savings increases with higher admission rate.

In Figure 5(b), cognitive radio considers both: channel condition and number of nodes to consider whether it will stick to the current channel or not.

In Figure 5(c), we observe positive energy savings for both ideal and non-ideal scenario. But we can save more energy in non-ideal channel compared to the ideal channel scenario.

In Figure 5(d), variable threshold vs energy savings are presented for ideal network scenario. Energy savings increases at higher threshold. But after a certain limit, cognitive radio does not try to find a better channel as it is comfortable with the current channel.

D. Selective Scanning

In Figure 6(a), node reduction and energy savings vs
admission/departure rate for ideal channel case.

In Figure 6(b), non-ideal case, cognitive radio considers number of nodes and channel condition at the same time. So, node reduction is reduced here compared to the ideal case.

In Figure 6(c), energy savings vs variable admission and departure rates are presented for ideal and non-ideal cases.

In Figure 6(d), variable time period (to update the subset) versus energy saving is presented for both ideal and non-ideal cases.

In Figure 6(e), variable subset length versus energy savings are presented for both ideal and non-ideal cases. In increasing subset length, scanning energy overtakes data transmission energy savings and causes small adverse effect on overall energy savings.

VII. CONCLUSION

From our simulation results, it is clear that all four schemes can save energy if the parameters are chosen carefully. If we assume channel conditions are always non ideal in real world then we can say cautiously, cognitive radios are more energy efficient than conventional radio at any time (any rate).

All four schemes can save energy but at different magnitude. Selective scheme seems outperform all other schemes in energy savings.

We formulated mathematical model for our proposed scanning schemes and presented analytical result in [1]. In this paper we simulated those schemes. Our simulation results approved analytical results. In this paper we used random channel condition and dynamic network scenario. Data transmission energy gets affected when cognitive radio moves from one frequency to other. So "frequency" impact on energy efficiency of cognitive radio can be explored in future.

REFERENCES