On the Energy Efficiency of Dynamic Spectrum Access under Dynamic Channel Conditions

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***Abstract*—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 of 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 rarely quantified in prior work. This work defines and studies the impact of important parameters on the energy consumption of a CR node under dynamic channel conditions. Results obtained include the range of parameter values under which a CR node is more energy-efficient than a conventional non-CR node, and a comparison of the effectiveness of different spectrum scanning algorithms.**

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

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 not paying as much attention to the energy consumed by 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 study the energy consumption of dynamic spectrum access in nodes employing the CR technique under dynamic channel conditions. 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) compare different spectrum scanning algorithms under dynamic channel conditions with energy consumption as a metric, and (iii) provide an operating range of parameters where a CR node can save energy for each scanning algorithm considered.

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. This ties in with other existing efforts in the area that includes the White-FI (IEEE 802.11af standard) working group. 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

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associated energy consumption.

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 [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 (e.g. [7], [8]). 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 [11], [12] and the duration to communicate packets [13]. It is important to distinguish between sensing and scanning. The SU senses one particular channel to check whether it's being used by a PU or not. However, multiple channels are scanned by one or more SU. Since scanning is energy intensive, energy consumed in scanning is classified as the number one problem that might delay the advance of CR [14]. In [15] authors proposed new MAC protocol to optimize scanning time while the authors of [16] worked on finding an ideal ordering of channels to sense.

The work in [17] 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 in [18] explores energy consumption aspects of CRNs but not on CR-techniques for a broader class of radios independent of PUs. The work in [19] 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 these works 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 three different approaches to scan for better spectrum. In early preliminary work [20], we had defined the problem and proposed some of the approaches mentioned in the paper, but conducted only a limited performance evaluations under a static channel condition scenario.

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 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.

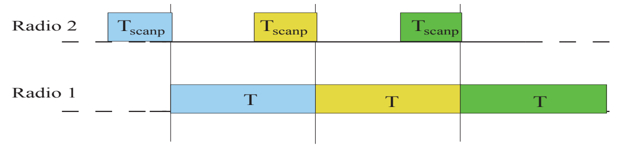


Fig. 1. Model of communication and periodic scanning with two radios at a CR node

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.

A. Problem Statement

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 [21], [22]. This occurs for a duration of T_{scanp} 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 CR node as opposed to n nodes on the current channel. Also, let T be the duration between beginning each scan, and $\hat{E}_{scan}$ be the expected energy consumed per scan. If $\hat{E}_{pkt}^{k,\gamma}$ and $\hat{T}_{pkt}^{k,\gamma}$ are the expected energy and time required to send a single packet with k nodes contending for specific channel conditions, γ, then the expected per-packet energy consumption of the CR node $\hat{E}_{CR}$ can be modeled as

$$\hat{E}_{CR} = \hat{E}_{pkt}^{k,\gamma} + \frac{\hat{E}_{scan}}{T/\hat{T}_{pkt}^{k,\gamma}}, \tag{1}$$

where the second term amortizes the cost of scanning over the number of packets sent in period T computed as $T/\hat{T}_{pkt}^{k,\gamma}$.

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

$$\hat{E} = \hat{E}_{pkt}^{n,\gamma_0}, \tag{2}$$

where n nodes contend on the current channel with channel conditions γ_0.

The CR node under consideration saves energy over a conventional radio for packet communication if

$$\hat{E}_{CR} < \hat{E}. \tag{3}$$

[1]Later in this paper, it will be shown 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.

Channel error rates could be modeled by letting γ be the bit error rate on a channel. Let $f(\gamma)$ be the expected number of re-transmissions needed per packet for a specific γ. For each packet sent by a node in ideal, no-error channel conditions, it would need to send $f(\gamma)$ additional packets under non-ideal conditions.

Thus, the above equations could be written as

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

and

$$\hat{E} = \{1 + f(\gamma_0)\}\hat{E}^n_{pkt}, \quad (5)$$

dropping the super-script for channel packet error rates under ideal scenario for simplicity.

B. Application Scenario and Assumptions

Greater contention and noise on the medium 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 packet error rates* 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. Finally, we also assume that channel packet error rates for receivers can be calculated at the sender side by monitoring channel activity during the scanning period. All information is gathered distributedly and acted upon by nodes without a fusion center; however, a common channel may be used for coordination of senders and receivers.

IV. Energy Consumption Model

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 $\hat{E}^k_{pkt}$.

A. Energy consumed to communicate a packet

The IEEE 802.11 DCF has been well analyzed by previous work in [23], [24]. Using the results of their analysis and the energy model and results presented in prior work [20], the energy consumption of communicating a packet with a total of k nodes contending can be given as

$$\hat{E}^k_{pkt} = E_{tx} + \frac{p_k}{1 - p_k}E_{coll} + \hat{R}(p_k)\hat{E}_{tick}, \quad (6)$$

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. $\hat{E}_{coll}$ and $\hat{E}_{tick}$ are the energy consumed for each packet collision and a tick (two successive decrements of a node's backoff counter) respectively. These (along with $\hat{R}(p)$ have been characterized in [20]. We can get the value of $\hat{T}^k_{pkt}$ in Equation 4 (without using the notation that includes γ) using the analysis above summing up all the time components.

B. Energy consumed to scan channels

The energy consumed by the scanning process ($\hat{E}_{scan}$ in Equation 4) depends on the scanning algorithm used. Here we propose three 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 CR node 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 three algorithms would represent most possible algorithms in the design space.

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 contending 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 consumes lower energy than a pre-defined threshold Δ, this channel is chosen over the currently used channel.

3 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. As the selected subset of channels might get worse over the period of time, a node scans all M channels again after $C \cdot T$ periods, where C is a configurable count that controls how often a node does a complete scan.

Assume that any scanning algorithm ends up scanning x channels to make its determination of the best channel to use for the subsequent period T (T was shown in Figure 1) to scan including the current channel. Let T_{scan} and T_{sw} be the time spent in scanning one channel and time required to switch between channels respectively. Let $\hat{E}_{chscan}$ 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

$$\hat{E}_{scan} = x\hat{E}_{chscan} + (x-1)P_{sw}T_{sw} + p_{sw}P_{sw}T_{sw} \quad (7)$$

where p_{sw} = 1 if a better channel is found than the current one else p_{sw} = 0. The expression in Equation 7 accounts for the energy consumed to scan x channels, including the energy to switch between them, and a final switch to the chosen channel, if needed. In the evaluations below, simulations are used to determine the value of x for each scanning scheme under different channel conditions. The value of $\hat{E}_{chscan}$ is a constant derived from prior work as described in following section.

V. Evaluation

This section begins with a description of our evaluation methodology followed by results when considered each of the the possible scanning algorithms described in the previous section.

A. Evaluation Methodology

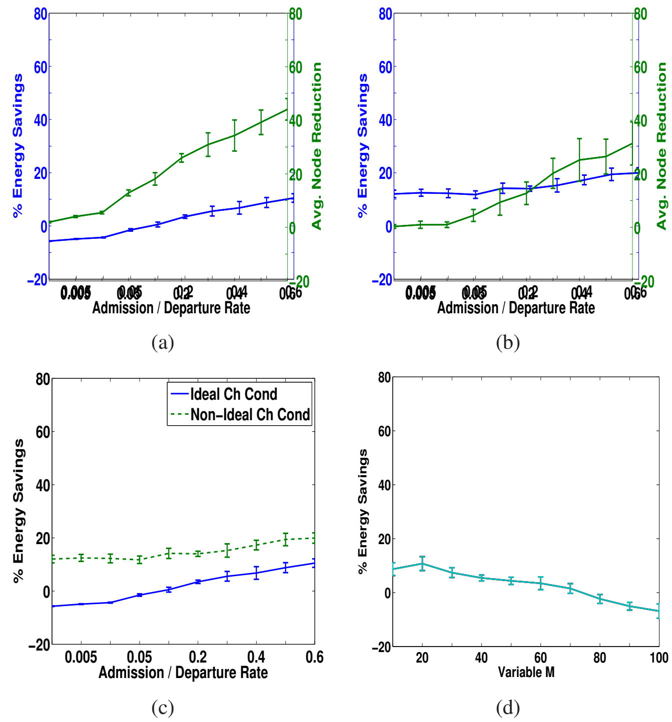
Due to the focus on studying dynamic channel conditions, our evaluations were based on a discrete-event simulator written in MATLAB. Dynamic channel conditions were simulated through a random node arrival/departure process and a random assignment of packet error rate $f(\gamma)$ to all M channels. The arrival and departure rates of nodes on channels were assigned from a poisson distribution with the average rates α and μ per time slot of size T respectively. We chose T as 10 seconds ensuring the time for communication (radio 1) would be greater than the time required to scan upto 100 channels if M were 100, with a single channel scanning time of 100ms (refer Figure 1). The average arrival and departure rates were set to be equal, ie. $\alpha = \mu$, on all channels at all times to ensure channels always had nodes within certain limits of the starting number. All M channels in the simulation were set to start with 200 nodes on each of them. Over time, with the arrival/departure of nodes from each channel, it could be seen that all M channels had a different signature of number of nodes with time as was desired for studying dynamic channel conditions. The packet error rate was assigned randomly to all M channels from a uniform distribution between 0 and 0.5, with channels with any greater error rates deemed to be unusable and not counted as part of the M channels under consideration.

Each simulation was run 1000 times with the mean value and 95% confidence intervals shown in our plotted results. Model parameters like power and time constants for the radio 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.[2] For our experiments, the size of a data packet was set at 800 bytes.

Some specific terminology used throughout when presenting our experiments include: (i) *channel load variability*, a term that specifies the rate at which the number of nodes on a channel is likely to change and can be controlled by the underlying arrival/departure rate of the poisson process used in the simulator, (ii) *ideal channel*, a scenario where the channel packet error rate is assumed to be negligible and set equal to zero on all channels, and (iii) *non-ideal channel*, a scenario where the channel packet error rate for each channel is drawn from a uniform distribution from the range 0 to 0.5.

[2]Due to space limitations these values are not listed here. Interested readers can look up our prior publication that used the same values [20]

B. Results for the Optimal Scan algorithm



(a) (b) (c) (d)

Fig. 2. Optimal Scheme

In Figure 2(a), we can see energy savings and node reduction versus admission/departure rate with all channels have a ideal zero packet error rate characteristic. Node reduction is defined as the reduction in contending nodes on the newly found channel compared to the original channel where the node was before switching. In Figure 2(b), with non-ideal channels and a packet error distribution across channels as described in V-A, node reduction achieved increases with admission/departure rate but not at the same pace like in the ideal channel error rate condition case. In Figure 2(a), negative energy savings at low admission/departure rates were due to very low node reduction as compared to the energy consumed for scanning. But in the non-ideal channel case, with node reduction not the only factor in achieving energy savings, a CR node has better opportunities to find a channel with characteristics that save more energy than what is lost in scanning. To make this conclusion clearer both the ideal and non-ideal channel results are plotted together in Figure 2(c). When admission/departure rate increases, node reduction effect gets increased compared to the channel condition effect. The result shown in Figure 2(d) indicates that energy savings increases with the optimal scanning scheme when number of channels increases from 10 to 20 and then it decreases. When a CR node has more channels to scan and select (from 10 to 20), it gets more opportunities to find a better channel and save more energy.

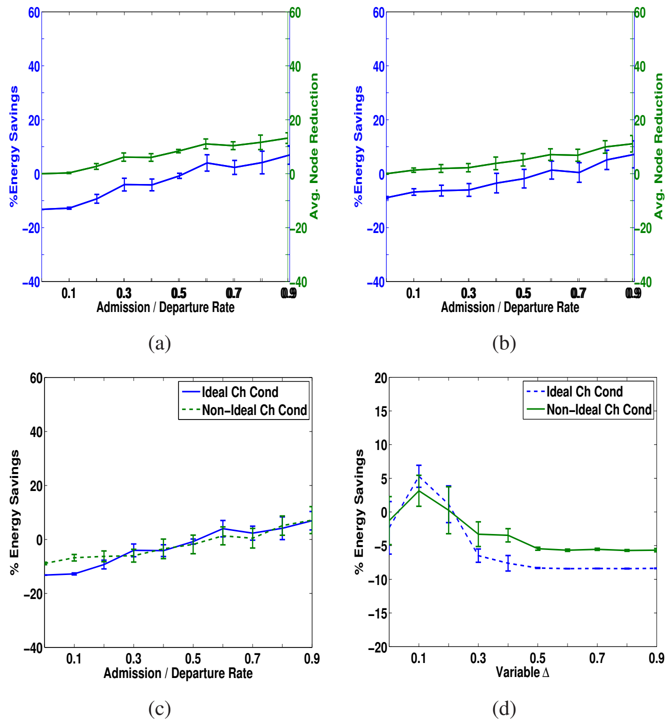


Fig. 3. Greedy Scheme

C. Results for the Greedy Scan algorithm

When using the greedy scanning scheme, a CR node scans channels until it gets a satisfactory channel that meets some percentage node reduction threshold Δ over the channel being currently used. In the experiments that follow we set $\Delta = 0.2$ to be the threshold. Figure 3(a) shows the result for the greedy scheme under ideal channel conditions. At low channel load variabilities a CR node will have difficulty in finding a qualified channel and may end up scanning all channels with nothing to show for it. Under non-ideal channel conditions (Figure 3(b)), a CR node considers both number of nodes and channel conditions by looking for a Δ percentage reduction in energy consumption instead of just number of nodes. However, similar to the result for ideal channel conditions, at low load variability, no energy savings are possible with gradual increase with greater load variability. Δ is an important parameter for greedy scanning. If a smaller Δ is used, a qualified channel will be found easily. However, smaller Δ could result in lower energy savings as well. A larger Δ could provide a larger node reduction and energy savings, but there is greater difficulty in finding a qualified channel easily which might mean excessive scanning is needed. The impact of this parameter is plotted in Figure 3(d) for a fixed arrival/deprature rate of 0.5. Energy savings for both ideal and non-ideal channel error cases increases first and then decreases. This result suggests that lower values of Δ may be more suitable and a node should not be too "greedy" when setting this value. It can also be observed that a CR node seems to do much better under non-ideal channel error conditions (as was seen in Section V-B).

D. Results for the Selective Scan algorithm

In selective scheme, a CR node creates a preferable subset of channels through a full scan of all channels and subsequently only scans that subset. To ensure the preferable list consists of the better channels all the time, this list is periodically re-created by scanning all channels. For these experiments, the period after which a full scan is done, C, is set to be 10. The subset size parameter τ is set to 0.25 which gives a subset size of 5 when $M = 20$. It can be observed from Figure 4(a) that, for ideal channel conditions, energy savings are typically higher at all variabilities compared to the optimal scheme due to the conservative approach to scanning most of the time. For non-ideal channel conditions, we see even greater energy savings in Figure 4(b), just like all the other schemes. A comparison of energy saved for ideal versus non-ideal channels is given in Figure 4(c). Two parameters of interest for the selective scanning scheme are the duration at which a complete scan of all channels must be done, and the cardinality of the subset of preferable channels. For the former, a "timer" is used to count down slots before the next full scan. If a large timer value is used, energy consumed to scan will be reduced, but it may be at the cost of "stale" channel information that may not provide the best opportunity to save energy for communication. On the other hand, a small timer value will provide updated information that could save energy for communication but increase scanning energy costs. In Figure 4(d), timer values used are varied for both ideal and non-ideal channel scenarios. The results show a fairly good balance between the two tradeoffs. A smaller cardinality of subset length (for smaller τ) will reduce the energy to scan that subset, but may become stale more quickly. A larger subset size would make the scheme mimic the optimal scheme more closely with all its advantages and disadvantages. Figure 4(e) shows energy saved as a function of the ratio of subset size to the full set size (M channels). A slowly decreasing trend of energy savings can be observed with increase in subset length. Thus, this result clearly demonstrates that the selective scanning scheme is a better alternative to the optimal scheme which uses the maximum subset length possible.

VI. Conclusions

The technical contributions made in this work include modeling and analyzing energy consumption of a CR node as opposed to a conventional node, comparing different spectrum scanning algorithms under dynamic channel conditions with energy consumption as a metric, and providing an operating range of parameters where a CR node can save energy for each scanning algorithm considered. A CR node employing any of the three proposed scanning schemes can save energy in highly dynamic channel scenarios with high channel load variability. However, in conditions of low channel load variability, the selective scanning scheme is more likely to save energy over a conventional radio due to a more conservative scanning approach that does not waste energy looking for

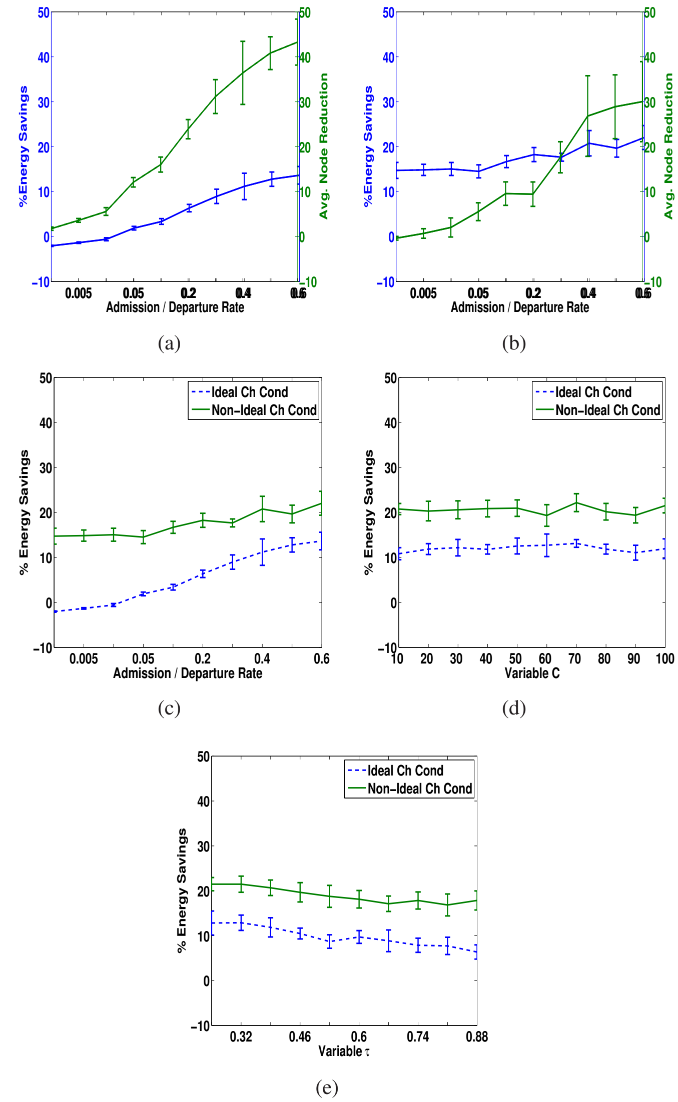


Fig. 4. Selective Scheme

better channels when one may not be available. Under non-ideal channel conditions in lossy environments, the optimal and greedy schemes provide much better performance, but may still not do as well as the selective scanning scheme. Though it might be tempting to conclude that the selective scheme may offer the best all-around reduction in energy consumption, it involves selecting two parameters that, if not chosen relatively carefully, could increase energy consumption considerably. Final technical conclusions from this study are that the CR-technique proves very useful in reducing energy consumption under highly variable channel conditions, but the scanning energy overhead may be too much to overcome under low variability scenarios where channel hopping may not provide significant energy savings. Additional work needed includes looking at the impact of various values of number of nodes and number of channels on all scanning schemes studied.

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